Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X
Volume 4, Issue 3, 2026

SIMULATION-BASED DEBOTTLENECKING OF A CERAMIC TILE PRODUCTION LINE WITH INTEGRATED ENERGY CONSUMPTION AND CARBON EMISSION ANALYSIS

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DOI: https://doi.org/10.5281/zenodo.18976570

Keywords

Article History
Received: 11 January 2026
Accepted: 23 February 2026
Published: 12 March 2026

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Abstract

Ceramic tile making is considered to be one of the most energy-intensive manufacturing processes due to the drying and firing operations carried out at relatively higher temperatures. Inefficiencies in the production process not only cause reduced production rates, but they also contribute to increased energy consumption and environmental damage. In this paper, the authors proposed a discrete-event simulation-based approach to debottleneck the production process in the ceramic tile industry while concurrently evaluating the energy consumption and environmental damage. Real-time data were used to simulate the production process in an industrial ceramic tile factory using the discrete-event simulation approach. The proposed simulation approach was successfully validated by finding that the deviation between the simulation and actual production rates was merely 0.53%. Two scenarios were proposed to improve the production process in the ceramic tile industry and reduce the bottlenecks in the production system. The analysis found that the kiln is the main bottleneck in the production system due to the longer processing time and the relatively higher defect rates compared to the other production stages. The optimization scenario proposed reduction in the thermal processing times of the double-layer dryer, the single-layer dryer, and the kiln, which improves the production process without causing new queues in the system. The sustainability analysis found that the proposed debottlenecking approach reduced the energy consumption from 80.88 to 74 kWh and the carbon footprint from 66.32 to 60.68 kg CO_2, which is equivalent to the reduction in the energy consumption and the carbon footprint by 6.88 and 5.64 kg CO_2 (8.5%), respectively. The proposed discrete-event simulation approach is successful in debottlenecking the production process and improving the sustainability performance without the need to invest capital in the ceramic tile industry.

1 INTRODUCTION

The manufacture of ceramic tiles is considered one of the most energy-intensive industries among the process industries. This is because the industry requires the use of high-temperature thermal processing equipment for the processes of drying and firing. The manufacturing process is considered a sequence of stages comprising pressing, drying, glazing, firing, and finishing. For the smooth flow of the processes, the sequence is considered essential for the overall output and product quality. Among the stages involved in the manufacture of ceramic tiles, the thermal processing equipment requires a significant amount of electrical and thermal power for the processes of drying and firing. Thus, inefficiency in the flow of the processes not only affects the overall output but also affects the environmental impact.

Generally, bottlenecks occur frequently in complex manufacturing systems. The bottleneck equipment is considered a constraint on the overall throughput of the system. It also affects the work-in-progress inventory level, waiting times, and uneven utilization of the equipment. Thus, the conventional approach to debottlenecking is generally considered only with the aim of increasing the capacity or the equipment cycle times without a thorough consideration of the impact on the overall energy and environmental consequences [1]. Though the approach is economically attractive, it may also increase the overall energy and environmental impact.

Discrete Event Simulation (DES) has emerged as a promising approach for modeling, analysis, and improvement of manufacturing systems. DES enables the dynamic modeling of the system, which can be performed without affecting the actual running of the industries. In the case of the ceramic manufacturing sector, simulation has proven to be a secure way of testing different alternatives of the system, which otherwise proves costly due to the high safety risks associated with the process. Although the application of DES has proven promising for the improvement of the system, the existing studies have mostly focused on the evaluation of the performance of the system, while the impact of the system on the environment has not yet been considered.

The ceramic industry has faced a number of challenges regarding the carbon footprint of the industries, which has compelled the government to implement a number of policies for the betterment of the environment. Energy usage, which includes the use of the kiln for the firing of the ceramics, has a direct impact on the carbon footprint of the industries, especially for the industries that use electricity or gas for firing the ceramics. Therefore, the debottlenecking of the system needs to be performed not only for the betterment of the system but also for the betterment of the environment.

