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LEAN AND SUSTAINABLE MANUFACTURING IN AGGREGATE PRODUCTION: A CASE STUDY

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Abstract: *This study analyzes aggregate production at Mill 1 by integrating value stream mapping with sustainability indicators to address capacity underutilization and resource inefficiency. The analysis identifies key challenges such as excessive energy consumption, high sludge generation, aging technology, and downtime. To mitigate the identified issues, the study proposes strategies such as predictive maintenance, optimized conveyor scheduling, screening automation, and improved resource management. These improvements are expected to significantly increase operational efficiency, reduce environmental impact, and improve worker safety, ultimately contributing to a more sustainable production of building materials. The resulting framework is replicable and applicable to other intensive resource industries.*
Keywords: *Lean manufacturing, sustainable manufacturing, Value Stream Mapping, aggregate production, sustainability indicators, process optimization.*

1. INTRODUCTION

The production of construction aggregates is key to the development of infrastructure and contributes significantly to the global construction industry. Aggregates, which include crushed stone, sand, and gravel, are essential raw materials for constructing roads, bridges, buildings, and many other major infrastructures [1, 2]. The production processes of aggregates, however, are generally energy-intensive and polluting, with frequent inefficiencies leading to increased resource consumption, material waste, and greenhouse gas emissions.

Current conditions of urbanization and the development of new infrastructure across the world point to an increase in demand for aggregates. Indeed, this rise in demand adds to the clear need to address the environmental and social challenges associated with the aggregate production sector [3], [4], [5].

Moreover, the traditional aggregate processing facilities are having problems like the aging of technology, poor transport logistics in moving the aggregates, and moisture present in the raw materials, which on some occasions is quite high, hence underutilization of the installed capacities [4, 6]. The inefficiencies, therefore, require further studies that suggest innovative alternatives to accomplish operational efficiency and sustainability. This is where the idea of combining lean manufacturing with sustainable manufacturing comes in.

Value Stream Mapping (VSM) is amongst the most used lean manufacturing tools for visualizing the production process and identifying the value-adding and non-value-adding activities as a basis for targeted improvements to the process. VSM has been successfully applied in various industries, including automotive, aerospace, and electronics, to reduce waste and improve efficiency [7], [8], [9].

The combination of the VSM with sustainability indicators in the environmental, economic, and social dimensions provides the VSM as a very effective tool for the pursuit of sustainable manufacturing. [10]. For example, integrating energy consumption and carbon footprint metrics into VSM can help identify opportunities to reduce greenhouse gas emissions by reducing waste and maintaining productivity.

This study examines aggregate production at Mill 1, a Cuban facility that faces problems related mainly to underutilization of its capacity, technological obsolescence, and inefficiency of its resources. The methodology used in this study follows a structured and systematic approach to analyze and optimize aggregate production by integrating sustainability principles.

Collection of data through observations and interviews is done to assess current operating conditions, production capacities, and key inefficiencies. Capacity determination is made, process mapping is followed, and simulation is performed using the software AnyLogic to account for realistic production challenges. The VSM is then integrated into the standards of sustainability in a way that allows for the assessment of environmental, economic, and social impacts. Such integration can then be used to propose strategies for sustainable manufacturing and continuous improvement.

The research identifies the poor quality of raw materials, high energy consumption, and equipment being out frequently as major challenges with surrounding strategies to optimize transport planning and implement predictive maintenance. Integrated sustainability improvements become evident in practice and demonstrate how process improvements driven by sustainability can increase efficiency, reduce environmental impact, and improve worker safety.

2. RESEARCH METHOD

Choosing the right research method is essential to ensure that the results serve as solid scientific references, contributing towards theoretical developments and future research directions [11, 12]. In alignment with this idea, a literature survey was conducted using reliable sources such as Google Scholar, Scopus, and Web of Science. The keywords used for the search were "lean manufacturing", "sustainable manufacturing", "value stream mapping" and "sustainability indicators" to identify related studies and best practices.

Following the literature review, relevant methodologies and frameworks were identified, particularly those with a focus on process optimization and sustainability. After analyzing various methodologies and evaluating the results obtained in their implementation, the Fitriadi & Ayob (2025) [13] proposal was chosen. This methodology, due to its recent development and effective integration of lean manufacturing and sustainable manufacturing tools, was successfully adapted to the context of aggregate production processes. A representation of the methodology is shown in Figure 1.

