Int j simul model 23 (2024) 4, 611-621
Professional paper

HYBRID DYNAMIC ANALYSIS OF THE MANUFACTURING PROCESS OF LIGHTWEIGHT BRICKS

Flores, B.; Rodriguez, L.; Silva, U. & Loyo, J.
Department of Systems, Division of Basic Sciences and Engineering. Autonomous Metropolitan University Azcapotzalco, Av. San Pablo 180, Col. Reynosa Tamaulipas, Mexico City (CDMX), Mexico
E-Mail: blfh@azc.uam.mx, lwra@azc.uam.mx, ussr@azc.uam.mx, lqj@azc.uam.mx

Abstract
In this study, the hybrid simulation approach was adapted using the System Dynamics methodology to characterize continuous and discrete variables in the lightweight brick manufacturing process. Vensim® software was used to evaluate the effects of delays in production flows at specific time intervals, and the continuous impact of variability in the stages of the process was established. The results demonstrate that carrying out a continuous evaluation of the input flow of raw material does not impact the accumulation of material. However, when assessing the monitoring of delay times in a discrete approach, there is a direct impact on batch formation and production capacity fulfilment, resulting in an 8.54 % increase. In conclusion, it is crucial to not only characterize the variables but also to assess their impact using an overarching indicator, such as production capacity, rather than focusing solely on subsequent stages. This comprehensive approach enables strategic decision-making to identify areas of opportunity within the process.

(Received in August 2024, accepted in November 2024. This paper was with the authors 2 weeks for 1 revision.)

Key Words: Manufacturing Process, Discrete Behaviour, Continuous Behaviour, Hybrid Simulation, System Dynamics

1. INTRODUCTION

When simulating a production process in a real-world scenario, it may be necessary to represent it with discrete or continuous variables. The classification and categorization of these variables depend significantly on the process behaviour. For instance, analysing the accumulation of processed material at a workstation may be required at a specific point or monitored over time. A key characteristic of simulation is the evolution of entities over time. Discrete changes occur when entities undergo specific alterations, whereas continuous changes are observed when entities vary consistently over time [1].

In most cases of analysis, the causal relationships between the performance of a process and key factors that determine it are complex problems that demand computer simulation. In fact, the use of systemic methods such as System Dynamics (SD) is recommended to understand the influence of performance factors in a discrete environment measured by performance indicators based on strategic, operational and control definitions [2]. Additionally, Matlab/Simulink® with Petri nets is suggested for simulating complex deterministic systems [3]. On the other hand, FlexSim software has also been used to evaluate the impact of product structure (customization) on the execution of current production orders [4]. Authors in [5] use discrete event simulation with Tecnomatix Plan Simulation software to design and analyse change scenarios and assist in decision-making, this was evaluated in a window manufacturing company. In [6] the authors use CPLEX software for the validation of a linear mathematical model to minimize the penalty for delay in the scheduling of manufacturing jobs and the optimization of the design in a reconfigurable manufacturing system.

Systems often exhibit hybrid behaviour, where discrete events cannot be confined to a defined space in time. In [7] it is explained that hybrid simulation offers a compelling approach to problem-solving due to the lack of formalization in methods, presenting a significant challenge, a recommendation for evaluating a production system with a hybrid approach is to

https://doi.org/10.2507/IJSIMM23-4-700

assess the continuous and discrete components independently, synchronizing them only when an event occurs. An example is the study in [8], who developed medium-complexity batch process models using Matlab and Simulink® for chemical plants, addressing complex sequences and decision logic in resource management. Similarly, in [9] it is employed a hybrid approach to address supply chain planning, developing a discrete event simulation model to evaluate system behaviour over time. Also, it is developed an optimization module using the hybrid simulation approach to consider interactions between material flow and production system behaviour [10].

From another analytical perspective, in [11] it is evaluated the effects of continuous and discrete variables within a given system. In the study it is established that material shortages lead to a decline in system performance, yet the relative performance of control systems remains unaffected by the continuous disposal of materials. Methodologically, it can be argued that combining System Dynamics (SD) with discrete simulation offers a compelling viewpoint due to the feedback approach and the level of detail it can incorporate [12].