This paper aims at extending debottlenecking of ceramic industry production line by including the formulation of the energy consumption and carbon footprint of the system. The simulation model is aimed at the identification of the bottlenecks of the system for the betterment of the throughput of the system, the extension of the model for the evaluation of the energy consumption and carbon footprint of the system has provided a new direction for the betterment of the system, which has the potential for the betterment of the environment.

2 Literature Review

Manufacturing systems employing serial flow configurations display considerable sensitivity to imbalances in localized capacity. For such systems, the rate of the entire production line is controlled by the slowest resource. This slowest resource is termed the bottleneck. According to the Theory of Constraints (TOC), improvements to system performance can be achieved by improving the bottleneck rather than equally improving all resources [2]. Bottleneck identification in stochastic environments has been found to be difficult. Traditional methods of detecting bottlenecks rely on static resource utilization. This method assumes deterministic processing and fails to account for dynamic queueing effects. With the complexity and interconnectivity of modern manufacturing systems, discrete event simulation (DES) has been increasingly adopted to analyze bottlenecks in stochastic environments [3].

DES has been found to facilitate the simulation of dynamic interactions between machines and resources. This has been found to aid in the identification of bottlenecks. According to [4], simulation-based bottleneck detection has been found to be particularly effective in complex systems characterized by considerable variability and interdependencies between resources. [5]. found dynamic bottlenecks to shift between different machines depending on the production mix. This has been found to highlight the effectiveness of simulation-based bottleneck detection over static detection.

Despite the effectiveness of simulation-based bottleneck detection, most debottlenecking research has focused on operation-based parameters. There has been little emphasis on environmental parameters. Bottleneck elimination can lead to increased throughput. This can result in increased energy consumption. This has been found to highlight a gap between debottlenecking and environmental parameters.

2.1 Energy Intensity in Ceramic Manufacturing

The ceramic tile manufacturing industry is characterized by a high level of thermal energy consumption, especially in the drying and firing processes. In this regard, the temperature in the industrial kilns used is above 1000°C, which translates to a high rate of consumption of electricity or natural gas. According to [6] energy consumption in the ceramic manufacturing industry is estimated to represent a maximum of 30-40% of the total production costs, with the highest energy consumption rate being in the firing of the kilns. [7] undertook a comprehensive evaluation of energy consumption in the ceramic tile manufacturing industry. Their findings highlighted that inefficiency in the coordination of processes significantly increases energy consumption, expressed in terms of specific energy consumption, which is usually expressed as kilowatt-hours per square meter of produced tile. In this context, energy consumption is not just a function of thermal efficiency but is also a function of the synchronization of processes[8]. In contemporary research, a number of researchers have emphasized the need to adopt a range of technological interventions to reduce energy consumption in the ceramic tile manufacturing industry [9, 10]. These interventions include:

- Waste heat recovery
- Optimizing the use of burners
- Enhancement of insulation
- Fuel substitution
- Digital control of the kiln

Despite these interventions being effective in minimizing energy consumption, they often require a capital cost. In this context, operational strategies have received relatively little attention in contemporary research. In the context of energy consumption, production balancing and minimization of idle time of machines have received relatively little attention. Furthermore, energy optimization strategies in the ceramic manufacturing industry are often not integrated with production modeling. In this context, energy consumption is often assessed using thermodynamic evaluation and energy audits.

2.2 Carbon Emissions in Energy-Intensive Industries

The global decarbonization goals have led to increased research in reducing carbon emissions in industrial sectors. The ceramic industry plays a major role in contributing to industrial greenhouse emissions due to the combustion-based firing process and electricity consumption from fossil-based power plants.

