Karmaoui, D., AlBalkhy, W., Lafhaj, Z. & Chapiseau, C. (2023). Lean and Industry 4.0 in brick manufacturing: a digital twin-based value stream mapping proposed framework. *Proceedings of the 31st Annual Conference of the International Group for Lean Construction (IGLC31),* 230–241. doi.org/10.24928/2023/0259

LEAN AND INDUSTRY 4.0 IN BRICK MANUFACTURING: A DIGITAL TWIN-BASED VALUE STREAM MAPPING PROPOSED FRAMEWORK

Dorra Karmaoui[1], Wassim AlBalkhy[2], Zoubeir Lafhaj[3], and Christophe Chapiseau[4]

ABSTRACT

As one of the most important industries to face the global housing challenges, brick manufacturing can benefit from the principles of lean and the applications of Industry 4.0 to achieve better organizational, environmental, and operational performance. This study reviews the efforts made on lean-Industry 4.0 integration in brick manufacturing and proposes a framework to support this integration. The proposed framework is based on the use of digital twin (DT) technology to create dynamic and automated Value Stream Mapping (VSM). The proposed framework aims to continuously visualize, monitor, and improve the flow, value creation, and waste elimination in brick production processes. The study also reports the state of the implementation of the framework in a brick company in France as a case study. Validating and testing the framework is possible in different types of manufacturing companies; even out of the brick manufacturing sector.

KEYWORDS

Brick manufacturing, Lean, Industry 4.0, Digital twin (DT), Value stream mapping (VSM), Internet of things (IoT), construction and housing, France.

INTRODUCTION

With roots going back thousands of years ago, brick manufacturing is one of the oldest industries in the world whose products (i.e. bricks) are among the oldest materials used in buildings and remain a basic ingredient in modern construction (Brick Development Association, 2017). Bricks nowadays are used in more than 25% of houses and construction projects (Singh et al., 2021). Therefore, with the exponential global population growth (the global human population increased by one billion people since 2010 to reach 8 billion people in 2022) (United Nations, 2023), brick manufacturing is considered among the most important industries to respond to the increased global housing problems.

Despite its significant role, brick manufacturing is facing numerous challenges. One clear challenge that has received a lot of interest in the last few years is the negative environmental performance of the brick manufacturing process and brick factories. This includes the increased energy consumption, pollutants, CO_2 emissions, and large amounts of physical waste (Baude

[1] Doctoral Candidate, Centrale Lille, CNRS, UMR 9013-LaMcube, Lille, France, dorra.karmaoui@centralelille.fr, https://orcid.org/0000-0001-7776-5456
[2] Doctoral Candidate, Centrale Lille, CNRS, UMR 9013-LaMcube, Lille, France, wassim.albalkhy@gmail.com, https://orcid.org/0000-0002-4772-8133
[3] Full Professor, Centrale Lille, CNRS, UMR 9013-LaMcube, Lille, France, zoubeir.lafhaj@centralelille.fr, https://orcid.org/0000-0003-1985-9176
[4] Factory Director, Briqueteries du Nord (BDN), Lille, France, christophe.chapiseau@bdn.fr

et al., 2021). Another important challenge that received less attention is related to the operational performance and the efficiency of the manufacturing processes while maintaining a high-quality final product. This includes efficiency, lack of adequate funding, lack of skills, poor operational performance, and low productivity and effectiveness (Arevalo-Barrera et al., 2019; Chavez et al., 2019; Utami Handayani et al., 2020).

Similar to any industry, and within the era of digitalization, brick manufacturing has the opportunity to benefit from the applications of the fourth industrial revolution; or what is known more now as "Industry 4.0". Additionally, lean, as a philosophy that has shown noticeable improvements in various industries can help the brick-manufacturing industry to find solutions for the problems it encounters (Aka et al., 2019, 2020; Karmaoui et al., 2022). This study proposes a framework to integrate lean and industry 4.0 in brick manufacturing. The framework was proposed based on studying the case of a French brick factory. More specifically, the proposed framework was built using the integration of digital twin technology to improve the results developed when using the known lean tool; value stream mapping (VSM).

LITERATURE REVIEW

LEAN

The philosophy of lean originated in Japan following the development of the Toyota Production System (TPS). Since the beginning of publications about this philosophy, lean has been understood based on different principles including the identification of value based on the client's needs and requirements, value stream mapping and waste elimination to achieve a better flow of materials and information, establishing pull and producing only what is needed, achieving continuous improvement, and respect for partners and people (Liker, 2004; Womack & Jones, 1996).

With these principles, various lean tools have been presented to improve quality, value generation, resource efficiency, reduction of the environmental impacts of waste, and productivity gains (Hines et al., 2023). Examples of these tools include Just-In-Time (JIT), Value Stream Mapping (VSM), error proofing (Poka-Yoke), Kanban, and others (Valamede & Akkari, 2020). The presentation of these tools in the manufacturing sector, and then in other sectors such as the medical and construction sectors, showed remarkable results regarding quality improvement, cost reduction, time saving, safety conditions, and environmental performance (Albalkhy et al., 2021).