Moreover, there exists a gap between real-world industrial applications and discrete simulation analysis, due to a lack of knowledge regarding the advantages of simulated environments, although with new technologies interactive this gap is increasingly closing. In contrast, discrete simulation has been extensively explored in applied cases within small and medium-sized industries [13].

Another approach to evaluate a production system is to integrate discrete dynamics into the continuous solution framework. Additionally, an interesting perspective it is presented, posing the question of when to use discrete, continuous, or hybrid simulation methods [14].

This research presents the formulation of a hybrid model based on the System Dynamics (SD) methodology, enabling the evaluation of a process's real behaviour by combining continuous and discrete characteristics. This evaluation analysed the impact on production capacity compliance by determining the effects of delays in production flows at specific time intervals for batch formation and establishing the continuous impact of variability across the stages of the manual process.

2. METHODOLOGY

In several investigations [15-17] it has been established that the methodological sequence for a simulation process, whether continuous or discrete, generally consists of six stages, ranging from task definition to experimentation and analysis. Alternatively, this sequence can be condensed into three stages: conception, implementation, and analysis, or into four stages: identification, definition, analysis, and verification [18]. To develop the proposed model, the SD methodology was employed, utilizing Vensim® software to simulate both discrete and continuous behaviours [19, 20]. Interdependence is an interesting case of analysis of the application of Vensim® software with discrete and continuous variables, as expressed in [21] where it is even combined with the value stream map to improve the process analysis approach.

According to the SD methodology, once the process information is available, the model's structure is defined by identifying flows, levels, and delays that represent the real behaviour of the case under analysis. At this stage, the variables and equations of the process are established. The model is then validated to ensure that the equations and parameters accurately reflect the real conditions of the process. Finally, the dynamic model is executed, and the simulation runs are evaluated based on the variables of interest.

In the system under analysis, the developed model represents continuous variables as the rate of change over time, necessitating continuous monitoring. Discrete variables, on the other hand, represent random phenomena, requiring observation at specific points in time.

2.1 Case study analysis

A company dedicated to the manufacture of light concrete bricks for construction was analysed. In Mexico, these bricks can be made using sand or *tepojal*, a type of volcanic stone that is very light and highly porous. Fig. 1 shows the brick and the batch manufactured. The finished bricks measure 10 cm in width, 5 cm in height, and 25 cm in length, with an average weight of 406 grams. The combination of materials in this product is not unique. In [22] it is mentioned that it has been shown that increasing the content of fillers led to a significant improvement in fresh properties. On the other hand, the hardened properties will generally decrease with the addition of these minerals. This is important to mention since, depending on the structure of the product, the mixing and drying times are defined.

To manufacture a batch of bricks, the process involves using 10 kg of sand, 5 kg of cement, and 3 litres of water. This mixture produces 3 sublots of 6 bricks each, resulting in a total of 18 bricks per batch. Once a homogeneous mixture is achieved, the forming process takes place, during which the bricks acquire their shape. Following this, the bricks undergo a setting process, requiring a waiting period for hardening. The company estimates that during an 8-hour workday, between 400 and 415 batches of bricks must be produced, equivalent to approximately 7,200 to 7,420 bricks.

Figure 1: Dimensions of a lightweight brick made with *tepojal*.

To determine the delay times and variability in the manual process, a time study was conducted. This study provided the time required for each stage of the process, allowing for a detailed analysis of the production system's configuration, both piece by piece and batch by batch. The results are presented in Table I.

Table I: Process time.