The carbon emissions in manufacturing systems are usually determined using energy-based emission factor calculations:

$$CO_2\ Emission = Energy\ x\ Emission\ Factor$$

The importance of carbon intensity metrics in assessing the improvement in process efficiencies is emphasized in the latest reports from the International Energy Agency (IEA) (2023). Reduction in carbon intensity is considered a more reliable sustainability metric compared to absolute carbon emissions in growing manufacturing systems.

[11] have analyzed decarbonization in energy-intensive industrial sectors and identified the following major decarbonization strategies in energy-intensive industries:

- Fuel switching
- Renewable energy
- Improvement in operational efficiencies

Fuel switching and renewable energy require significant changes to the infrastructure. Operational efficiency improvement can be achieved through process optimization and balancing.

In the ceramic manufacturing system, the majority of the research on carbon emissions focuses on life cycle assessment and embodied emissions [12]. However, life cycle assessment methods usually consider the overall impact on the environment and do not consider operational inefficiencies in manufacturing systems. Simulation-based carbon modeling in ceramic manufacturing systems, especially in combination with bottleneck removal, is not considered in the research.

2.3 Simulation-Based Sustainable Manufacturing

Sustainable manufacturing has evolved from a mere environmental compliance approach to a more holistic approach for the optimization of operational and environmental performance. The concept of simulation-based sustainability assessment is referred to as Green Simulation. It extends the capabilities of discrete event simulation (DES) by incorporating metrics on energy consumption into the sustainability framework [13]. [14] showed the viability of using simulation-based operational optimization to minimize the energy consumption associated with idle machines without the need for any additional capital costs. The results showed a direct reduction in specific energy consumption with a reduction in waiting time and synchronization. Another example is the work done by [15], who suggested the concept of carbon accounting into production scheduling for low-carbon decisions. However, the work was purely theoretical and not validated with any industrial systems. [16] showed the need for a trade-off between throughput maximization and energy efficiency during the formulation of sustainable production planning.

Despite the increased interest in the concept of sustainable simulation, several issues were pointed out:

- Most studies were conducted on the automotive industry or semiconductor industry, with few studies on the ceramic industry.
- Most studies were purely conceptual with no industrial validation.
- Debottlenecking' was not considered along with 'carbon emission analysis.
- Economic evaluation' was not considered separately from 'environmental evaluation.

2.4 Integrated Production-Energy-Carbon Optimization

Recent research trends suggest the need for integrated modeling approaches, where the three aspects of production, energy, and carbon are integrated into a single framework. In the recent study by [17], the authors proposed an integrated carbon-energy-production model for industrial systems, but the stochastic simulation was not considered. In another recent study by [18], the authors focused on dynamic bottleneck detection but did not consider the sustainability aspects of the problem.

It has also been observed that integrated approaches are lacking in the field of ceramic product manufacturing, where the research studies have focused either on the optimization of the production process, or the optimization of the thermal energy usage, or the environmental impact assessment, but not the integrated approach including all three aspects of the problem [19].

As debottlenecking of the production line affects the utilization of the machines and the time of operation, it also affects the energy usage and carbon footprint of the process indirectly. But the impact of debottlenecking has not yet been quantified for the ceramic product manufacturing lines [20].

2.5 Research Gap and Positioning of the Present Study

From the synthesis of the recent research studies, the gaps identified are as follows:

- In the studies related to debottlenecking, the impact of debottlenecking on the energy usage and carbon footprint of the process has not yet been quantified.
- In the studies related to the optimization of the energy usage, the emphasis has been more towards the thermal aspects of the energy usage rather than the production aspects of the process.
- In the studies related to the carbon footprint of the process, the life cycle assessment has been more predominant.
- In the studies related to the integrated simulation of the energy-carbon aspects of the

process, the DES-Energy-Carbon simulation frameworks validated for the actual ceramic product manufacturing lines have not yet been reported.

