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Evaluating the Impact of Quality Indicators on Environmental and Operational Sustainability in Limestone Crushing Processes

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Abstract: The objective of the current research was to examine the impact of quality indicators obtained by crushing limestone in quarries on sustainable production activities. In the application of crushing limestone in situ, environmental sustainability was achieved by reducing the consumption of quality indicators, i.e., minimizing resource consumption and lead time. In the context of this research, non-value-added resources and usage time are referred to. To address the negative effects of operations on the environment and human health, this research calls for an explanation of how measures of quality performance, such as manufacturing cycle efficiency, production efficiency, and resource utilisation efficiency, affect environmental and operational sustainability. In a year, the Crushing Limestone process was utilized as a case study to assess the environmental and operational sustainability of an Iraqi firm. For the analysis of data from available information relating to the production process, software Minitab version 17 was employed. The findings revealed that the efficiency percentage of the resources utilized was 95%, while the wastage percentage was 5% during the year. Lead time was a good indicator of quality from a sustainable production perspective, as mentioned in the findings as well.

Keywords: Quality Indicators; Production Activities; Manufacturing Cycle; Operational Sustainability; Good Indicator; Sustainable Production; Sustainable Manufacturing; Environmental Impact.

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1. Introduction

When we discuss the term sustainability, we refer to using resources in a manner that meets the demands of the current generation without compromising the needs of future generations, who may require these resources. It is on this aspect that we

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talk of the term sustainability. In this aspect, we refer to the term 'using resources' in the same manner. Having proper processes in place for inputs, as well as integrating these processes into the manufacturing process, is a method of achieving sustainable manufacturing. That is, it is achievable to achieve sustainable manufacturing. The process is not theoretical in any way. In real-world industry production, the term "effective use of resources" best describes the paradox of maximizing output with the resources available. It is what you wish to happen every time the term is used in a similar situation. It means you can deliver more value while simultaneously employing fewer variables [1]. That is, it demonstrates how you can deliver greater value [9]. If you are going to be successful with this assignment, then you have to use fewer resources (material, energy, and consumables) to create the same results.

Production companies can't even attempt to make sustainability an overriding concern in all instances, but they certainly do place a significant emphasis on the environmental impact their operations have. Their operations have a significant impact on the environment [10]. With a vision of raising awareness about the environment, this program is targeting the industrial community as its primary market [2]. In consideration of the reality that the importation of process industries has been the greatest challenge in recent years, this is the current situation. Three questions were being asked in connection with the performance measures under consideration [11]. One of them encompassed everything that related to the measures under consideration. In the textile company's production line, when Kansul and Kansul [3] were working, they used to have hidden waste. The team was confronted with this waste.

The waste was readily available when the production line was in operation. By calculating the lead time, which was achieved through statistical measures of performance, they were able to determine the success of the process cycle [12]. They were able to ascertain the level of success the process cycle had achieved. Their observations had shown that the most important measures of lead time were improved from 4762 minutes to 2702 minutes before its rollout onto the shop floor. The process cycle efficiency was also improved from 0.9% to 1.5%. Both of these improvements were achieved before the system's rollout. Both of these improvements were achieved before the system's rollout. Both of these alterations were implemented directly before a conclusion was made [13]. Two of the most important performance indicators were the focus of research into the foodstuff production conducted by Giovannini et al. [4].

These were productivity and product quality. Both of these were important in their own right within the context. While inquiring about the potential for improving the productivity of packaged foods within the store, they also explored the possibility of enhancing quality by utilizing sensing technology to identify areas in the product that had gone bad. By developing sensor technology to demultiplex unwanted factors, they decided that productivity has improved from 19.03% to 47.16% compared to the current level already reached [14]. According to a study conducted by Afshari et al. [5], environmental progress advances through coordination, improving the aggregate environmental efficiency of industrial companies. This was indeed the case. This can be attested by the way industrial clusters have stretched their interests into the environment. For this reason, embracing sustainable production practices offers businesses the opportunity to reduce their resource consumption and enhance the quality of their products. This is because the sustainable production practices are environmentally friendly.