The used tool in this study is the VSM, which is a 2-D map that visualize all the actions in the production line and covers adding-value and non-adding-value activities. Via this 2D visualization of the flow, VSM helps to eliminate waste, streamline work tasks, reduce lead time and costs, and increase productivity quality (Valamede & Akkari, 2020).

INDUSTRY 4.0

Over history, energy sources and disruption in production have been the main reason for moving toward new revolutionary actions in production systems (Dakhli & Lafhaj, 2018; Valamede & Akkari, 2020). These actions started with the mechanization efforts that resulted in the emergence of the steam engine, by which, the first industrial revolution started. The second industrial revolution happened following the increased use of electricity and introduced the principles of mass production. Then, with the development of computerized systems, an automation-based era started as the third revolution. The fourth industrial revolution appeared in 2011 and aimed to apply the principles of robotization, cyber-physical systems (CPS), the internet, smart-oriented technologies, and application in human-machine interaction systems (Hines et al., 2023).

Understanding Industry 4.0 can either be based on the purposes of the application of the new smart technologies or based on the used technologies (Hines et al., 2023). An example of the first classification was that proposed by Tortorella et al (2022), who classified Industry 4.0 into six use categories: "interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity". An example of the technology-based classification was raised by Pagliosa et al (2021) and included the Internet of Things (IoT), Cyber-Physical Systems (CPSs), cloud computing, big data, Digital Twin (DT), Virtual and Augmented Reality (VR and AR), 3D Printing, simulation, and others.

The main used technology in this study is the DT, which can be defined as *"a living model of the physical asset or system, which continually adapts to operational changes based on the collected online data, information, and can forecast the future of the corresponding physical counterpart"* (Qi & Tao, 2018).

LEAN AND INDUSTRY 4.0

The last few years have witnessed several calls to integrate lean and industry 4.0 practices (Hines et al., 2023; Ramadan et al., 2020; Rosin et al., 2020; Sanders et al., 2016; Santos et al., 2021). In some of these calls, lean was considered one of the new principles of industry 4.0 due to the shared objectives with industry 4.0 concerning value creation, modularity, visualization, and service orientation (Albalkhy et al., 2021).

Supporters of the lean-Industry 4.0 integration believe that with the rapid technological advancement, lean alone is not enough, and at the same time, Industry 4.0 alone is not enough as well (Hines et al., 2023; Santos et al., 2021). While Industry 4.0 helps achieve changes in the business model, social level, and technological levels due to the integration of real-time data that can help improve decentralization and rapidness of the decision-making process, it still needs to be integrated with lean to support creating changes on the managerial and organizational level (Santos et al., 2021). Additionally, despite the changes in nature between lean as a low-tech approach that supports standardization and simplicity, and Industry 4.0 as a high-tech that calls for innovation, there are rooms to benefit from their integration and creation of a better flexible system that ensures the rapid reaction to market changes, provide a higher quality of products, and achieve higher customer satisfaction (Hines et al., 2023; Santos et al., 2021).

In their study that was based on the perspectives of 87 academic experts in the field of lean and Industry 4.0, Hines et al (2023) defines lean Industry 4.0 as: *"An innovative socio-technical paradigm that uses both human and artificial intelligence and relies on the strategic, cultural, systems, and tools of Lean as well as the various Industry 4.0 digital technologies continually and discontinuously used to improve both single organizations and their supply chains with a focus on simplifying and managing complexity to benefit the triple bottom line and hence meet specific customer and organizational needs as well as the expectations of employees and wider society"*.

LEAN AND INDUSTRY 4.0 IN BRICK MANUFACTURING

Brick manufacturing is characterized as a small-medium enterprises (SMEs)-based industry (Kumar & Sharma, 2021). This type of enterprise has many opportunities to benefit from the adoption of lean Industry 4.0 such as cost reduction, faster growth, and flexibility increase (Elhusseiny & Crispim, 2022). Nevertheless, many barriers hinder this adoption in SMEs. Among them, the lack of financial capabilities, lack of information communication technology (ICT) infrastructure, lack of managerial flexibility and support, fear of change, lack of knowledge, and lack of skilled employees (Agostini & Nosella, 2020; Albalkhy et al., 2021; Albalkhy & Sweis, 2021; Elhusseiny & Crispim, 2022; Kolla et al., 2019). In addition, according to Kolla et al (2019), most of the lean Industry 4.0 frameworks and models are too complex and do not fit the nature of SMEs.

All these barriers might explain the lack of sufficient studies about lean Industry 4.0 adoption in brick manufacturing. During the conduction of the literature review, a limited number of studies were found about both topics. The aims of these studies were the identification and removal of lean wastes in brick manufacturing processes (Aka et al., 2019, 2020; Arevalo-Barrera et al., 2019), identification of possible actions for quality improvement (Cabrera & Oliveros, 2017; Carrero et al., 2021), and design of status analysis system for brick machines using IoT (Xu et al., 2020). This study aims to contribute to the existing literature and propose a lean Industry 4.0 framework that is developed to fit the requirements and nature of brick factories.

RESEARCH METHODS AND PROPOSED FRAMEWORK

The research adopts the case study as the methodology as this approach that is used to generate an in-depth, multi-faceted understanding of a complex issue in its real-life context. The proposed framework followed the conduction of different field investigations in a brick manufacturing factory (will be explained in the case description below).