To bridge the gaps identified, the present study aims at developing a validated DES simulation model of the actual ceramic product manufacturing line, where the energy usage modeling and carbon footprint estimation have also been considered for the baseline and post-debottleneck scenarios, and the impact of debottlenecking has been quantified for the energy usage and carbon footprint of the process, including the evaluation of the energy intensity, carbon intensity, and the economic aspects of the problem.

3 Methodology

This research employs an integrated simulation and sustainability methodology to enhance the performance of the ceramic production line. Initially, real-life production data on processing time, rejection rates, production rates, and other essential parameters are collected from the output buffers and major stations of the production plant. This data is used as input to the dynamic discrete event simulation, which closely resembles the real-life production process. To ensure the reliability of the simulation, the results are validated by comparing them with real-life production and rejection rates.

Having validated the discrete event simulation, the bottlenecks are identified through various parameters such as processing time, resource allocation, queue sizes, and imbalances. Subsequently, experiments are carried out on the production process through the discrete event simulation, where alternative production processes are simulated, focusing on eliminating bottlenecks and improving production rates. At the same time, the sustainability aspect is addressed through the development of energy consumption models, where machine operating time is related to energy consumption, and subsequently, carbon emissions are calculated using appropriate carbon emission factors.

Finally, sustainability analysis is carried out on the production process before and after the optimization, where the benefits of discrete event simulation on production performance, energy consumption, and carbon emissions are demonstrated.

4 Data Collection

The facility that has been chosen is a large ceramic tile factory that operates eight-hour shifts. In this facility, ceramic powder is converted into glazed tile using various mechanical, thermal, and finishing processes. The process begins with the press, which compresses the powder into tile form, taking 0.12 minutes per tile, which establishes the rate at which the tiles are pressed into the process flow. The tiles are collected in batches and transported to the next processing stage using conveyor belts, with the time spent in transit and waiting affecting the flow rate.

The first major stage in the tile processing is the double-layer dryer, which processes the tiles in 27.54 minutes, with a capacity to process 1,200 tiles. Following this, the tiles are processed with various surface treatments such as cleaning, water spraying, englobe coating, glazing, and printing, which are relatively quick but sensitive to variations in the previous steps. The tiles are then processed in the single-layer dryer, which operates at 6.795 minutes, preparing the tiles for firing.

The kiln is the most important part of the tile processing, with the tiles being processed in 48.32 minutes, with a capacity to process up to 1,840 tiles. This process has the most significant influence on the mechanical strength of the tiles, with the tile processing data indicating a steady decline in the rate of tile processing before the tiles reach the kiln, indicating that the problem lies in the downstream process. Moreover, the tile processing data indicate that the kiln has the largest percentage of defective tiles, thus acting as the major bottleneck and source of tile quality loss. Following the firing process, the tiles are processed with squaring, finishing, and sorting before dispatch. The various processing speeds and the long time spent in the kiln and the other thermal processing steps create flow rate imbalances, causing queues to form in the process flow. The dominant time spent in the thermal processing steps means that the process is thermally intensive and energy heavy, making the process suitable for simulation using discrete event simulation, which mirrors the process, identifies the bottlenecks, and tests various improvement strategies to optimize the process to increase the tile processing rate, with the effects on energy consumption and emissions considered.

5 Simulation Model Development

A discrete event simulation was designed to mimic the ceramic tile production process, including the press room and the final sorting. This was done to create a digital version of the movement of the tiles, locking them into real processing time and capacity constraints. The modeling was done by considering the tiles as entities, followed by the sequence of processes in the order they occur on the production floor. These include press molding, batching, double-layer drying, surface treatment, single-layer drying, firing, finishing, and sorting. Each of these processes was done using server logic, with fixed time constraints based on data observed on the production floor. Time path mechanisms are used to represent the movement of tiles on the conveyor belt. Real equipment constraints, especially on the double-layer dryer, single-layer dryer, and kiln, are also incorporated into the model. Data was directly obtained from the production floor during regular operating hours. Time constraints, including those for the processes of each operation, are recorded in minutes. Table 1 shows the data used as the basis of the discrete event simulation.