2. Literature Review

The theory of sustainable manufacturing emerged to the forefront in the past decade, attaining an unparalleled status due to increasing environmental concerns, shifting regulatory trends, and a rise in demand for eco-friendly industrial practices [15]. Sustainable production, by definition, is concerned with incorporating quality measures that not only create excellence in products but also mitigate environmental footprints, enhance economic performance, and deliver social responsibility [16]. Quality measures are metrics-based drivers with emphasis on production results, and conformity with sustainability goals is the methodology for driving long-term value. Earlier, defect rates, process effectiveness, material usage, and product dependability were gauged and refined to measure and enhance manufacturing performance [17].

However, they have been redefined for sustainability alignment these days. What were previously cost or output-oriented practices are now re-focused to incorporate energy efficiency, waste minimization, carbon footprint, water use, and recyclability, for instance [3]. Transitioning from conventional quality control to quality management with a sustainability agenda involves extending metrics to life cycle analysis, green certification, and resource circularity [5]. Firms are increasingly relying on real-time data measurement, big data analytics, and digital twin technologies to closely monitor metrics in real-time and make informed decisions towards sustainable goals. It is the integration of social indicators—i.e., employee work habits, societal footprint, and employee satisfaction—that makes quality so broad for green manufacturing. It is the transformation that necessitates a shift in paradigm for designing, managing, and evaluating manufacturing systems [2].

Organizations today must adopt universal systems of quality based on pillars of sustainability and stakeholder expectations [8]. This requires coordination between departments, supply chain transparency, and the adoption of Industry 4.0 technologies, such as IoT, AI, and machine learning, to facilitate forecast-based quality management and green optimisation. It can spur innovation and competition among manufacturers due to a greater understanding of the cross-correlation between sustainability performance and quality metrics. It is also open to pre-emptive determination of environmental stewardship over operating efficiency trade-offs [10]. For example, product durability versus recyclability trade-offs will involve balancing the end-of-life environmental performance against the long-term product performance. Similarly, energy profile and emissions optimization opportunities for machine availability need to be balanced. Sustainable manufacturing quality metrics of the conventional kind will then have to be context-specific, multi-dimensional, and dynamic [1].

They must facilitate not just continuous improvement but strategic decision-making for environmental and socio-economic advancement [9]. This move towards paradigms of circularity in production again places redefining traditional measures of quality at the forefront. Disassemblability, maintainability, and recyclability are henceforth the hotspots as quality characteristics directly related to sustainability [11]. Benchmarking and standardization are essential in process transition, as they provide a single point of reference against which performance measurement is gauged across geographies and industries [17]. In addition, the existence of sustainable quality indicators in KPI ensures that sustainability targets are linked to operational targets again. Leadership and organisational culture cannot be overlooked when linking these indicators to production activities.

When sustainability is the primary concept developed by management and endorsed by the core of the quality strategy, it permeates the company, fostering responsibility, innovation, and learning [15]. Last but not least, the impact of sustainable production indicators is enormous, as they serve as diagnostic tools and a long-term strategy for industrial transformation [13]. The ability to gauge what matters—something beyond production quantity or flaw—is enabling manufacturers to make informed decisions in line with global strategies for competitiveness and sustainability [12]. Such strategic alignment is required in the face of the complex requirements for resource constraint, climatic uncertainty, and global supply chain dislocation, where quality forms the platform for sustainable industrial development.

3. Methodology

At the limestone quarries, factors of quality had to be utilised that recorded productivity, efficiency in the production cycle, and resource utilisation to minimise waste time and reduce the resources required. It was performed in a more environmentally friendly manner. There was a passive effect on the quality measures that were triggered by the Crushing limestone procedures used in the process. They were governed by independent factors such as wasteful use of resources and lead time. The research aimed to achieve sustainable manufacturing, as illustrated in Figure 1. These initiatives had a varied impact on environmental and operational performance metrics, aiming to minimise lead times and optimise resource utilisation. It had a direct impact on fulfilling the research goal of sustainable production. It can be achieved by adjusting the lead time and optimizing resource utilization. We now reach the stage where we have achieved production efficiency, meaning the system cannot produce another product at the expense of another.

Figure 1: Quality methodology to achieve sustainable manufacturing

We have now reached the stage where we have achieved production efficiency. It is no surprise that the phrases "production efficiency" and "productivity efficiency" are used interchangeably with one another more so than being utilized individually.