Stage	Time
Water addition (in a range of 3.19 to 3.93 L)	5 min
Cement addition (in a range of 4.77 to 5.79 kg)	5 min
Tepojal addition (in a range of 9.37 to 11.89 kg)	5 min
Mixing and pouring	69.68 s
Hand forming	14.9 s
Setting (3 sublots)	44.7 s
Drying	24 h

The entry of raw materials, including water, cement, and *tepojal*, is recorded every 5 minutes (interarrival time) in different quantities. This is followed by a mixing process lasting 69.68 seconds. During the forming process, there is a delay of 11.89 seconds attributable to the pouring of raw materials. The formation of batch sizes in the forming process evaluates the discrete behaviour of the system, considering the accumulation of raw materials at a specific point in the evaluation scenario. This accumulation is impacted by the incidences of delay time and process variability.

2.2 Mathematical model

The parameters and equations are detailed below, identifying the variables with continuous and discrete behaviours.

Raw material input flows: Water, Cement, and Tepojal. These variables determine the discrete behaviour of the entry of the three types of raw materials into the process before moving to the mixing area. To simulate the entry of a certain batch of raw materials at a set time, the *Pulse Train* function was used. This function allows the variable to adopt a specific value for a set duration and at a defined frequency, expressed through four arguments: {start}, {duration}, {repeattime}, and {end}. Eq. (1) presents the parameterization for the input flow of the raw material "water".

$$\begin{aligned} Water = {} & Pulse\ train\left(0,1,\left(\frac{85.2}{60}\right),480\right)\cdot \text{randon uniform}(3.19,3.93\ ,0\ ) \\ & + Pulse\ train\left(1440,1,\left(\frac{85.2}{60}\right),1920\right)\cdot \text{randon uniform}(3.19,3.93\ ,0\ ) \\ & + Pulse\ train\left(2880,1,\left(\frac{85.2}{60}\right),3360\right)\cdot \text{randon uniform}(3.19,3.93\ ,0\ ) \\ & + Pulse\ train\left(4320,1,\left(\frac{85.2}{60}\right),4800\right)\cdot \text{randon uniform}(3.19,3.93\ ,0\ ) \end{aligned} \tag{1}$$

The initial value corresponds to the entry of the raw material. For water, the entry duration is 85.2 seconds, which represents the addition and replenishment time, and it concludes at the end of the workday, 480 minutes after the start. Given that this is a manual process, operator performance causes variability and incidents in the process. Consequently, the *Pulse Train* variable is influenced by the variability in the manual process times, represented by the *random uniform* variable. The parameters used to represent this variation are the maximum and minimum times recorded in the time study. Table I shows the parameters for the variables Cement and *Tepojal*.

Accumulation of level variables. These variables include *raw material*, *mixed product*, *moulding inventory*, *finished product*, *final product*, and *pending orders* to be delivered. They are represented as level variables since they reflect the accumulation of semi-processed products, raw materials, or finished products over time. This accumulation is based on the difference between the input flow from the preceding station and the output flow to the subsequent station, corresponding to the processed material. Eq. (2) presents the mathematical expression for the raw material variable.

$$Raw\ material = Water + Cement + Tepojal - Mixture \tag{2}$$

The level entry is governed by the flows of water, cement, and *tepojal*, while the variation in the accumulation of the raw material level is influenced by the velocity of the mixing process. All level variables exhibit this behaviour, except for the final product, which lacks an output flow. Instead, the final product variable displays the accumulation of batches produced throughout the workday within the evaluation scenario.

Continuous production flows – mixing: The flow rate of the mixing process is represented by the *Delay* function, which accounts for the delay in flow behaviour. The output variable is proportional to the average delay time and is applied continuously over time. Eq. (3) presents the mathematical expression for this variable.

$$Mixture = DELAY1I(Raw\ material, 69.68/60, 0) \tag{3}$$

The entry of raw material is delayed by an average of 69.68 seconds. This delay results in instability in the output behaviour of the mixing flow, leading to a discontinuity in the accumulation of subsequent processes. Specifically, this instability affects the accumulation of the mixed product before it moves on to the forming process.

Discrete production flows – moulding, transport, drying, delivered orders, and client orders: The production flow for these variables is characterized by discrete behaviour. After the mixing process, batches of lightweight bricks are formed, meaning that the rate of change in these variables occurs at specific intervals determined by the batch configuration. This rate depends on the inventory levels from preceding processes.