The proposed framework is based on the use of green-digitalized VSM. The use of VSM provides opportunities to identify production wastes and achieve improvement in the process. VSM can be linked with environmental metrics to identify the existing problems that affect environmental performance (Nguyen & Sharmak, 2022). Normally, VSM is applied on levels; starting with the current VSM, which shows the current situation and the existing bottlenecks and wastes in the process, then the future VSM, which aims to integrate changes in the process to provide improvements and waste elimination, and then, the frequent (normally yearly) VSM that aims to evaluate the progress based on the recommendations of the future VSM. Nevertheless, many SMEs face difficulties in VSM implementation. These difficulties are a result of the reluctance to continuously invest in VSM as a static tool that requires continuous updates (Lu et al., 2021). Therefore, the proposed framework aims to benefit from the advancement of DT and IoT to improve the implementation of VSM.

The selection of DT and IoT was firstly due to their ability to deliver real-time information and connectivity that help achieve continuous monitoring and rapid decision-making to make improvements and optimizations in energy consumption, materials management, process management, and safety (Dardouri et al., 2022; Karmaoui et al., 2022; Lu et al., 2021). The second reason was due to the flexibility of DT systems that can facilitate the application of lean thinking due to the ability to monitor the flow, eliminate waste, and provide visual and real-time access to the management and teams to ensure the continuous improvement and error proofing in the process (Barkokebas et al., 2022; Lu et al., 2021). The third reason was due to the business need of the studied company to deploy DT; similar to what was described by Agrawal et al (2022) as the implementation of DT as a “need pull”.

As shown in Figure 1, the proposed framework is based on two main phases:

- The first phase covers the identification of bottlenecks and wastes in the process. This is based on the use of different data collection methods such as interviews with workers or management staff, surveys, or observations, in addition to the possibility of the use of different types of sensors to collect data about workflow, temperature, humidity, and others. In this phase the current production process can be translated into current VSM using different measures such as cycle time (C/T), change over time (C/O), machine time (M/T), processing time (P/T), and others. Benefiting from the IoT, measures like energy consumption and CO_2 emissions are also possible to be integrated into the VSM. The first phase results in building the virtual model using simulation or software.

- Building the virtual model helps to create a flow of data from the physical model (the production process) to the virtual model. The latter is responsible for processing the data to produce useful information to improve production control and automate decision-making (Agrawal et al., 2022). By making this connection between the physical and virtual models, frequent testing and integration for scenarios and improvements are possible. In this phase, and using the bidirectional data flow between the physical and virtual models, the development of VSM and the monitoring of the production line are done continuously. It is worth mentioning that the second phase is not implemented once. It is continuously implemented aiming at achieving the principle of continuous improvement.

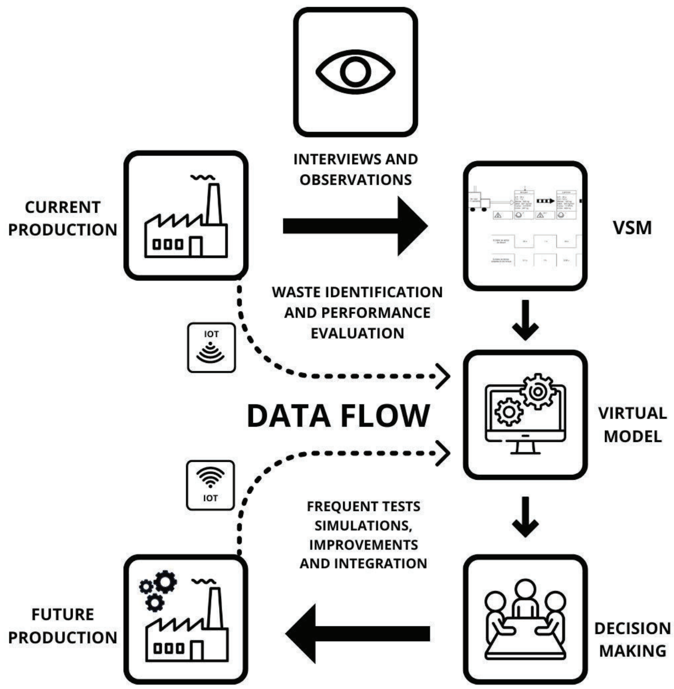


Figure 1: The proposed DT-based VSM framework.

CASE STUDY

CASE DESCRIPTION

Applying the proposed model started in a brick manufacturing company in the North of France. The company, which is a family-based company more than 100 years old and produces different types of clay-based bricks (solid bricks, perforated bricks, and clay brick plates) is a provider of bricks for many projects in France, England, Ireland, and many other locations. Nevertheless, the company faced several challenges during the last few years.

Similar to any company in France, the second largest producer of tiles and brick in Europe (Carole Fossey & Massieu, 2020), the company is experiencing instability in production and an increase in materials prices due to the fluctuated demand due to the impact of the recent war in Ukraine and the pandemic of COVID-19. In addition to the need to deal with the negative environmental and operational performance that results from the levels of pollutants and energy consumption, low machine performance, efficiency rates, strong competition, and skills shortage. Accordingly, to overcome these challenges, the company wanted to adopt lean and industry 4.0 practices to create a flexible, zero-waste, and efficient production line. This paper reports one of the actions taken in this regard.