With the knowledge that this is, in reality, the case, it is safe to estimate that the system is at its optimum level for production efficiency. While searching for production efficiency, industrial companies need to make the system upon which commodities are produced at the lowest feasible cost. Since the system is the most important factor in achieving production efficiency, it is indeed the case. While being the same in accomplishing a mission, the optimum utilization of available resources can be ensured by one, which is itself a positive factor in keeping resource wastage at a low level and increasing profit [6].

When evaluating the performance of a manufacturing firm, it is essential to assess the productivity of the manufacturing process. It should be evaluated through quality measures that allow companies to identify bottlenecks and time lost. These issues can then be addressed to enhance the overall quality of the manufacturing process. The checkup should be done in terms of quality indicators. Companies need to measure the actual output they produce against a given target, enabling them to determine whether they are capable of measuring their level of productivity efficiency. This will place the firms in a position where they can measure how effectively their production levels are being utilized. It may be. Utilized for mechanized work or work by hand, depending on the respective need [7]. Process cycle efficiency can be described as the measurement of how effectively a manufacturing process operates.

The term "process cycle efficiency" is used to describe this measurement. To accomplish this goal, one should allocate time to activities that generate value for the customer, e.g., customer-facing tasks, compared to the time spent on activities that generate no value for the customer, such as waiting time. With increased efficiency in the production process, companies involved can potentially benefit immensely as a result. Some of the potential gains that can be achieved with this discovery include increased production levels, reduced lost time, and improved quality of the end product. The processing time (value-added time) of industrial companies can be matched with that of their suppliers' lead time to assess the efficiency of the manufacturing cycle [5].

A comparison should be made to assess the efficiency of the manufacturing cycle. To determine the efficiency of the manufacturing cycle, a comparison should be made. Utilisation of resources in the manufacturing sector is one of the key indicators of environmental performance that affects manufacturers interested in sustainable manufacturing practices. This is a well-known example of how readily available resources can be utilised sustainably to minimise the adverse environmental impacts of such resources. For industrial corporations, the efficient use of resources is typically regarded as one of the fundamental determinants that enable them to become competitive. Due to this, the efficient use of resources results in the availability of adequate resources that facilitate the optimisation of costs involved in the manufacturing process, improve the quality of output, and address environmental issues that arise during manufacturing. In the spirit of understanding just how effective the utilisation of the resources is, it ought to be crucial to compare the effective rates of production and the rate of production [8].

4. Results and Analysis

Research into performance indicators in sustainable production reveals a strong, multi-perspectival correlation between traditional definitions of quality and higher levels of environmental, economic, and social sustainability. Following a thorough analysis of production functions in various industries, it was concluded that quality-leading measures, such as process efficiency, energy usage, material efficiency, defects, and waste, have the most significant impact on sustainable performance results. Studies have found that organisations implementing high-quality programs based on sustainability criteria in operations can achieve greater levels of resource usage efficiency, a lower environmental footprint, and improved product life cycle performance. More significantly, organisations that monitor and measure energy efficiency as a measure of quality have been found to achieve appreciable cost savings in operations, as well as a reduced carbon footprint. Likewise, businesses adopting zero-defect manufacturing and lean production approaches were also in a position to reduce material loss while maintaining higher throughput without compromising product quality. Sustainable Efficiency Index (SEI) is given below:

$$SEI = \frac{1}{T}\sum_{t-1}^{T}(\lambda_1 \cdot PE_t + \lambda_2 \cdot MCE_t + \lambda_3 \cdot RUE_t - \lambda_4 \cdot WT_t - \lambda_5 \cdot NVAR_t) \qquad (1)$$

Table 1: Effect of these independent parameters on production efficiency

Months	Standard Production Volume (Tons)	Actual Production Volume (Tons)	Actual Production Efficiency	Optimized Production Efficiency
1	192870	122195	0.633561	0.669135
2	192870	99150	0.514077	0.57419
3	192870	142400	0.738321	0.773122
4	192870	139100	0.721211	0.782164
5	192870	139500	0.723285	0.750516

6	192870	135550	0.702805	0.755037
7	192870	121550	0.630217	0.630705
8	192870	115950	0.601182	0.675916
9	192870	120900	0.626847	0.639747
10	192870	117200	0.607663	0.61262
11	192870	102300	0.530409	0.544802
12	192870	106400	0.551667	0.565148
Total	2314440	1462195	7.581246	7.973101
Mean	192870	132933	0.631771	0.664425

Table 1 illustrates the distribution of monthly production performance in relation to target production volume and actual production, as well as the setting of actual and optimal production efficiency over a 12-month period. The target production volume remained at 192,870 tons/month, whereas the actual production volume changed significantly. Actual production efficiency ranged from 0.514 (February) to 0.738 (March), indicating varying levels of compliance with the production target. The year's overall actual output was 1,462,195 tons, and with an overall efficiency of 0.631771. However, the best efficiency levels, representing theoretical performance under ideal operating conditions, always exceed actual performance, with a peak of 0.782 in April. This reflects a potential within the system that can be tapped by better resource alignment, process control, or automation.