For the *Moulding* variable, Eq. (4) uses the *Pulse Train* function with the incorporation of the *Delay* variable. The moulding process targets the production of 18 bricks per batch and there is a delay of 11.89 seconds attributable to manual process variations. The *If* condition applied to this function ensures that when no *mixed product* is available, the flow of the moulding process is zero, that is, it is not possible to mould the bricks.

$$Setting = If\ then\ else\ (mixture\ product > 0, Delay1I(Pulse\ train(0,1,1,6000) \cdot 18), Delay\ time, 0), 0) \tag{4}$$

The functions for the *Transport* flow and *Drying* are presented in Eqs. (5) and (6) respectively.

$$Transport = (PULSE\ TRAIN(480, 1, 480, 5000) \cdot Moulding\ inventory)/TIME\ STEP \tag{5}$$

$$Drying = (PULSE\ TRAIN(480, 1, 1440, 5000) \cdot Finished\ product)/TIME\ STEP \tag{6}$$

These functions are determined by a starting point, both at the end of the working day, after the first 8 hours and will be repeated every 8 and 24 hours respectively. The *pulse* size or duration for each batch in the equations is constrained by the available *Moulding inventory* and finished products. The *Time Step* variable is utilized solely to adjust the scale of data display.

The *Delivered orders* variable follows the same flow pattern as the *Drying* variable. In contrast, the *Orders required by the client* variable is an assumption of three scenarios considering maximum, minimum and intermediate levels, delimited by the *Pulse Train* function. These assumptions will be assessed during the results analysis.

2.3 Causal loop diagram

Fig. 2 illustrates the causal diagram for the bricks production process. This diagram captures the overall structure of the process behaviour, characterized by the feedback from four positive causal relationships identified in the model by B1, B2, B3, and B4 (highlighted with red lines).

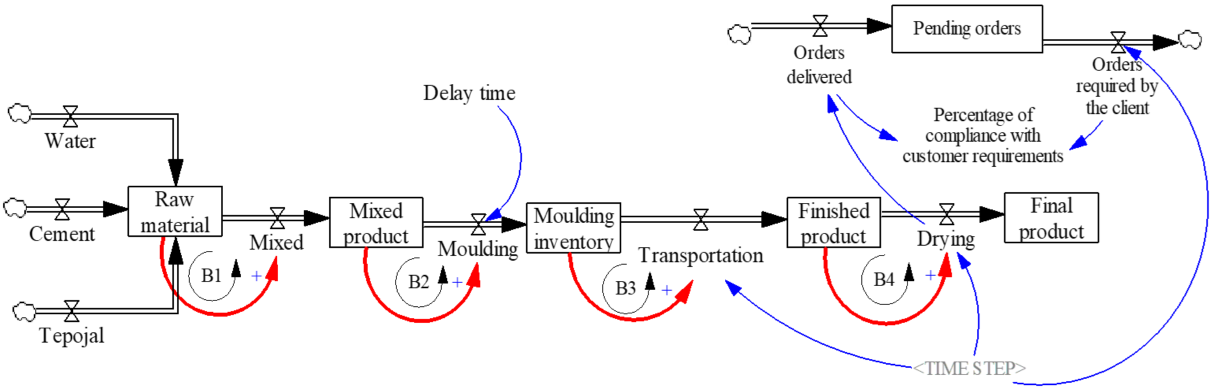


Figure 2: Causal model of the lightweight brick production system.

The causal relationships in the model make it possible to evaluate the interactions between the variables and the impact that these can have on the production process. Furthermore, they allow establishing that each output flow is limited by the levels of accumulated semi-processed product, which indicates that, if there is a deficit in inventory levels, production will not be activated. This is the main reason why feedback is positive, since increasing the previous variable also increases the next variable.

3. RESULTS

The interaction between discrete and continuous variables reflecting the behaviour of the lightweight brick production process was analysed. Simulation scenarios were conducted over an 8-hour workday, enabling the evaluation of batch inventory behaviour and the effects of delays on the continuous flow of the process.