The first step of the methodology focuses on problem identification and consists of direct observation and interviews with mill operators to gather essential data on operating conditions, cycle times, and resource consumption. Observations along the production line are used to measure the length of processing cycles for different aggregate volumes, allowing the actual production capacity to be calculated about the installed capacity of the mill.

In addition, a process flow chart was developed to show the flow from raw material receipt through primary and secondary crushing, screening, and sorting into different product categories. A VSM was then developed, incorporating critical KPIs.

This part of the study involves problem identification to differentiate between Value-Added Time (VAT) and Non-Value-Added Time (NVAT) activities within the overall production process's Production Lead Time (PLT). VSM analysis reveals waste in several categories, including transportation, motion, waiting, and storage.

Equations (1), (2), and (3) are used to calculate PLT, VAT, and NVAT, respectively. The last part of this step is to calculate the Process Cycle Efficiency (PCE) using Equation (4), which quantifies the ratio of VAT to PLT.

In step 2, sustainability indicators are selected to address the unique characteristics of the aggregated production process, focusing on the environmental, economic, and social dimensions of sustainability. The indicators selected outlined the important aspects of sustainable manufacturing: energy consumption, material efficiency, greenhouse gas emissions, production costs, worker safety, and well-being.

Step 3 evaluates the critical analysis of VSM and sustainability indicators.

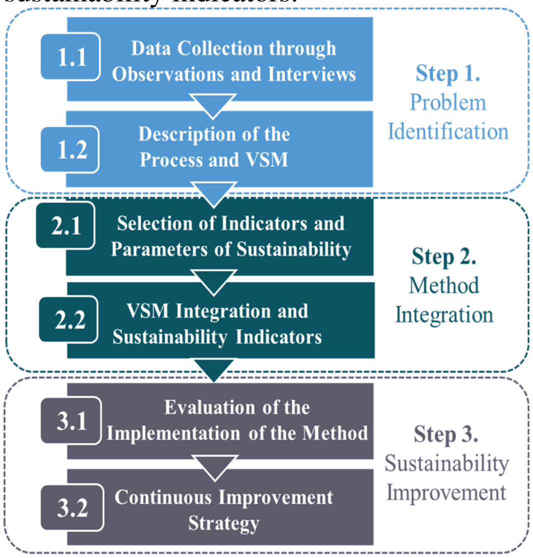

Fig. 1. Research Methodology.
Adapted from Fitriadi & Ayob (2025).

$$PLT = \sum(Process\ Cycle\ Times) + \sum(Waiting/Inventory\ Times) \quad (1)$$

$$VAT = \sum(Value - Added\ Cycle\ Times) \quad (2)$$

$$NVAT = PLT - VAT \quad (3)$$

$$PCE = \left(\frac{VAT}{PLT}\right) \times 100\% \quad (4)$$

This reflects the current situation of the mill, indicating the areas in which process efficiency and sustainability could be improved. The results inform the development of strategic recommendations for the optimization of aggregate production processes. The strategies are practical for the transition of the building materials sector into sustainable and lean manufacturing.

3. METHODOLOGY APPLICATION AND RESULTS

The selection of Mill 1 as a case study is based on several key aspects. First, the mill is representative of the typical conditions and challenges of aggregate production in the region. Operating since 1978, it faces common problems such as capacity underutilization, technological obsolescence, and resource inefficiencies. This makes it an ideal scenario for applying improvement methodologies, such as the one proposed in this study.

The findings will be divided into four major parts: an analysis of the mill's operational conditions; the identification of inefficiencies using VSM; the integration of VSM with sustainability indicators to assess environmental, economic, and social impacts; and the construction of a continuous improvement plan.

3.1 Overview of Mill Operations

The aggregate production mill operates according to a structured workflow designed to process raw materials efficiently while meeting production requirements. The mill functions 312 days per year with a 16-hour work shift, incorporating planned preventive maintenance to minimize unexpected downtimes. Raw material, primarily stone, is delivered in truckloads with a capacity of 30 m³, and each truckload is processed in approximately 25 minutes.

The production process consists of several automated stages, including primary and secondary crushing, screening, and classification of aggregates into three main product types: sand, 3/4-inch stone, and 3/8-inch stone. Despite the automation, inefficiencies are present due to factors such as suboptimal quarry blasting reducing raw material availability, excessive sludge generation from high moisture content, outdated machinery leading to frequent breakdowns, and energy inefficiencies contributing to high operational costs. Additionally, water stagnation in storage areas impacts resource utilization and overall productivity.