PROCESS

The process of brick manufacturing in the studied case is shown in Figure 2. In this process, clay is extracted and transported to the production sites and then stored in a warehouse for an average of four weeks. The production starts with the preparation of the brick mixture from the extracted earth and the other raw materials, in particular sand and water. It is first put into dosing devices and then sent to the grinding mill to make the mixture more homogeneous. The material is then conveyed, using a conveyor belt, to a second, more massive aerial dosing unit which mixes a second time and distributes the clay uniformly. Once the mixture reaches the mixer, additional products are added, such as iron oxide and colorants, to give the brick the desired color. The mixture then passes through the extruder, which shreds the clay and compacts it under a vacuum. The strand is then cut with metal wires. After shaping the brick becomes wet and requires drying to remove surface water and reduce its humidity. The firing stage is done in a tunnel kiln that runs on natural gas, with burners and gas injectors. The quality control work is done by hand when the robot unstacks the wagon, so the pace has to be a little slower to give the employees time to spot any non-conforming bricks; stains, cracks, and damaged faces.

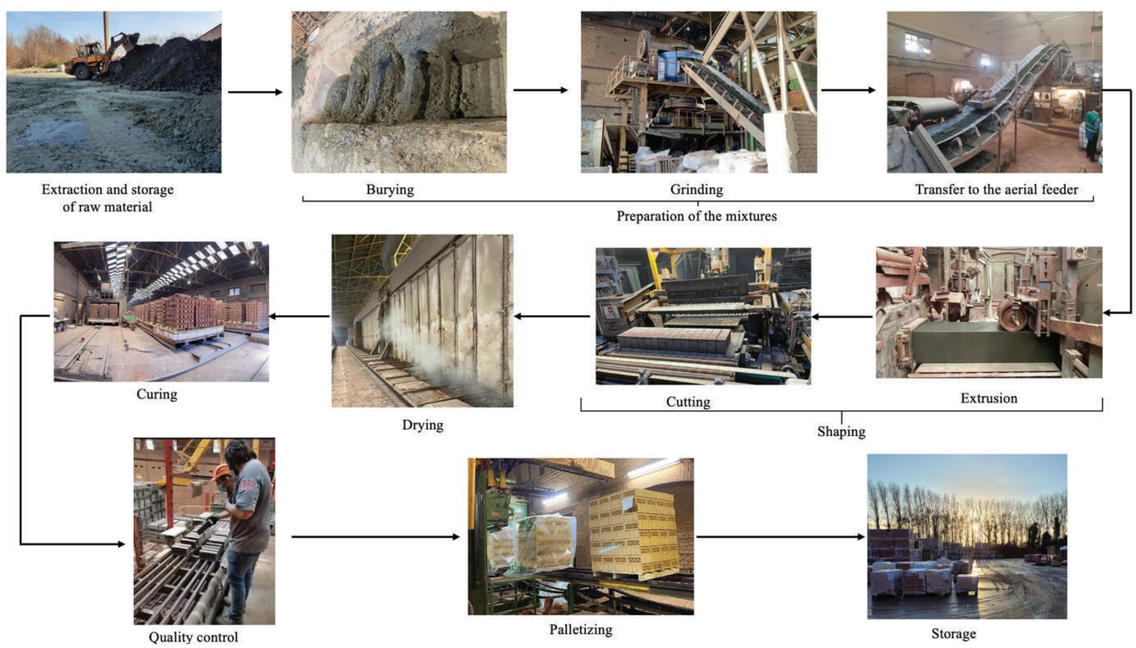


Figure 2: Clay-based brick manufacturing process.

CURRENT VSM AND ENCOUNTERED BOTTLENECKS

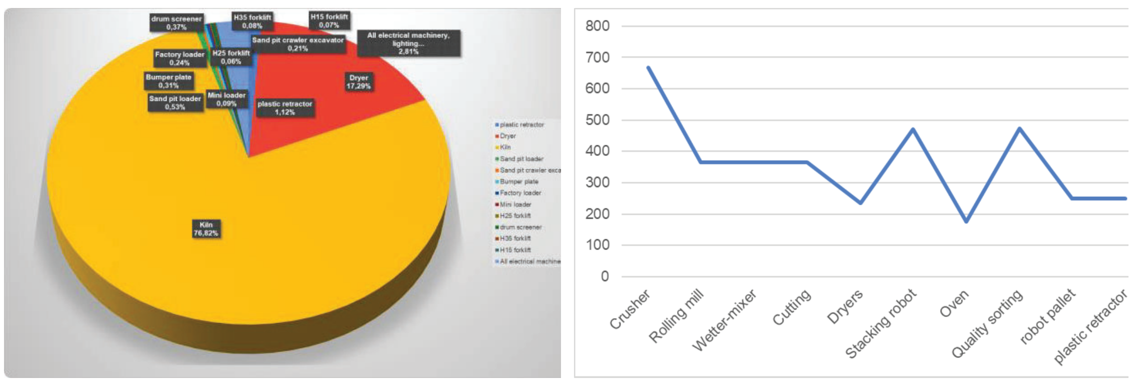
The current VSM was developed following studying the production line. The study covered the red bricks in this phase. Studying the production line was based on a set of observations to identify the different value adding and non-value adding activities and identifying the different phases of production. During these observations, the average time of each phase and at each machine and the bottlenecks in the flow were identified. To confirm the results of the observations with the real situation, the developed VSM was validated through conducting interviews with workers and management staff. Based on the VSM, the total time of non-value-adding activities is 35.5 hours, constituting around 28.4% of the total time in the production process (starting with the arrival of the raw materials and ending with arrival to the storage area). Nevertheless, the efficiency is not optimal as the time spent in the kiln (72 hours) was considered a value-adding activity. This means that neglecting the time needed in the kiln, the percentage of waste in time can reach 67% of the overall process time. In addition to the visualization of the production process and identification of the wasted time, the use of VSM was also helpful to identify the current flow rates, consumed energy, and CO2 emissions in each machine in the process (as shown in Figure 3). This helped to identify the bottlenecks and problems in the process, which can be summarized in:

1) High levels of energy consumption and CO2 emissions in the kiln (the kiln is responsible for more than 75% of CO2 emissions and more than 70% of energy consumption).

2) High levels of defects in different places along the process including for instance defects resulting from bricks falling after getting out from the kiln due to wrong positioning and bricks due to instability of the old wagons.

3) Stoppages in the production line due to some reasons such as fallen bricks in the wagon path, problems in machines, and stoppages due to the cutting machine. The latter is responsible for a lot of stoppages (5-6 times per day) due to frequent failures in the cutting wires, which require their replacement.

4) Levels work-in-progress (WIP), which affects the freedom of movement and creates problems in brick storage.



CO2 emissions per machine | Flow rate in each machine (Kg/min)

Figure 3: Used metrics in the current VSM.

Accordingly, the proposed solutions include:

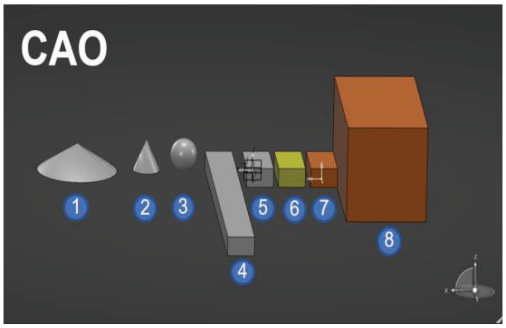
1) Continuity of the process monitoring to identify the reasons for the wastes in the production process.
2) Apply lean principles and tools such as pull, Just-In-Time (JIT), 5S, and supermarket to eliminate wastes and reduce levels of WIP.
3) Use of IoT to provide alerts when stoppages in the production line happen.
4) Conduct numerical simulations and study the different placement of the bricks in the kiln (so that the heat reaches the brick in the middle of the bottom car faster) which will reduce the firing temperature and the firing time. As a result, trying to improve efficiency and reduce energy consumption and CO2 emissions.
5) Implement predictive maintenance to predict future failures in machines and avoid machines breakdown that would cost productivity loss.

Building DT model and Future Directions

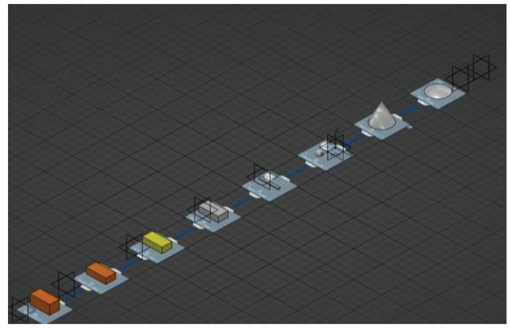
Despite the role that VSM played in identifying problems in the production process, some limitations require the use of more dynamic and digitalized VSM. Firstly, the current VSM is static; therefore, with the stoppages in the production line, its results need to be updated frequently. Secondly, the current VSM was done for only one product in the factory. To apply the principle of leveling (i.e. Heijunka), there is a need for a flexible system that can integrate more than one product; such improvement can be done using DT as stated by Lu (2021). Thirdly, due to the changes in the production line (affected by the stoppages and unexpected events), it is not easy to identify improvements in efficiency and WIP reduction; especially with the presence of workers turnover (Lu et al., 2021), which happens in the studied case. Finally, the use of an interactive model that links the physical process and the digitalized process can provide real-time data and updates about the effectiveness of the changes in the production process (e.g. due to repositioning of bricks in the kiln, changes of current wagons, and predictive maintenance implementation).