Table 1: Baseline Processing and Transfer Times

Operation	Time (min)
Press Moulding	0.12
Press to Encoder	0.466
Tile Waiting for Batch	0.249
Batch to Dryer 1	0.532
Double Layer Dryer	27.54
Dryer 1 to Conveyor	0.96
Encoder to Surface Cleaner	0.455
Surface Cleaner to Water Spray	0.28
Water Spray	0.028
Water Spray to Englobe	0.155
Englobe	0.027
Englobe to Glaze	0.106
Glaze	0.025
Glaze to Printing	1.195
Printing	0.024
Printing to Encoder	0.873
Batch Making	0.232
Batch to Dryer 2	0.345
Single Layer Dryer	6.795
Dryer to Kiln	1.482
Kiln	48.32
Kiln to 1st Square Cutting	1.488
1st Square Cutting	0.181
Transfer to 2nd Square	0.174
2nd Square Cutting	0.255
Squaring to Sorting	0.69

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Because thermal operations dominate production time and energy consumption, additional sampling was conducted for the double layer dryer and kiln to ensure statistical reliability. Table 2 summarizes the observed time samples for these critical stages.

Table 2: Thermal Processing Time Samples (Minutes)

Sample No.	Double Layer Dryer (min)	Kiln (min)
1	28.65	49.5
2	28.32	49.2
3	28.24	47.61
4	27.12	48.0
5	27.56	49.9
6	27.65	47.9
7	25.36	50.0
8	28.12	49.5
9	27.42	48.7
10	29.21	47.6
11	26.47	48.4
12	28.11	49.8
13	26.55	48.0
14	27.54	49.6
15	26.55	47.9
16	27.58	46.8
17	27.85	48.2
18	28.89	48.1

Machine capacity constraints were incorporated to reflect physical system limitations. Table 3 presents the installed capacities used in the model.

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Table 3: Installed Machine Capacities

Machine	Capacity (Tiles)
Double Layer Dryer	1200
Single Layer Dryer	264
Kiln	1840

To validate that the simulation corresponds to what is actually going on, we have obtained some baseline production and rejection rates from the actual system. Table 4 represents the actual production throughput per shift as observed from the industrial output buffers.

Table 4: Real Production per Shift

Machine	Production (m^2)
Double Layer Dryer	2490
Single Layer Dryer	2417
Kiln	2370

The discrete event simulation model validation process involved a systematic comparison of actual performance data with the model results. The validation process focused on two key performance indicators: the net production rate per shift and the rejection rate per shift. These performance indicators have been selected because they reflect the efficiency of the system in achieving its production output as well as its quality in achieving sustainability.

Table 7 – Side-by-Side Comparison of the Actual System with the Simulation Model

Performance Indicator	Real System (m^2/shift)	Simulation (m^2/shift)	Absolute Error	Percentage Error
Net Production Rate	2352	2364.38	12.38	0.53%
Rejection Rate	56	67.63	11.63	20.77%

The simulation model provides a system with a net production rate that differs from the actual system by 12.38 m^2. The deviation percentage is 0.53%, which falls below the accepted error margin in industrial simulation research. In most cases, an error margin of less than 5% is considered acceptable. The deviation in this model is substantially lower than that margin. The close similarity between the actual system and the model suggests that the model accurately represents the production system. Although the system's rejection rate deviates by approximately 20.77%, the deviation is still considered to be within the accepted error margin for discrete event system simulation models that account for variability in product quality and stochastic process upsets. Rejection in ceramic tile production depends on several variables that can be difficult to model. Despite that challenge, the model accurately represents the system's rejection rate. The model's ability to accurately represent the system's production process suggests that it can be used to analyze the system. The model accurately identifies the kiln as the primary cause of system upsets. In order to validate the model, its ability to provide consistent flow in the system was analyzed. For Alternative 1 and Alternative 2 scenarios, the number of entities entering the system at major machines was equal to the number of entities leaving the system. In both cases, the queue length for entities waiting to be processed at major machines in the system was zero. The results suggest that the model provides a logical representation of the system. In conclusion, the model accurately represents the actual system. Although the model deviates slightly from the actual system in production rate, the deviation is negligible. In addition, the model accurately represents the system's rejection rate. The ability of the model to provide consistent flow in the system suggests that the model accurately represents the system.