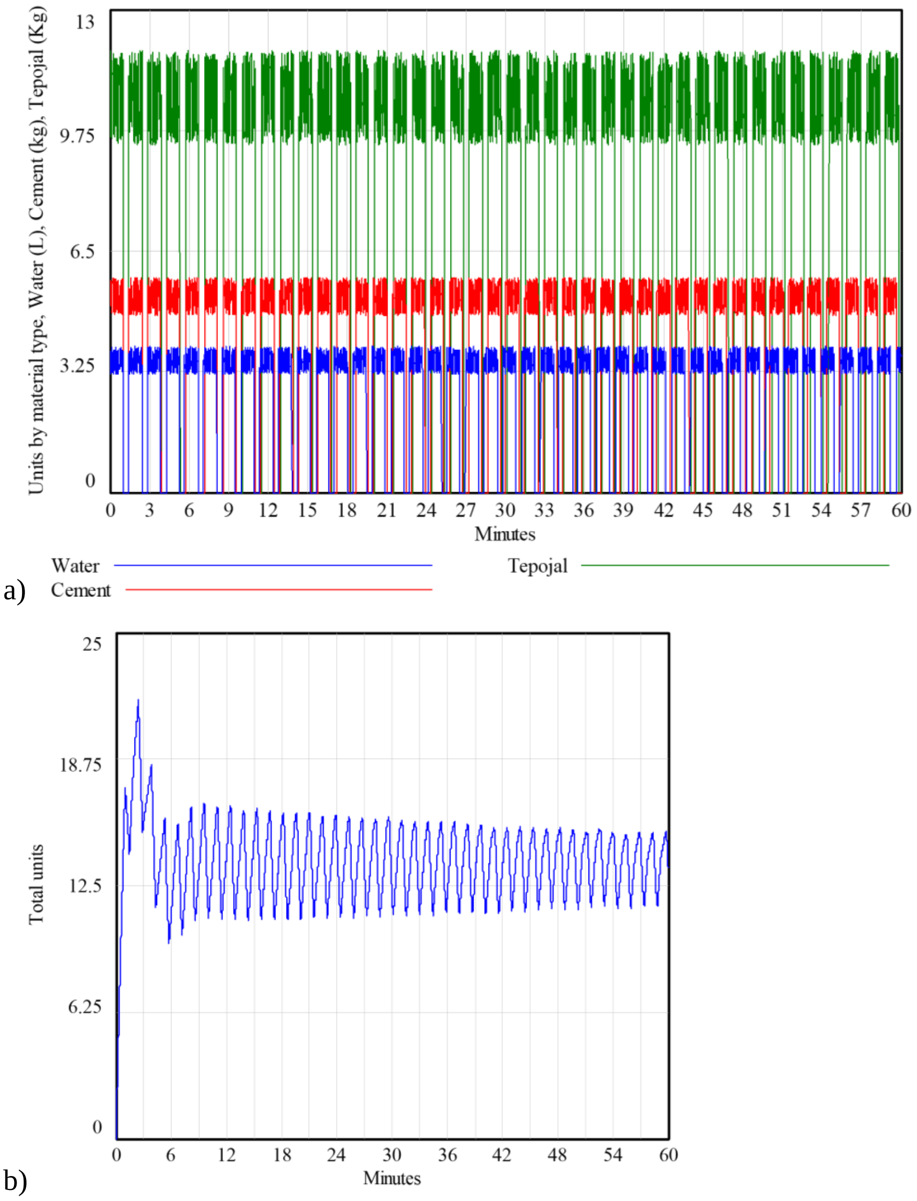
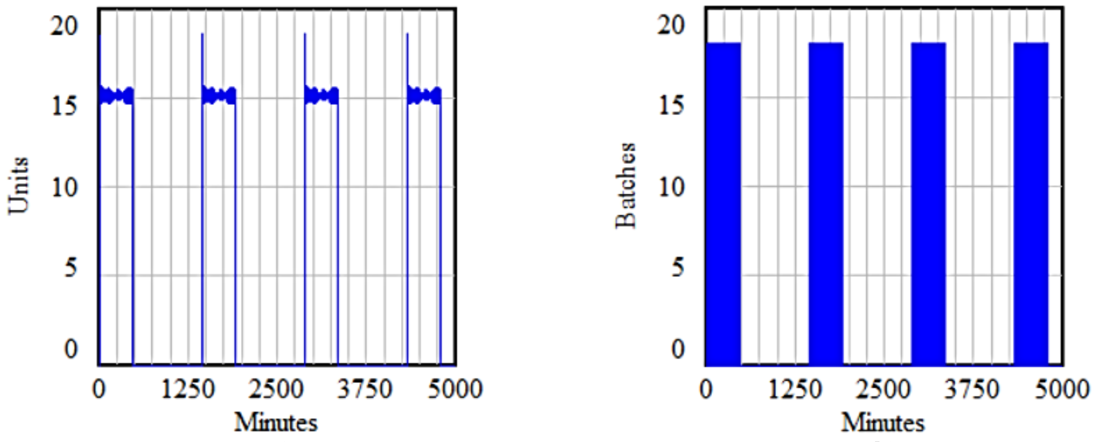