Therefore, the work started to build the digital twin model. So far, the team was able to build the 3D model and distribute a set of needed sensors linked with the IoT platform. The 3D model was built using “The 3DEXPERIENCE platform from Dassault Systèmes”. The current work covers:

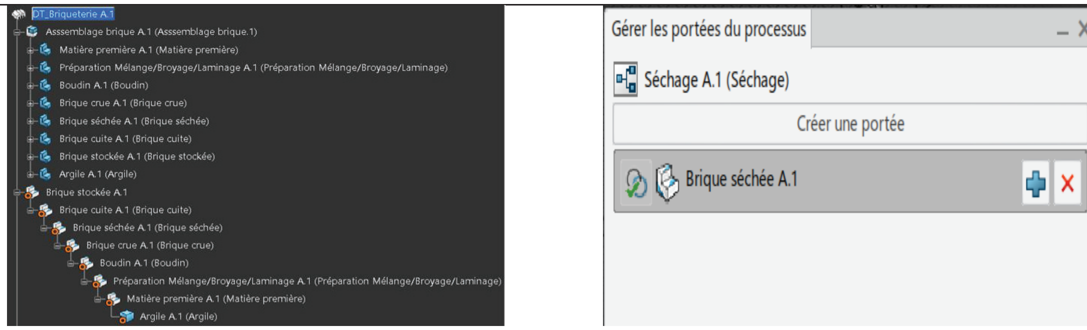
- Building the 3D design and modeling the brick in its different states (as shown in Figure 4-a). Each transformation of the brick corresponds to a visual of the brick, starting with the extracted earth, then the preparation of the earth, the molded, cut, dried, baked, and stored brick
- Building the Manufacturing Bill of Materials (MBOM) (Figure 4-b), which integrates the different 3D models of the brick in the logical order of the manufacturing process.
- Process planning and flow simulation (Figures 4-c), which covers creating workstations consistently with the flow in the original process and linking them to the two previous phases. This step also covers the creation of the workstations, which is a critical step as it allows the definition of the different workstations, the production line as well as the time that the brick spends at this station. In this step, several parameters are defined such as throughput, cycle time, estimated operation time, and the interval between failures and repair time.
- Scenarios testing and monitoring (Figure 4-d): as a result, the digital twin system, presents useful information in the shape of a Gantt Chart about the systems, operation, parts, and resources. The most important criterion is the utilization rate of the systems/machines. This enables checking how the systems are used in the production line, and if a change is made, observing the repercussions on the other systems, especially the storage areas, and checking if this affects the production downstream. An example of the testing of different scenarios was predicting the stoppages of the cutting machine, which as mentioned above, was one of the identified bottlenecks that affect the flow in the process based on the results from the VSM. The machine is made of steel wires that allow cutting the raw brick. However, the process must be stopped manually when the wires break. This leads to other problems that increase the workload and impact the productivity of the company. The digital twin can predict the breakage of a wire and automatically stop the process. For this, it is necessary to implement sensors on the machine (a noise sensor (a microphone), force, and proximity). Thus, the implementation of sensors and alarming system to provide alerts when the machine stopped.
- Building sensors network and connecting the IoT platform with the developed virtual model: to ensure the bidirectional flow of data between the virtual model and physical model, a network of sensors is currently under construction to be connected with the developed virtual model. A complete digital twin should make it possible to monitor the work for each machine of the brick factory and to show their impact on the production line in the event of a problem or modification. Therefore, the built network aims to cover all the production phases and machines that were covered in the virtual model.



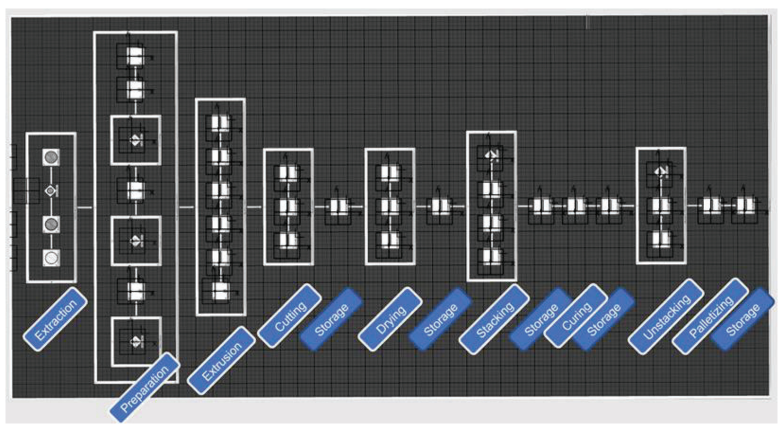
(a) Modeling different states of the brick



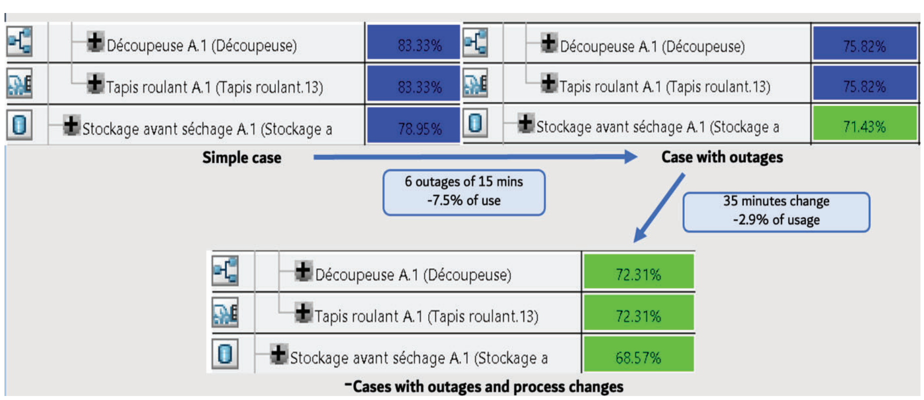
(b) MBOM



(c) Process planning and flow simulation.