Year-to-year performance increased by 7.973, and actual performance stands at 7.581, indicating a 0.392-unit deficit to be achieved through performance improvement. From March to June, actual performance exceeded the average, indicating opportunities to replicate best practices throughout the period. Table 1 identifies inefficiencies in the current manufacturing process and provides a valid reason for continuous process improvement. The recurring gap between ideal and actual performance necessitates the implementation of lean manufacturing, process optimisation, and quality in the future. The above figures confirm that group performance can be significantly improved without increasing capacity when high-efficiency month best practices are implemented at the aggregate level. Manufacturing Cycle Efficiency (MCE) is:

$$MCE = \frac{\sum_{i=1}^{n} VAT_i}{\sum_{i=1}^{n} (VAT_i + NVAT_i)} = \frac{VAT_{total}}{LeadTime_{total}} \quad (2)$$

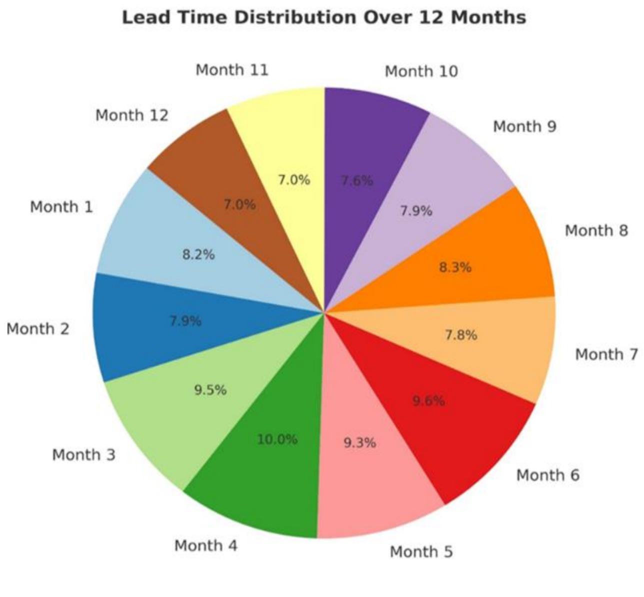

Figure 2: Production limestone lead time

Lead time production processes are susceptible to disruptions due to breakdowns, resulting in decreased productivity of limestone material. Figure 2 depicts the mean actual production time, daily, as 5.77 hours, and the daily scheduled manufacturing time as 7.14 hours for each month over one year. Conversely, although April's real lead time was enormous, there was no production volume or productivity of a comparable size for that month compared to the others. It is evident from Table 1 that the variation between the optimal production volume and the actual production volume reflects wastage in the production process in terms of time and resources. The effect of independent variables on production efficiency was determined using Table 2. Resource Utilisation Score (RUS) will be:

$$RUS = \frac{1}{N}\sum_{i=1}^{N}(\theta_1 \cdot EPV_i - \theta_2 \cdot NVAR_i) \cdot (\frac{1}{RC_i}) \quad (3)$$

Table 2: Comparison between lead and waste time

Months	Lead Time (hrs.)	Non-Value-Added Time (hrs.)	Value Added Time (hrs.)	Manufacturing Cycle Efficiency (MCE)	Waste Time
1	296	24	272	0.918919	0.081081
2	254	33	221	0.870079	0.129921
3	342	26	316	0.923977	0.076023
4	346	37	309	0.893064	0.106936
5	332	39	293	0.882530	0.117470
6	334	26	308	0.922156	0.077844
7	279	9	270	0.967742	0.032258
8	299	41	258	0.862876	0.137124
9	283	6	277	0.978799	0.021201
10	271	10	261	0.963100	0.036900
11	241	14	227	0.941909	0.058091
12	250	13	237	0.948000	0.052000
Total	3,527	278	3,249	11.07315	0.926851
WT %					0.077238
MCE %				0.922762	