Figure 2 presents the process flow chart of the mill operations, visually depicting the structured flow from raw material input to the final classification and storage of processed aggregates. This diagram highlights interdependencies between process steps, technological requirements, and potential inefficiencies that may arise due to machine downtime, bottlenecks, or material losses.

The calculation of available time and production capacity is essential for assessing the efficiency of Mill 1. The Total Available Time for production is determined based on the operational schedule of the mill, which functions 312 days per year. Given that each day consists of 24 operational hours, the total available time is 7,88 hours/year.

However, routine Planned Maintenance activities account for a total of 702 hours per year, reducing the actual productive time available for aggregate processing. Additionally, unplanned Downtime, estimated at 3% of the time remaining after planned maintenance, further reduces productivity. The downtime is 203.58 hours/year. Beyond these scheduled and unscheduled interruptions, the mill operates under a work shift of 16 hours per day, meaning that within the 312 working days per year, 4,992 hours are effectively utilized for direct production, leaving a total of 936 not-working hours per day.

Taking all these factors into account, the Effective Productive Time (EPT) is determined by subtracting planned maintenance, downtime, and work shift limitations from the total available time, resulting in a total of 4,086 hours per year to produce. The production process in Mill 1 is heterogeneous, meaning it produces three distinct types of aggregates: sand (40%), 3/4-inch stone (37%), and 3/8-inch stone (23%). Given that the process is fully automated and the technological operating times are consistent across product types, the analysis is conducted for the mill rather than for each product individually.

Following the calculation of effective available time, the next step is determining the installed production capacity for each aggregate type. The processing time per unit is defined as the time required to process 1 m³ of stone in normal conditions, which has been determined to be 0.83 minutes or 0.01 hours per cubic meter. This value serves as the basis for installed capacity calculations.

The Installed Capacity for Mill 1 is obtained by dividing the Effective Productive Time by the processing time per unit and multiplying it by the operational coefficient (Roj = 0.75) to account for realistic efficiency levels.

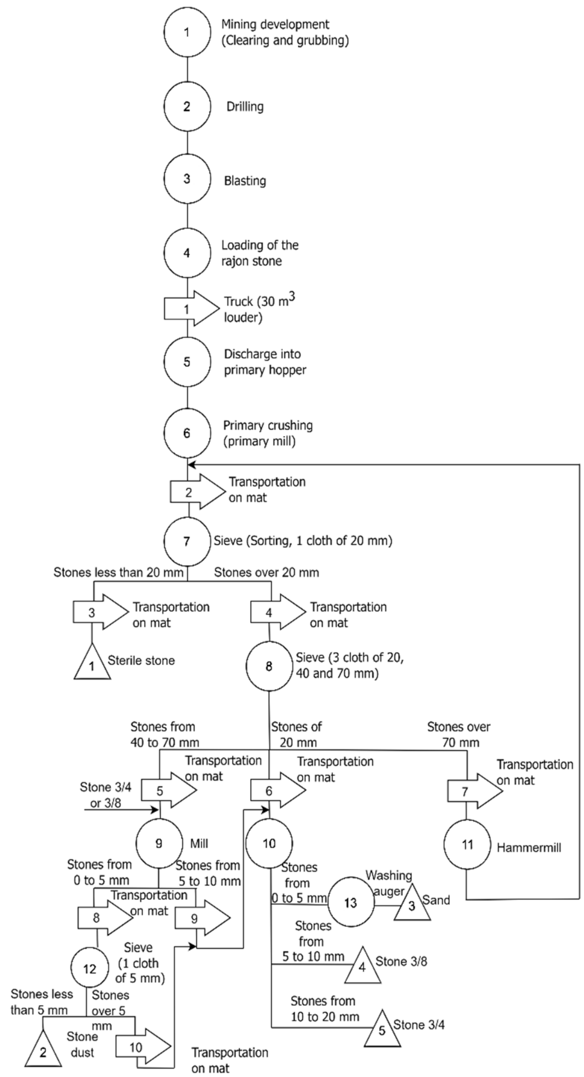

Fig. 2. Aggregate Process Flow Chart.

The following results were obtained (summarized in Table 1).

Table 1

Installed Capacities of the Mill.