(d) Modeling of the production line



(e) Example of scenario testing

Figure 4: Building the DT model.

DISCUSSION AND CONCLUSIONS

The current study proposed a framework that is based on the integration of lean and Industry 4.0 to improve production performance in brick manufacturing. The proposed framework is based on the use of VSM and digital twin. While the former is well recognized in visualizing and improving flow in manufacturing processes, the latter serves as a supporting tool that aims to maximize the benefits of process mapping. Digital twin is helpful as well in mitigating the impact of the static state of the VSM and continuously providing improvements to the production process. Therefore, the proposed framework goes beyond the use of static tools to visualize the production process and proposes the use of dynamic model that is linked with IoT platform to ensure monitoring the production process, testing different production scenarios, and integrating real-time data to improve predictability, and autonomous and information-based decision-making processes. Additionally, the integrated data from the IoT platform and digital twin is helpful to continuously monitor production and achieve continuous VSM models. As a result, generating greater value for the client, creating stable and smooth flow, and achieving continuous improvement.

The proposed framework is currently implemented in a French brick factory. While the implementation is still in its early phases, the framework has shown some potential to improve predictability, waste elimination, visibility, and decision-making in the factory. Nevertheless, further investigations are needed to validate the framework. Future works can be done based on case studies to modify and test the framework even in other industries. Other research works can investigate the impact of the model on the performance, identify key performance indicators for the framework, or identify the barriers to implementing it.

This study aims to contribute to the ongoing efforts to integrate lean thinking and Industry 4.0 practices aiming at benefiting from the two concepts. In addition, the study serves as a good example of how to improve performance in brick factories in particular and SEMs in general using lean-digitalized models.

REFERENCES

Agostini, L., & Nosella, A. (2020). The adoption of Industry 4.0 technologies in SMEs: results of an international study. *Management Decision*, *58*(4), 625–643.

Agrawal, A., Fischer, M., & Singh, V. (2022). Digital Twin: From Concept to Practice. *Journal of Management in Engineering*, *38*(3), 06022001.

Aka, A., Bamgbade, A. A., Saidu, I., & Balogun, O. M. (2019). A conceptual framework for waste identification and reduction in Nigerian sandcrete blocks production process. *Construction Innovation*, *19*(3), 405–423.

Aka, A., Isah, A. D., Eze, C. J., & Timileyin, O. (2020). Application of lean manufacturing tools and techniques for waste reduction in Nigerian bricks production process. *Engineering, Construction and Architectural Management*, *27*(3), 658–679.

Albalkhy, W., & Sweis, R. (2021). Barriers to adopting lean construction in the construction industry: a literature review. *International Journal of Lean Six Sigma*, *12*(2), 210–236.

Albalkhy, W., Sweis, R., & Lafhaj, Z. (2021). Barriers to Adopting Lean Construction in the Construction Industry—The Case of Jordan. *Buildings*, *11*(6), 222.

Arevalo-Barrera, B. C., Parreno-Marcos, F. E., Quiroz-Flores, J. C., & Alvarez-Merino, J. C. (2019). Waste Reduction Using Lean Manufacturing Tools: A Case in the Manufacturing of Bricks. *IEEE International Conference on Industrial Engineering and Engineering Management*, *December*, 1285–1289.

Barkokebas, B., Alsakka, F., Hamzeh, F., & Al-Hussein, M. (2022). Digital Twins to Enable Flexibility in Off-Site Construction. In V. A. González, F. Hamzeh, & L. F. Alarcón (Eds.), *Lean Construction 4.0: Driving a Digital Revolution of Production Management in the AEC Industry*. Routledge.

Baude, M., Baudry, M., Dussud, F.-X., Duvernoy, J., Bultheel, C., & Vailles, C. (2021). *Chiffres clés du climat : France, Europe et Monde. I4Ce, 80.* https://www.i4ce.org/download/datalab-chiffres-cles-du-climat-2021-france-europe-et-%0Amonde/

Brick Development Association. (2017). *The UK clay brickmaking process*. https://www.brick.org.uk/admin/resources/g-the-uk-clay-brickmaking-process.pdf

Cabrera, C. J. O., & Oliveros, E. F. S. (2017). Decrease of the rates of rupture, in a brick company, during the transport of the product to the client, by using lean six sigma methodologies. *Proceedings of the International Conference on Industrial Engineering and Operations Management*, 161–176.

Carole Fossey, & Massieu, A. (2020). *France, Europe's Second-Largest Producer of Bricks and Tiles - Insee Focus - 178*. Insee. https://www.insee.fr/en/statistiques/4492823

Carrero, L., Gomez, B., Velásquez, P., & Santis, A. (2021). Design of a strategy for the quality management system in a bricks manufacturing company in Colombia. *Chemical Engineering Transactions*, *86*(September 2020), 643–648. https://doi.org/10.3303/CET2186108

Chavez, J., Osorio, F., Dominguez, F., & Raymundo, C. (2019). *Modelo esbelto de gestión de producción para la reducción de desperdicios en PYMES del sector alimentos procesados*. *August*, 40–52.