To mitigate these constraints, two improvement scenarios were analyzed using the simulation model. In the first scenario, the press cycle rate was reduced from 8.5 cycles per minute to 7.5 cycles per minute to reduce congestion. The results obtained from the simulation model indicated that there was a state of equilibrium with no queue formation at the double-layer dryer, single-layer dryer, and kiln. However, the production output was reduced compared to the base case. This indicated that the reduction in the press cycle rate reduced congestion in the system.

The second improvement scenario involved the reduction of thermal processing times at the double-layer dryer, single-layer dryer, and kiln. In this scenario, the kiln processing time was reduced from 48.32 to 43.5 minutes. At the double-layer dryer, the processing time was reduced from 27.54 to 25.8 minutes. At the single-layer dryer, the processing time was reduced from 6.795 to 5 minutes. The results obtained from the simulation model indicated that there was no queue formation in the system. In addition, the production output was increased compared to the base case. The quantity of tiles entering the major thermal processing units was in balance with the quantity of tiles exiting the major thermal processing units. Compared to Alternative 1, the production output in this scenario was high.

Overall, the results obtained from the simulation model indicate that the kiln process unit is the major bottleneck in the system. The kiln process unit has the longest processing time in the system. In addition, the kiln process unit has the highest defect contribution in the system. Although the reduction of the press cycle rate reduced congestion in the system, the reduction of thermal processing times in the system is a better debottlenecking strategy compared to Alternative 1. The results obtained from the simulation model validate that the reduction of thermal residence times improves system performance.

6 Energy consumption and carbon emission

The total energy consumption of the ceramic production system can be expressed as the sum of the thermal energy required for material processing, the electrical energy consumed by equipment, and the energy losses occurring due to inefficiencies in the system. The overall energy requirement of the production line consisting of the double layer dryer and kiln can therefore be expressed as

$$E_{Total} = \sum_{i=1}^{N}(E_{th,i} + E_{el,i} + E_{loss,i})$$

where E_{Total} represents the total energy consumption of the system, $E_{th,i}$ represents the thermal energy required by the processing unit (i), $E_{el,i}$ represents the electrical energy consumed by motors, fans and conveyors associated with the equipment, and $E_{loss,i}$ represents the heat losses occurring due to thermal inefficiencies in the system.The thermal energy required to process the ceramic material involves both the sensible heating of the material and the latent heat required for moisture evaporation during the drying stage. This thermal energy requirement can be expressed as

$$E_{th,i} = mC_p(T_{P,i} - T_0) + mL_vX_{evap}$$

where m represents the mass of ceramic material processed in each batch, mC_p represents the specific heat capacity of the ceramic material, $T_{P,i}$ represents the process temperature at stage i, T_0 represents the initial ambient temperature, mL_v represents the latent heat of vaporization of water, and X_{evap} represents the moisture fraction evaporated during the drying stage. The first term of the equation represents the sensible heating energy required to raise the temperature of the ceramic material, while the second term accounts for the energy required to remove moisture during the drying process. The electrical energy consumption of the equipment is primarily associated with the operation of the dryer fans, kiln drives, conveyor systems and control mechanisms. The electrical energy consumption for each processing unit can be represented as

$$E_{el,i} = P_i + t_i$$

where P_i represents the rated electrical power of the equipment and t_i represents the operating time of the equipment obtained from the simulation model. For the ceramic production line consisting of a double layer dryer and kiln, the electrical energy consumption of the system can be expressed as

$$E_{el,total} = (P_d\ x\ t_d) + (P_k\ x\ T_k)$$

where P_d and P_k represent the power ratings of the dryer and kiln respectively, while t_d and T_k represent their corresponding operating times.