Figure 3: a) Raw material input flow, b) Raw material accumulation.

The flow of raw materials during the first hour of production is shown in Fig. 3 a. An approximate duration of 1.5 minutes was established for each material, resulting in average quantities of 3.25 litres of water, 4.27 kg of cement, and 12 kg of *tepojal*. These inputs are affected by process variation interruptions caused by operator performance, with allowable variability primarily due to 4 or 5 percent fatigue.

Fig. 3 b illustrates the accumulation of raw materials throughout the first hour of production. The accumulation fluctuates between 8 and 15 units. This variability is due to the differing velocities of material input and output flows once the raw materials have undergone the mixing process, which takes approximately 1.16 minutes.

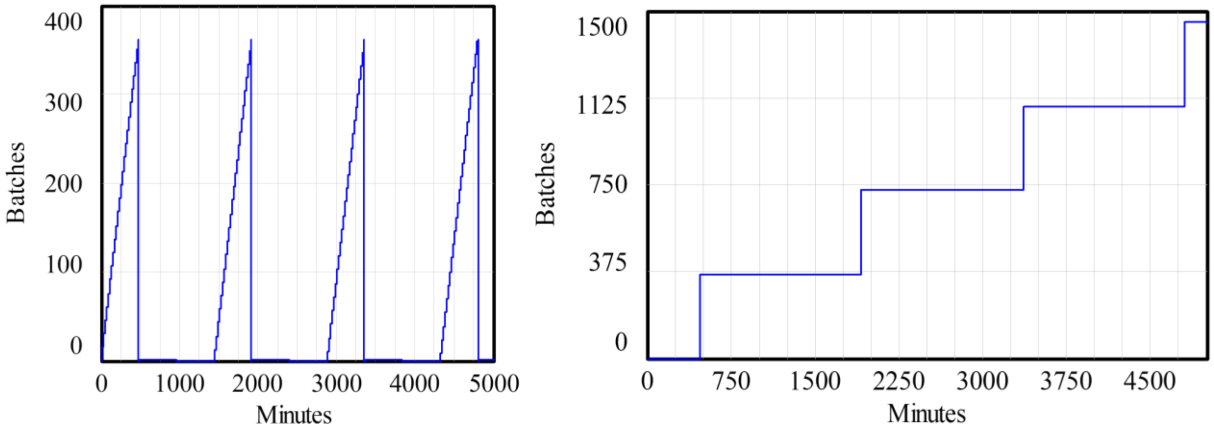


a) b)

Figure 4: a) Continuous production flow of the mixing process, b) Discrete production flow of the mixing process.