Dakhli, Z., & Lafhaj, Z. (2018). *La révolution de la construction lean*. Auto-edition.

Dardouri, S., BuHamdan, S., Albalkhy, W., Dakhli, Z., Danel, T., & Lafhaj, Z. (2022). RFID platform for construction materials management. *International Journal of Construction Management*, *ahead of p*(ahead of print). https://doi.org/10.1080/15623599.2022.2073085

Elhusseiny, H. M., & Crispim, J. (2022). SMEs, Barriers and Opportunities on adopting Industry 4.0: A Review. *Procedia Computer Science*, *196*, 864–871.

Hines, P., Tortorella, G. L., Antony, J., & Romero, D. (2023). Lean Industry 4.0: Past, present, and future. *Quality Management Journal*, *30*(1), 1–25.

Karmaoui, D., Albalkhy, W., Danel, T., Jullien, A., Lafhaj, Z., & Chapiseau, C. (2022). IoT-based architecture to improve workflow in bricks manufacturing. *Modular and Offsite Construction (MOC) Summit Proceedings*, 42–49. https://journalofindustrializedconstruction.com/index.php/mocs/article/view/263/227

Kolla, S., Minufekr, M., & Plapper, P. (2019). Deriving essential components of lean and industry 4.0 assessment model for manufacturing SMEs. *52nd CIRP Conference on Manufacturing Systems*, *81*, 753–758.

Kumar, S., & Sharma, P. (2021). Adoption of cleaner production innovations by micro, small and medium enterprises: lessons from the clay-fired brick manufacturing sector in India. *International Journal of Management and Enterprise Development*, *20*(1), 49–74.

Liker, J. K. (2004). *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer McGraw-Hill Education*.

Lu, Y., Liu, Z., & Min, Q. (2021). A digital twin-enabled value stream mapping approach for production process reengineering in SMEs. *International Journal of Computer Integrated Manufacturing*, *34*(7–8), 764–782.

Nguyen, D. T., & Sharmak, W. (2022). Hybrid Simulation for Value Stream Mapping to Improve the Environmental Performance of the Construction Phase. *Proc. 30th Annual Conference of the International Group for Lean Construction (IGLC)*, 421–432.

Pagliosa, M., Tortorella, G., & Ferreira, J. C. E. (2021). Industry 4.0 and Lean Manufacturing: A systematic literature review and future research directions. *Journal of Manufacturing Technology Management*, *32*(3), 543–569.

Qi, Q., & Tao, F. (2018). Digital Twin and Big Data Towards Smart Manufacturing and

Industry 4.0: 360 Degree Comparison. *IEEE Access*, *6*, 3585–3593.
Ramadan, M., Salah, B., Othman, M., & Ayubali, A. A. (2020). Industry 4.0-Based Real-Time Scheduling and Dispatching in Lean Manufacturing Systems. *Sustainability*, *12*(6), 1–18.
Rosin, F., Forget, P., Lamouri, S., & Pellerin, R. (2020). Impacts of Industry 4.0 technologies on Lean principles. *International Journal of Production Research*, *58*(6), 1644–1661.
Sanders, A., Elangeswaran, C., & Wulfsberg, J. (2016). Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing. *Journal of Industrial Engineering and Management*, *9*(3), 811–833.
Santos, B. P., Enrique, D. V., Maciel, V. B. P. P., Lima, T. M., Charrua-Santos, F., & Walczak, R. (2021). The Synergic Relationship Between Industry 4.0 and Lean Management: Best Practices from the Literature. *Management and Production Engineering Review*, *12*(1), 94–107.
Singh, H., Nazeer, M., & Kumar Tiwary, A. (2021). An Experimental Study of Bricks Made with Different Mineral Additives. *IOP Conference Series: Earth and Environmental Science*, *889*(1), 012049.
Tortorella, G., Fogliatto, F. S., Gao, S., & Chan, T. K. (2022). Contributions of Industry 4.0 to supply chain resilience. *International Journal of Logistics Management*, *33*(2), 547–566.
United Nations. (2023). *Global Issues, Population*. https://www.un.org/en/global-issues/population
Utami Handayani, N., Agung Wibowo, M., Mustikasari, A., Wahyu Nurwidanto, I., & Akbar Dilaga, D. (2020). The implementation of lean construction and six sigma concepts in light brick installation: A case study in Cordova apartment project. *IOP Conference Series: Materials Science and Engineering*, *909*(1).
Valamede, L. S., & Akkari, A. C. S. (2020). Lean 4.0: A new holistic approach for the integration of lean manufacturing tools and digital technologies. *International Journal of Mathematical, Engineering and Management Sciences*, *5*(5), 854–868.
Womack, J., & Jones, D. (1996). Beyond Toyota: How to root out waste and pursue perfection. *Harvard Business Review*, *74*, 1–16.
Xu, Z., Liu, X., Li, X., Gao, X., Xie, R., & Xia, Y. (2020). Design of Status Analysis System for Brick Machines Based on Industrial Internet of Things. *Proceedings - 2020 Chinese Automation Congress, CAC 2020*, 6539–6543.