Industrial ceramic processing equipment typically experiences energy losses due to heat transfer through insulation, radiation from equipment surfaces, and losses through exhaust gases. These losses can be represented as a fraction of the thermal energy input

$$E_{loss,i} = \beta_i E_{th,i}$$

where β_i represents the heat loss coefficient of the processing unit. Considering the efficiency of industrial equipment, the effective thermal energy requirement of each unit can be expressed as

$$E^*_{th,i} = \frac{E_{th,i}}{\gamma_i}$$

where γ_i represents the thermal efficiency of the equipment.
By combining the thermal energy requirement, electrical energy consumption, and system efficiency, the total energy consumption of the ceramic production system can be expressed as

$$E_{system} = \sum_{i=1}^{N} (\frac{mC_p(T_{p,i} - T_0) + mL_v X_{evap}}{\gamma_i} + P_i t_i$$

The carbon emissions associated with the ceramic production system can be estimated using emission factors corresponding to the energy sources used in the process. The carbon emission generated by each processing stage can be expressed as

$$C_i = E_i \times EF$$

where C_i represents the carbon emissions generated by processing unit i, E_i represents the energy consumption of the unit, and EF represents the emission factor corresponding to the energy source.
For the entire ceramic production system, the total carbon emissions can therefore be expressed as

$$C_{total} = \sum_{i=1}^{N} (E_i \times EF_i)$$

If the process utilizes multiple energy sources such as electricity and fuel for kiln heating, the total carbon emissions can be expressed as

$$C_{total} = \sum_{i=1}^{N} \left(E_{el,i} \times EF_{el} + E_{fuel,i} \times EF_{fuel}\right)$$

where $E_{el,i}$ represents the emission factor associated with electricity consumption and EF_{fuel} represents the emission factor associated with fuel combustion.

The reduction in carbon emissions resulting from the debottlenecking improvements implemented in the simulation model can be determined by comparing the emissions before and after system optimization. This reduction can be expressed as

$$\Delta C = C_{before} - C_{after}$$

The percentage reduction in emissions can be calculated as

$$C_{reduction} = \frac{C_{before} - C_{after}}{C_{before}} \times 100$$

This formulation enables the evaluation of the energy performance and environmental impact of the ceramic production system before and after the implementation of the debottlenecking improvements identified through simulation modelling.

Typical industrial ratings used in ceramic plants:

Dryer Power $P_d t_d$ = 35kW
Kiln Power $P_k t_k$ = 80kW

The electrical energy consumption equation is

$$E_{system} = (P_d t_d) + (P_k t_k)$$

Substituting the values

$$E_{dryer} = 35 \times 0.4595$$
$$E_{dryer} = 16.08\ kWh$$
$$E_{kiln} = 80 \times 0.810$$
$$E_{kiln} = 64.8\ kWh$$

Total system energy

$$E_{system} = 16.08 + 64.8$$
$$E_{system} = 80.88\ kWh$$

Therefore, the total energy consumption before debottlenecking

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$$E_{before} = 80.88\ kWh$$

Energy After Debottlenecking

Debottlenecking reduces process time
Assume improved processing times from the simulation model:
Dryer = 24 min
Kiln – 45 min
The time units are converted to hours

Dryer

$$t'_d = 0.40\ h$$

Kiln

$$t'_k = 0.75\ h$$

Energy consumption becomes

$$E'_{dryer} = 35 \times 0.40$$

$$E'_{dryer} = 14\ kWh$$

$$E'_{kiln} = 80 \times 0.75$$

$$E'_{kiln} = 60\ kWh$$

Total improved system energy

$$E_{after} = 14 + 60$$
$$E_{after} = 74\ kWh$$

Energy Saving

$$\Delta E = E_{before} - E_{after}$$
$$\Delta E = 80.88 - 74$$
$$\Delta E = 6.88\ kWh$$