Fig. 4 shows the behaviour of the continuous and discrete production flow with delay effects of the mixing process. Fig. 4 a shows the production flow of the mixing process, which is restricted by the levels of accumulated raw material. It is observed that the levels present certain variability that generates oscillations in the flow. This is attributable to the changes in the variation of the raw material input flows and the time of the mixing process. The flow is considered continuous due to the gradual changes that occur over time, necessitating continuous monitoring.

On the other hand, Fig. 4 b shows the formation of batches of 18 units throughout the working day, which is repeated every 24 hours. To form these batches, the accumulation of mixed product is required, in this case, the delay time does not represent a major impact on the flow behaviour, so the variations are not significant over time, so this behaviour was considered discrete.



a) b)

Figure 5: Analysis of the real scenario; a) Inventory of the moulding process, b) Behaviour of the final product.

Fig. 5 a presents the material accumulation for the moulding process, taking into account that the material input flow is affected by a delay time in this stage. It was previously mentioned in Fig. 4 b that the variability in manual performance was not evident in the behaviour of flow and accumulations in the mixing process, however, in the material accumulation process for the forming process it has a gradual performance until it reaches 375 lots, when in reality it would be expected that at least 400 lots would be formed.

Fig. 5 b illustrates the accumulation of the final product throughout the working day. By the end of the first day, 375 batches are accumulated, continuing in this pattern until reaching 4 series of 375-unit batches. Therefore, this lot size represents the actual production capacity, accounting for process effects such as delays and variability inherent in manual processes.

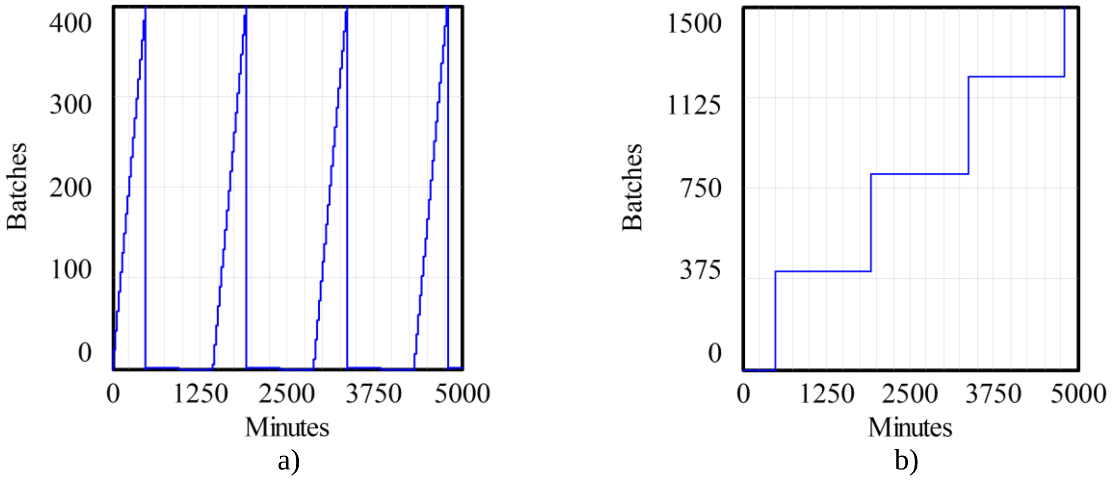


Figure 6: Analysis of the scenario without process variability; a) Inventory of the moulding process, b) Behaviour of the final product.

To assess the impact of these process incidents, a scenario was evaluated where delays and variability in process performance are eliminated. This assumes the implementation of continuous improvement tools, such as automation, in the mixing and moulding processes.

By eliminating process incidents related to variability and delay times, production capacity increases by 8.54 %, rising from 375 to 410 batches. In Fig. 6 a, the accumulation of material is shown according to the raw material input flow without the effects of delays and variability. Fig. 6 b demonstrates the accumulation of finished products based on the moulding batches.

4. DISCUSSIONS

By continuously analysing the impact of variability in the manual raw material input process on its accumulation after mixing, it is observed that there is no direct impact on the process flow since the range of variation oscillates between 8 and 15 units. This level of material availability is sufficient to prevent delays in the moulding process.