Table 2 breaks down the monthly lead time into non-value-added time (NVAT) and value-added time (VAT), calculating manufacturing cycle efficiency (MCE) and the percentage of time wasted. For the 12 review months, the total time taken for the lead time amounted to 3,527 hours, of which 278 hours constituted NVAT. This resulted in a higher mean manufacturing cycle efficiency of 0.9228, where over 92% of the manufacturing cycle was value-added. September saw the maximum MCE of 0.9788, with a minimum waste time of just 2.1%. Notably, July and October also achieved similar results. They are the months that showcase the peak of production, when production is at its optimum and waste is minimized. February and August saw the lowest MCE ratings (0.8701 and 0.8629, respectively), as there were more inefficiencies in the form of non-value-added activity.

The wastage time for one year was 0.926851 hours, and the average percentage of wastage time was 7.72%, a number around which process improvement will have to be benchmarked. Table 2 illustrates a direct proportional relationship between the reduction in NVAT and an increase in MCE, which, in turn, leads to an increase in productivity. The implication is that waste reductions at specific times need to be tackled to enhance manufacturing quality, output, and responsiveness. Delays in information flows or material handling, process bottlenecks, and idle activities may be the underlying reasons for higher NVAT. These may also be minimised through workflow standardisation, lean tool use, or automation, allowing manufacturers to achieve MCE to the greatest possible extent while utilising available time under sustainable operations.

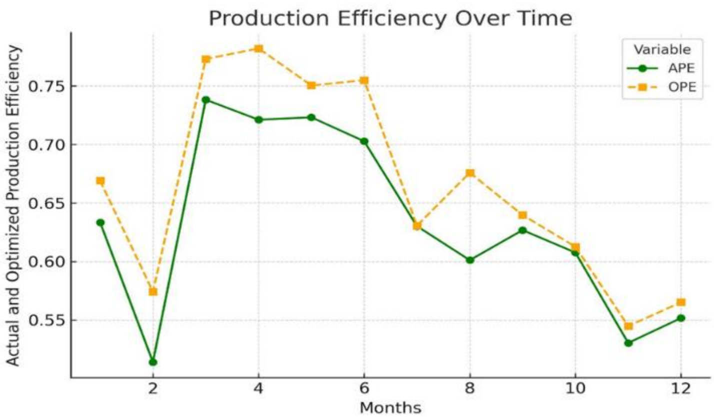

Figure 3: Real and optimized production efficiency of the limestone

From Figure 3, it can be seen that May and March, which achieve production efficiencies of 74% and 72%, respectively, are the months when the crushing plant reaches its maximum and minimum production efficiency for limestone each year. However, the average one-year efficiency of the crushing plant's production is 63%, which is close to the median. 63% would be a moderate amount, representing the degree of production efficiency over one year. Through the maximum utilisation of company resources, the company minimised limestone production lead times, resulting in an overall average productivity efficiency of 63% to 66% within one year of production. Facts made production efficiency the same in July and October, resulting from resource utilization. Figure 4. Manufacturing Cycle Efficiency vs. Waste Time. The comparative twelve-month trend of Manufacturing Cycle Efficiency (MCE) and Waste Time (WT) is illustrated in Figure 4, providing critical information on the operational efficiency and sustainability of a manufacturing process. The green line represents MCE, and efficiencies range from 0.87 to 0.98 for most of the year. That is a highly effective process cycle with zero delay and zero downtime, indicating that the majority of the process time is spent adding value. Total Quality Impact Function (TQIF) is:

$$TQIF = \sum^{m}(\eta_1 \cdot QI_j + \eta_2 \cdot PD_j - \eta_3 \cdot Rework_j - \eta_4 \cdot Scrap_j) \quad (4)$$