Product	Installed Capacity Calculated (m^3)	1-month Production (Real)	1-month Production (Simulation)
Sand	120,320	5,875	5,990
3/4-inch Stone	112,800	5,533	5,662
3/8-inch Stone	71,440	3,295	3,387

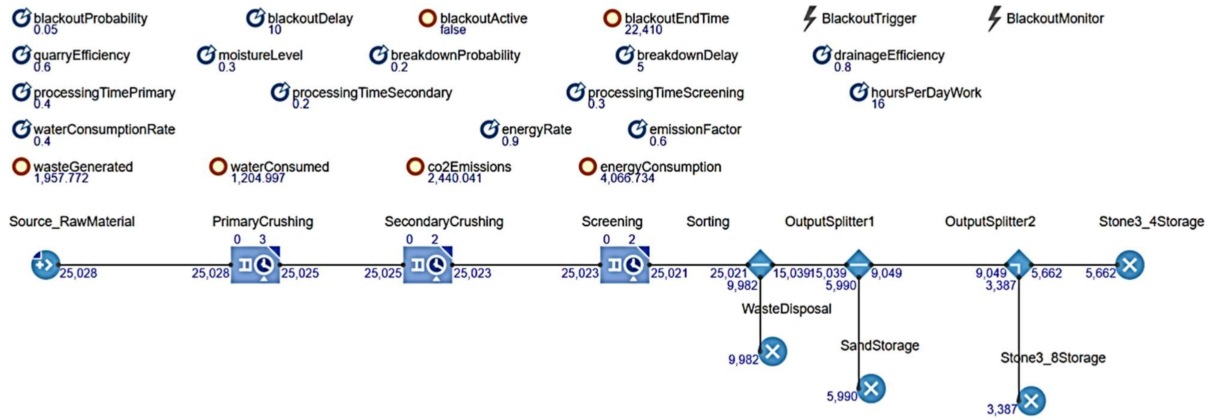

Fig. 3. Simulation of One Month Production Under Current Mill Conditions

In addition to determining the mill's installed capacity for one year, the AnyLogic software was used to simulate the production process for one month under current conditions and compare the production results recorded during the same period. A solid and realistic representation of the system performance was attained by entering the complete data and restrictions into the model. As is demonstrated in Figure 3, the results of the simulation parallel real life closely, with only minor changes in producing quantities; hence, these data could serve as reliable benchmarks. These findings present valuable insights into production flow, resource utilization, and process inefficiencies, thus providing a basis for pinpointing improvement opportunities and enhancing overall production. The data also indicates that, under current conditions, the installed capacity for aggregate production at Mill 1 is underutilized by 42.06%.

3.2 VSM-Based Problem Recognition

The continuous improvement of the production of Mill 1 through the VSM, integrated with the sustainability indicators, follows a structured process in three parts.

The process begins with time measurement, where LPT, VAT, and NVAT are analyzed to assess operational efficiency. Next, a current-state process map is developed to identify sources of waste, which is then improved by assessing sustainability indicators related to energy use, material waste, and emissions. Finally, in the third stage, targeted strategies for continuous improvement are developed based on the insights derived from these indicators, aiming to optimize efficiency, reduce environmental impact, and improve overall performance.

Table 2 presents the key data utilized for the development of the VSM map shown in Figure 4. This map outlines the flow of materials and information throughout the production system, highlighting the distinction between value-added and non-value-added activities. By providing a comprehensive visualization of production lead time and cycle time, it enables the identification of inefficiencies and waste.

The analysis presented in Figure 4 and Table 2 reveals that the total production lead time for the analyzed month is 24,978.3 minutes, of which 22,803.3 minutes constitute value-added time and only 2,175 minutes are non-value added. This yields a high PCE of 91.29%, indicating that the majority of the cycle is dedicated to productive activities. Key value-added operations, primary crushing (10,011.20 minutes), secondary crushing (7,507.50 minutes), and screening (5,004.60 minutes) dominate the production process.

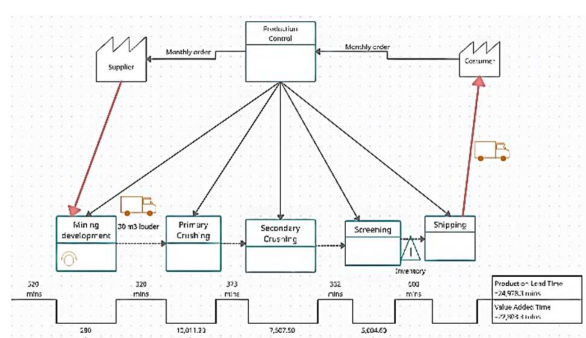

Fig. 4. VSM of Aggregates Production.