The company estimates that between 400 and 415 batches of bricks can be produced per working day. In this particular case, the level variable representing the accumulation of the finished product impacts the process output with discrete behaviour. This is because the change occurs over a specific period when the batch from the manufacturing process has been formed. However, the overall accumulation process exhibits continuous changes influenced by the delay time in the mixing flow. These changes are not perceptible until the conformation in the batch is analysed in a working day.

Evaluating improvement scenarios for a key indicator, such as production capacity, enables the determination of delivery times and maximum capacities while considering current process conditions and client requirements. This analysis highlights the importance of identifying areas of opportunity to meet established requirements, it is necessary to evaluate process variations and incidents and analyse their effects on the process. This contributes to making strategic decisions that align efforts with achieving strategic objectives.

Table II presents a summary of the characterization of the variables of interest and their incidence in subsequent stages.

Table II: Characterization of variables of interest and incidence analysis.

Variable	Behaviour	Incidence		Impact on production capacity
Delay time (moulding process)	Continuous	It was not perceptible in the subsequent stage (finished product)	Current production capacity of 375 batches	8.59 %
	Discrete	It was noticeable when determining the lot size		
Variability in the manual process (raw material)	Continuous	It was not perceptible in the subsequent stage (mixing) but became evident in the final stage (finished product).	Variation from 8 to 15 units per batch in the mixing process	

5. CONCLUSIONS

The developed model effectively characterizes and analyses the actual behaviour of the lightweight brick production process. It clarifies how the interplay between continuous and discrete variables influences the fulfilment of production requirements.

The production system combines batch production with continuous processes, where delay times and variability effects in the manual process impact continuous evaluation. Consequently, points of interest for evaluation vary throughout the process. For discrete variables, such as batch formation, specific time intervals must be assessed, such as the beginning and end of the workday. In contrast, continuous variables, which change gradually over time, require constant monitoring for accurate evaluation. This is particularly evident in the accumulation of semi-processed product inventory, such as the mixed product level variable, where continuous assessment is crucial.

To achieve an adequate representation of the process, it was essential to define the mathematical expressions for both discrete and continuous behaviours. The *Pulse Train* function, in conjunction with the *Delay* functions, enables the modelling to establish the frequency of appearance of a combined variable (discrete and continuous) and analyse the impact of the incident by delay time. The Delay function in the evaluation framework of continuous variables enabled the assessment of how delays from preceding stages affect subsequent stages, particularly manifesting in material accumulation. In this case study, the continuous changes observed are attributed to the inherent variability of manual processes and delays resulting from process disruptions.

Once the interactions were defined, the evaluation scenario revealed that the incidents of the process affect compliance with the production plan by 8.59 %. This underscores the necessity of considering the actual process conditions when formulating improvement plans to meet production requirements. In line with Mourtzis [7] and based on the results obtained, the continuous and discrete components were not evaluated independently. Instead, causal relationships were considered to thoroughly analyse the impact of process incidents in a given event as inventory accumulation.

Finally, it was confirmed that a process of this type must be evaluated using a hybrid approach that accounts for both its continuous and discrete behaviours. This method facilitates the assessment of control points at critical system changes and aids in the development of control systems for adequate management in the process opportunity areas such as competitiveness.

Future work may include developing a comparative analysis with another simulation program such as FLEXSIM$^{\circledR}$ of the results of this study to determine whether the characterization of variables established in this work can be adequately replicated. It is recommended to include in future works other variables of interest such as material costs and productivity.

The significant contribution of this research could be found in that, by successfully characterizing the continuous and discrete variables, it was possible to demonstrate their impact on the behaviour of key process variables and their interrelation with the integrated system. Likewise, derived from this work, a methodological sequence consisting of 3 stages can be established: first, it is necessary to establish the process sequence and analyse the causal relationships of the same, then define the mathematical expressions for the discrete and continuous behaviours (this will vary according to the type of program used), and finally, the impact on indicators of interest must be evaluated. This methodology can be replicated in other industrial processes.

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