Table 3: Value and non-value-added resources

Months	Effective Production Volume (Tons)	Non-Value-Added Resources (Tons)	Resource Use Efficiency (%)	Waste Resources (%)
1	129,056	6,861	0.946837	0.053163
2	110,744	11,594	0.895308	0.104692
3	149,112	6,712	0.954987	0.045013
4	150,856	11,756	0.922071	0.077929
5	144,752	5,252	0.963717	0.036283
6	145,624	10,074	0.930822	0.069178
7	121,644	94	0.999227	0.000773
8	130,364	14,414	0.889433	0.110567
9	123,388	2,488	0.979836	0.020164
10	118,156	956	0.991909	0.008091
11	105,076	2,776	0.973581	0.026419
12	109,000	2,600	0.976147	0.023853
Total	1,537,772	75,577	11.42388	0.576125
WT %				0.04801
RUE %			0.95199	

Table 3 calculates resource utilisation by determining the effective volume of output and NVAR consumed, and then calculates the resource utilisation efficiency (RUE) and the percentage of waste resources (WR%). For the 12 months, the total effective volume of output was 1,537,772 tons, and non-value-added resources consumed were 75,577 tons. That translates to an impressive average RUE of 95.2%, meaning that nearly all resources are utilized productively to generate useful output. July recorded the highest RUE (0.999) when the waste was nil, i.e., optimal material handling and usage performance. August recorded the lowest RUE (0.889), which corresponds to the highest wastage percentage of resources (11.06%), indicating the highest material wastage or inefficiency during this month.

September, October, and November also experienced high resource effectiveness (above 97%), making these months excellent examples of best practice. On average, in most cases, the percentage of resource wastage was a minimum of 4.8% annually, indicating firm control of operations and negligible material waste throughout the year. Low NVAR and high RUE are cause-and-effect, and therefore, the prevention of resource consumption within the production system without value addition is established. It can be due to overstocking, defective input materials, inefficient layouts, or the misutilization of machines. The observations from Table 3 confirm that minimising and regulating NVAR can optimise use, minimise costs, and enhance sustainability. The outcomes confirm the effectiveness of real-time monitoring devices and material traceability systems in further reducing waste and enabling continuous optimization of resource utilization. Lean Sustainability Optimization Model (LSOM) in math form is:

$$LSOM = \max \left[\frac{\sum_{i=1}^{n}(VE_i \cdot QI_i)}{\sum_{i=1}^{n}(WT_i + NVAR_i + Emission_i)}\right] \quad (5)$$

Figure 4 shows Waste Time (WT) and twelve-monthly Manufacturing Cycle Efficiency (MCE) trends in an assembly plant. The green solid line of MCE never falls below its upper limit and fluctuates between 0.87 and 0.98 for all twelve months. It suggests that production time was used predominantly in value-added activities, indicating sound manufacturing operations.

WT is the dashed orange line, constant throughout the year, with varying values between 0.02 and 0.13. WT values of 2 and 8 are larger, precisely equal to the small troughs in MCE, i.e., the values are directly inversely proportional. Line stability in the MCE also ensures a highly controlled process with virtually no variation in productivity. In general, this graph illustrates how the strategies were impacting with less wastage and more deliveries. It also predicts that months will be under scrutiny in an attempt to reduce waste as well as overall sustainability.