Table 2

Time evaluation for 1 month demand.

Process Step	Cycle Time (mins)	Value Added?
Discussion of the month's production plan	120	No
Preparation of conditions for mining development	400	No
Mining development	280	Yes
Transportation of raw materials	120	No
Primary Crushing	10,011.20	Yes
Secondary Crushing	7,507.50	Yes
Screening	5,004.60	Yes
Inventory	600	No
Total waiting time in the process (breakdown, blackout, high levels of moisture)	935	No
PLT	**24,978.3 mins**	
VAT	**22,803.3 mins**	
NVAT	**2175 mins**	
PCE	**91.29 %**	

In contrast, non-value-added activities, including preparation for mining development (120 minutes), a non-value-added segment of mining development (400 minutes), transportation of raw materials (120 minutes), inventory (600 minutes), and waiting time due to breakdowns, blackouts, and high moisture levels (935 minutes), are relatively minor but still represent potential areas for improvement. These results suggest opportunities to further streamline non-productive activities, thereby improving overall process efficiency and sustainability.

3.3 Integrating VSM with Sustainability Indicators

The integration of VSM with sustainability indicators involves correlating the problem identification results from the VSM analysis with data gathered through direct observations and interviews. This part is structured around three key sustainability dimensions, environmental, economic, and social, which together provide a comprehensive assessment of the production process. Linking these tools not only identifies operational inefficiencies, but also assesses their broader impact, ensuring that any improvements are in line with sustainable manufacturing goals.

When evaluating the process flow, equipment performance, execution and processing times, and inventory management, significant opportunities for improvement are identified. Enhancements are guided by environmental, economic, and social sustainability criteria to ensure a comprehensive and balanced optimization strategy. Using the selected sustainability indicators from the methodology, current performance is assessed.

Several critical issues are addressed. First, the poor condition of the quarries, exploited since 1978, has led to limited raw material availability due to inadequate blasting depth (3 meters instead of the required 12 meters). This deficiency disrupts supply consistency. To mitigate this, deeper blasting techniques and improved mining development quality are proposed in collaboration with Mining and Geological Services Company, alongside integrating sustainability indicators for quarry resource management.

Second, excessive sludge generation caused by high moisture content in raw stone impacts sieving performance and final product quality, leading to customer dissatisfaction. Solutions include improving moisture control, redesigning sieving operations with automated classification systems to enhance throughput and introducing a waste management indicator to monitor and classify sludge appropriately.

Third, the obsolete technology in the mill, operating since 1978, contributes to frequent breakdowns and inefficiencies. Predictive maintenance is recommended to extend equipment lifespan, along with phased modernization using energy-efficient machinery.

Fourth, high energy consumption and frequent blackouts hinder productivity. While overhead power lines replaced underground systems, inefficiencies persist. Installing energy management systems and using backup energy sources will optimize usage and ensure continuous operation. Additionally, an energy consumption per m³ indicator will track improvements.

Lastly, water stagnation in aggregate storage areas reduces process efficiency due to poor drainage and leaks. Drainage improvements, repairing washing system leaks, and adding a water consumption indicator are proposed to increase resource efficiency. Table 3 summarizes the sustainability indicators assessed throughout this analysis, providing a comprehensive evaluation of the process's environmental, economic, and social impacts.

The environmental indicators reveal that the production process consumes a total of approximately 4,066.73 kWh of energy and generates around 2,440.04 kg of CO_2 emissions, which underscores the process's environmental footprint. Additionally, nearly 1,957.77 m³ of waste is produced, while the process consumes roughly 1,205 m³ of water, and only 25% of the waste material is recyclable. From an economic perspective, capacity utilization remains relatively low at 57.94%, and production costs range from 12 to 20 USD per cubic meter of aggregate. Maintenance downtime is also significant, ranging between 15-25% of total operational time, and the production lead time is 416.30 hours, indicating potential inefficiencies in process flow.

Socially, although transport-related safety incidents are minimal (1 incident per year), worker exposure to dust and noise is high, highlighting occupational health concerns.

In addition, it is important to note in terms of sustainability that blasting in quarries has a significant impact on local ecosystems, altering biodiversity and generating changes in the landscape that can compromise the long-term sustainability of raw material extraction.