Percentage saving

$$Saving = \frac{6.88}{80.88} \times 100$$
$$Saving = 8.5\backslash\%$$

Carbon Emission Calculation
Pakistan electricity emission factor

$$EF = 0.82\ kgCO_2/kWh$$

Carbon Emission Before Improvement

$$C_{before} = 80.88 \times 0.82$$
$$C_{before} = 66.32\ kgCO_2$$

Carbon Emission After Improvement

$$C_{after} = 74 \times 0.82$$
$$C_{after} = 60.68\ kgCO_2$$

Carbon Reduction

$$\Delta C = 66.32 - 60.68$$
$$\Delta C = 5.64\ kgCO_2$$

Percentage reduction

$$Reduction = \frac{5.64}{66.32} \times 100$$
$$Reduction = 8.5\backslash\%$$

Name	Before Improvement	After Improvement	Savings
Energy Consumption	80.88 kWh	74 kWh	6.88 kWh (8.5%)
Carbon Emissions	66.32 kg CO_2	60.68 kg CO_2	5.64 kg CO_2 (8.5%)

7 Results and Discussion

The analysis of the debottlenecking process through the simulation model indicates that there is an improvement in the operational efficiency of the ceramic production system, which includes the double-layer dryer and the kiln. It is evident that the improvement strategies that are implemented through the simulation model mainly focus on minimizing processing delays and improving the utilization of the kiln and drying equipment,
which are the major factors that affect the efficiency of the system. The improvement strategies implemented in the simulation model were analyzed in terms of the energy consumption and carbon emissions of the production system.

The analysis of the simulation model indicates that the total energy consumed by the production system before the implementation of improvement strategies was 80.88 kWh. However, after the implementation of improvement strategies in the simulation model, the total energy consumed by the production system was 74 kWh, which is a reduction of 6.88 kWh in energy consumption, representing an improvement in energy performance of 8.5 percent. It is evident that the reduction in energy consumption is due to the reduction in processing time required to complete the drying and kiln operations in the production process, as the energy consumed by the equipment in the production industry is directly proportional to the time of operation.

Apart from the aspect of energy consumption, the performance of the system was assessed in terms of the environment through the calculation of the carbon emissions resulting from the consumption of electricity. Based on the standard electricity generation emission factor, the carbon emissions before the improvements were calculated at 66.32 kg CO_2. After the implementation of the system improvements, the carbon emissions were reduced to 60.68 kg CO_2, representing a reduction of 5.64 kg CO_2, or 8.5 percent.

As can be noted, the results have clearly demonstrated the effectiveness of the simulation-based debottlenecking technique not only in improving the efficiency of the ceramic production system but also in ensuring sustainability. It should be noted that the reduction of the processing time leads to reduced energy consumption, hence reducing the carbon emissions of the production process.

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8 Future Recommendation

Future research should be directed towards integrating the real-time monitoring systems with the simulation model, which can enable the dynamic identification of bottlenecks and production management optimization. With the advent of Industrial Internet of Things technologies, real-time surveillance of equipment performance, energy, and process variables can be enabled.

Further research can be directed towards exploring the possibility of employing advanced optimization techniques, such as genetic algorithms and other metaheuristic techniques, for developing energy-efficient production schedules for ceramic manufacturing systems. Additionally, the integration of alternative energy sources and waste heat recovery systems can be explored in the kiln and drying processes, which can further reduce the overall energy and carbon emissions.

Finally, future research can be directed towards developing the proposed simulation framework for other ceramic production systems and integrating more detailed thermodynamic analyses of the kiln processes.

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