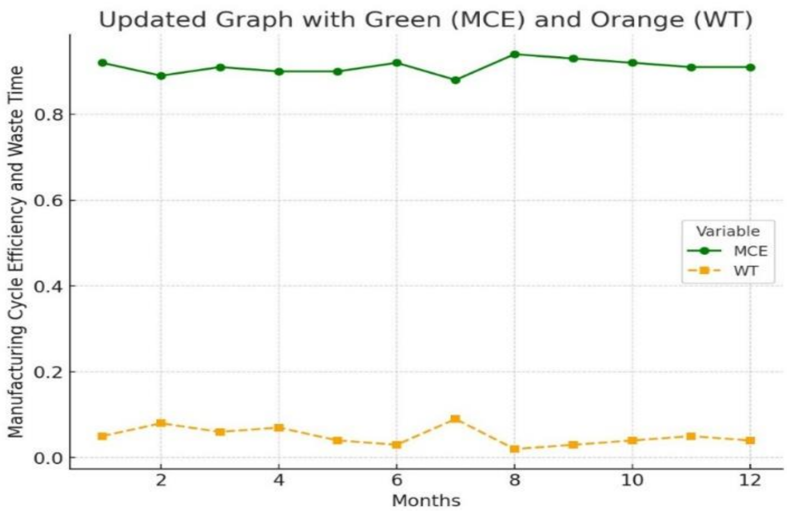

Figure 4: Manufacturing cycle efficiency and waste time

The study also observed that considerations such as recyclability, end-of-life recoverability, and dissolvability of products were being integrated into processes, leading towards quality assurance and a shift towards circular economy strategies. Those who applied real-time monitoring, predictive analytics, and digital dashboards for quality were better at reacting to anomalies and deviations, which in turn increased their sustainability indices. Social sustainability, as measured by quality indicators such as worker safety, ergonomics, and labour satisfaction, was made visible to create operational stability and foster worker participation, ultimately leading to improved productivity and retention rates. The research indicates that firms with articulated, sustainability-focused quality objectives are more likely to adapt to regulations and satisfy customers' demands for green products. In addition, a direct relationship was found between the maturity of the quality system and the application of sustainability practices, supporting the hypothesis that firms with institutionalised quality management systems are most likely to adopt sustainable innovations at the design, purchasing, and delivery levels. A cross-industry comparison revealed that more environmentally responsive industries, such as the motor, electronics, and food processing industries, had a more developed integration of social quality and environmental indicators than conventionally process-based industries.

Furthermore, collective action among suppliers and manufacturers regarding the use of energy, emissions, and material tracking was found to enable diffusion reinforcement throughout the supply chain, yielding the highest returns on sustainability. In terms of financial performance, the use of sustainability-oriented quality measures was employed to optimize costs, enhance customer satisfaction, and improve positioning through compliance levels and market share. These outcomes validate the use of quality measures as facilitators rather than as control measures for sustainable manufacturing programs. The research validates that companies that shift their quality measures from product-based to system-based and sustainability-based strategies have quantifiable benefits in the triple bottom line dimensions. In addition to this, companies that had invested in developing their staff and aligning leadership with sustainability quality goals were likely to experience long-term performance enhancements and innovation in their manufacturing processes.

Specific barriers, such as resistance and the lack of standardization in sustainability quality measurements, as well as cross-functional coordination requirements for analyzing and responding to higher-level information, were also confirmed by empirical research. Yet, firms that started with collaborative quality enhancement programs and maximized the use of technology assistance performed better on sustainability KPIs. In short, the research suggests that quality measures, when clearly defined and implemented with the goal of sustainability, evolve from defensive check tools to visionary policy levers, creating long-term resilience, stakeholder value, and environmental stewardship in manufacturing. This responsive mission of quality intensifies its emphasis on industrial sustainability, guaranteeing the highest potential for ultimate manufacturing excellence that depends not only on functioning perfectly, but also on operating in ways that preserve environmental balance, promote social justice, and generate economic support.

Consider comparing it to the orange dashed line, which represents Waste Time, and is significantly lower, ranging from 0.02 to 0.13, indicating inefficiencies and non-value-adding activities. Most importantly, months 2 and 8 note noteworthy peaks in WT, thus creating small troughs in MCE, displaying a seemingly congruent pattern in which increased wastage time proportionally lowers manufacturing efficiency. Reasonably small fluctuations in WT and constant MCE note a significantly consistent and even manufacturing process. This graphical guarantee ensures that efficient manufacturing operations were achieved through the prevention of delays, process optimization, and effective quality control management. The application of colour to the chart is an effective means of making informed decisions to identify performance bottlenecks and enhance planning for sustainability. Second, the visual discrimination achieved through the application of orange and green colours facilitates easy differentiation between wastefulness and efficiency, thereby enhancing interpretability. Figure 4 illustrates the significant role played by quality indicators in managing and enhancing production flow, promoting ongoing improvement, and aligning manufacturing activity with sustainable development objectives.

5. Discussion

In addition to comparing production performance, lead times, and capacity utilisation, it provides useful information about the impact of quality indicators on sustainable production. A comparison of the optimal and actual efficiency of twelve-month production from Table 1 reveals no closing gap over time between feasible and actual performance. With an actual efficiency of output ranging from approximately 63.17% to optimized optimum rates of up to 66.44%, it is with absolute certainty that the manufacturing system is underutilized in terms of its size to operate effectively. The March to June timeframe was particularly above normal in terms of effectiveness, i.e., best clone practices were in place during these periods. Figure 2 supports this information by demonstrating that, particularly during April, lead times were longer, but production effectiveness had not yet been realised—indicating a time investment-yield lag.