These activities not only affect the natural environment but can also have negative consequences on community health by influencing air and water quality, which in turn impacts costs and local economic viability. In this context, the involvement of various stakeholders like workers, managers, environmental experts, and the local community is essential to provide a holistic view of the challenges and opportunities.

These results lead to opportunities for improvement in energy efficiency, waste management, process throughput, and worker safety to achieve a more sustainable and cost-effective production system.

Table 3

Evaluation of Sustainability Indicators at Mill 1 Aggregates Production Site.

Indicator	Value	Unit
Environmental		
Total energy consumed	4,066.734	kWh
Total CO_2 emissions	2,440.041	Kg
Total waste volume	1,957.772	m^3
Total water consumed	1,204.997	m^3
Recyclability of Waste Material (%)	25	%
Economic		
Capacity utilization (%)	57.94	%
Cost per m³ of aggregate	12 -20	USD/m^3
Maintenance Downtime (% of Total Time)	15 -25	%
Production Lead Time (hours)	416.30	hours
Social		
Safety incidents related to transport	1	incidents/ year
Worker dust/noise exposure	High	Qualitative

3.4 Strategies for Continuous Improvement

After a thorough analysis of the identified deficiencies and the possible solutions, a comprehensive set of strategies is developed to optimize mill capacity utilization and enhance sustainability in aggregate production. These strategies, summarized in Table 4, focus on process efficiency, resource optimization, and environmental impact reduction, integrating lean manufacturing principles and sustainability indicators. By addressing key inefficiencies, such as high energy consumption, excessive material waste, outdated technology, and operational bottlenecks, these interventions aim to create a more efficient, cost-effective, and environmentally responsible production system.

In addition, a future projection was made using simulation with AnyLogic software, incorporating the proposed strategies. This projection made it possible to anticipate the impact of the improvements on the overall performance of the process, showing a higher utilization of the installed capacity, a reduction in downtime, and a lower environmental impact. The results obtained support the feasibility of implementing the proposed strategies. Therefore, the sustainability of aggregate production depends on the successful implementation of these continuous improvement measures.

Table 4

Strategies for Continuous Improvement.

Proposed Strategies	Expected Outcomes
Process Optimization	
Optimized Transport Scheduling: Reduce idle machinery and fuel consumption by improving logistics and routing	Lower transportation costs and CO_2 emissions
Predictive and Preventive Maintenance: Use real-time monitoring to reduce unplanned downtime and prolong equipment lifespan	Increased reliability, lower maintenance costs, and fewer disruptions
Environmental Sustainability	
Energy Efficiency Measures: Implement energy management systems and alternative energy sources	Lower energy consumption per m^3 of aggregate, reduced operational costs
Reduction of CO_2 Emissions and Dust Pollution: Optimize extraction and crushing processes, introduce dust suppression systems	Improved air quality and reduced carbon footprint
Water Management and Waste Reduction: Improve drainage systems, repair leaks, and adopt closed-loop water recycling	Minimized water waste, reduced operational disruptions
Material Circularity and Waste Recycling: Classify and repurpose by-products for secondary applications (e.g., road construction)	Higher recyclability rates, lower environmental impact, additional revenue streams
Economic and Operational Performance	
Cost Reduction via Resource Optimization: Optimize raw material extraction and streamline energy and fuel consumption	Lower production costs, reduced material loss
Capacity Utilization Enhancement: Increase production efficiency through process automation and real-time monitoring	Utilization rates improved from up to 75-80%
Social Responsibility and Workforce Development	
Occupational Health and Safety Improvements: Implement noise and dust control, improve safety audits	Safer working conditions reduce health risks
Employee Training and Workforce Development: Offer technical training on sustainable manufacturing and equipment operation	Enhanced workforce skills, better compliance with lean and sustainable practices
Community Engagement and Stakeholder Collaboration: Develop environmental responsibility programs and research partnerships	Strengthening corporate social responsibility, improved community relations

4. LIMITATION AND FURTHER RESEARCH

This study has limitations that must be acknowledged. The first limitation of this study is the absence of a detailed cost-benefit analysis to confirm the economic viability of the proposed measures. While strategies aimed at improving operational efficiency and reducing environmental impact were identified, it is essential to evaluate these interventions to ensure that they are cost-effective and sustainable in the long term. Also, having concentrated on a single facility, this case study, therefore, has limited generalizability of its results to other production environments and warrants further research to validate and extend the proposed framework to different environments and scales.

In terms of future lines of research, future studies could explore the application of advanced automation technologies, including machine learning for predictive maintenance and real-time monitoring systems for process control.

Expanding the scope of sustainability indicators to include life cycle analysis beyond the production stage, extending to transportation, usage, and disposal of aggregates to gain a more comprehensive understanding of environmental impacts throughout the supply chain. Incorporating circular economy principles, such as the reuse of quarry by-products and the development of alternative aggregates from recycled materials, could further reduce the impact of resource extraction while promoting sustainability in the production of building materials. In addition, the integration of renewable energy sources to mitigate high energy consumption and carbon emissions associated with aggregate production is a promising area for future research.

The economic impact of implementing lean and sustainable practices should also be further investigated. Future studies could conduct cost-benefit analyses to assess the financial viability of process improvements and explore payback periods for technology improvements, waste reduction systems, and renewable energy integration. The scalability of sustainable strategies in different operational contexts, including small-scale versus large-scale aggregate production, would be valuable in determining the adaptability of lean and sustainable methodologies in different industrial settings.

Lastly, comparative studies across multiple production sites and geographic regions could provide insights into how different environmental conditions, regulatory frameworks, and resource availability affect the effectiveness of process optimization strategies. This would contribute to a more general and adaptable framework for improving the sustainability and operational efficiency of aggregate production worldwide.

5. CONCLUSIONS

This study demonstrates the effectiveness of integrating VSM with sustainability indicators to optimize production efficiency and promote sustainable practices in aggregate manufacturing. The analysis identified critical issues, including capacity underutilization, excessive material waste, high energy consumption, and frequent equipment breakdowns, stemming from outdated technology, poor transport scheduling, and suboptimal quarry management.

By implementing targeted strategies, such as predictive maintenance and transport scheduling optimization, proposed improvements strategies reduce production lead time, enhance capacity utilization, and align with environmental, economic, and social sustainability goals.

The enhanced VSM, incorporating sustainability metrics, not only visualizes process flow improvements but also serves as a decision-making tool for continuous process enhancement. The results highlight the potential to reduce energy consumption, CO_2 emissions, and material waste while improving worker safety and operational reliability. These findings contribute to the growing body of research advocating for sustainable manufacturing in resource-intensive industries, providing a replicable framework for similar production systems. Sustainable production practices in the construction materials sector are essential to meeting global infrastructure demands while minimizing environmental and social impacts, and this study offers actionable solutions to achieve those goals.

Finally, it is concluded that the integration of lean manufacturing and sustainable manufacturing is validated as a synergistic strategy that leads to significant improvements in operational efficiency and reduced environmental and social impacts. Lean manufacturing, with its focus on eliminating waste and optimizing processes, facilitates the identification and correction of inefficiencies, resulting in higher productivity and lower operating costs. In turn, sustainable manufacturing extends this paradigm by incorporating environmental and social criteria that promote the rational use of resources, the reduction of emissions and waste, and the well-being of workers and the community. Together, these methodologies not only optimize the performance of the production system but also ensure responsible and resilient operations over the long term.

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Îmbunătățirea sustenabilității unui sistem de producție prin utilizarea instrumentelor lean. Studiu de caz

Acest studiu prezintă o metodologie de îmbunătățire a utilizării resurselor în producția de bunuri, prin integrarea Value Stream Mapping cu indicatorii de sustenabilitate. Analiza identifică provocări cheie, inclusiv consumul excesiv de energie, generarea ridicată de deșeuri, tehnologia învechită și timpul de nefuncționare frecvent. Pentru a atenua aceste probleme, studiul propune strategii precum întreținerea predictivă, optimizarea programării transportoarelor, automatizarea operațiunilor de sortare și îmbunătățirea gestionării resurselor. Aceste intervenții sunt concepute pentru a îmbunătăți semnificativ eficiența operațională, a reduce impactul asupra mediului și a îmbunătăți siguranța muncitorilor, contribuind în cele din urmă la o producție mai sustenabilă de materiale de construcție. Cadrul rezultat este replicabil și aplicabil altor industrii intensive în resurse.
Cuvinte cheie: *Lean manufacturing, producție durabilă, Value Stream Mapping, producție agregată, indicatori de sustenabilitate, optimizarea proceselor*

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