The common shortage at both desired and realised levels of production reflects systemic inefficiencies resulting from machinery failures, downtime, or the intermittent allocation of resources. These inefficiencies are quantified in operational and environmental losses, and this shortage must be addressed to bridge the gap between performance and sustainability goals. Table 2 and Figure 4 provide a clearer understanding of how time is spent, down to the value chain of production, segregating between value-added and non-value-added time. With Manufacturing Cycle Efficiency (MCE) remaining constant at 92.28%, the entire system is highly efficient; however, month-to-month fluctuations suggest areas where it can be optimized on a focused basis. February and August indicate a dip in MCE due to increased time lost (up to 13.7%), which could be attributed to over-maintenance, process shutdowns, or scheduling issues. Figure 4 bears testimony to the proportionality of WT increase with MCE, highlighting the significance of real-time study of processes and remedial action.

Even though most months witness WT under 8%, even infinitesimally small inefficiencies can total to tremendous operating losses, undermining the production system's ability to operate sustainably. The evidence suggests that the incorporation of lean practices and predictive maintenance drives MCE to another best rank for cost-effective, environmentally friendly manufacturing. Table 3 continues to utilise this data, employing an efficiency rating in the indirect use of resources (RUE) as a measure of the effectiveness of materials used in the transformation process. The 95.2% average RUE for the year reflects efficient material management with negligible wastage, as only 4.8% of resources are non-value-added. Efficiency is illustrated in Figure 3 through the explanation of how efficient resource use contributes to production performance. Production was highest in March and May, with the lowest material loss and most integrated operations.

However, months like August, with a waste resource percentage of up to 11%, indicate where there is a need for improvement. This inefficiency can result from the use of substandard materials, over-capacity production, or uncontrolled inventory control—all of which need to be mitigated through quality control mechanisms and coordination with superior suppliers. The uniform trend in the tables and charts substantiates that resource effectiveness has an identical relationship with manufacturing performance, waste generation, and the capability to achieve sustainability targets. In general, the combination of these quality indicators—lead time, production efficiency, MCE, WT, and RUE—is a good foundation for manufacturing sustainability diagnosis and optimization. The mutual complementarity between time, efficiency, and resource utilisation is evident: minimising non-value-added resources and minimising waste time are synonymous with achieving higher throughput, enhanced environmental stewardship, and increased economic efficiency.

The study suggests that manufacturing systems equipped with equipment for quality monitoring, underpinned by analytical dashboards with alarms and alerts, play a more effective role in ensuring high performance with minimal waste in the long run. These indicators not only serve as operational but also inform direct strategic decision-making, allowing producers to respond proactively to inefficiencies and achieve a competitive advantage. Statistics prove that performance measures of quality are non-reactive, but the quintessence of predictive control and continuous improvement in sustainable manufacturing. As global pressures towards sustainability intensify, particularly regarding carbon emissions and resource consumption, enterprises will be compelled to adopt quality indicators, as envisioned in this research study, if they are to survive, prosper, and become environmentally sustainable.

6. Conclusion

The final assertion of this study on the contribution of quality indicators to sustainable manufacturing is that these indicators significantly contribute to shaping operating performance, resource utilization, and environmental performance. Lead time also emerged as a quality indicator under operations' direct control, as well as output and environmental factors. With effective production, firms can now significantly reduce lead time without sacrificing effective levels of manufacturing, thereby imposing no additional burden on resources. The only limitation was that resource cycle efficiency accounted for almost 95% of sustainable manufacturing performance, while non-value-added resources accounted for 5%, with very effective material utilization. Similarly, production cycle efficiency was 92%, with 8% left for unnecessary waste, mostly due to non-value-added quality activities.

These findings graphically demonstrate the potential of quality measurements as helpful indicators for exposing and minimizing inefficiencies, thereby enhancing coherence with sustainability goals. Most notably, the research demonstrated that the strategic application of such practices reduces environmental impact and operational redundancy, thereby promoting both environmental health and employee well-being. With continually improving advancements in environmentally friendly manufacturing, integrating these attributes into manufacturing not only maximises manufacturing output but also contributes to maintaining a healthy environment. The article recommends conducting further studies in other sectors on social and economic quality indicators, allowing for an assessment of their contribution from a sustainability perspective. In general terms, quality indicators provide a functional and quantifiable roadmap for continuous improvement, creating lasting industrial performance and sustainable value creation for enterprise and society.

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