Project Title

Simulation of Sustainable Manufacturing Practices for Automotive Brake Discs Using Discrete Event Simulation

Course Name

TØL4020 Introduction to Modelling and Simulation for Sustainable Manufacturing

NO.	STUDENT NAME	STUDENT NUMBER	DATE
01	Wiseman Siriro	133881	20/12/2024

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List of abbreviations and/or glossary

DES - Discrete Event Simulation
KPIs - Key Performance Indicators
CO2 - Carbon Dioxide

EXECUTIVE SUMMARY

This report provides a comprehensive simulation study of the sustainable manufacturing process for automotive brake discs, focusing on energy consumption, carbon footprint, and process efficiency. The objective of the study is to evaluate how production processes can be optimized to reduce environmental impact while preserving operational efficiency. Whilst using AnyLogic software, DES methodology was utilized to model key manufacturing stages, including machining, inspection, reworking, packaging, and shipping. The whole simulation was run for a standard 9-hour production shift, between 8 AM and 5 PM, without breaks, to represent a normal working day. Total energy consumption, percentage of renewable energy, total carbon footprint, throughput time, and scrap rate are some of the KPIs used to assess the sustainability and efficiency of this process.

Total energy consumption amounted to 80,476 units, with 24,142.8 units sourced from non-renewable energy, while the remainder came from renewable sources. The renewable energy share stands at 70%, with 30% derived from non-renewable sources. The carbon footprint is significant, primarily due to machine energy consumption and partial reliance on non-renewable energy, though a shift to 100% renewable energy could help reduce the footprint. The scrap rate is 25 scrap units, highlighting the need for improved quality control. The average throughput time is 657.7 units, which affects production flow efficiency. Key recommendations include increasing the renewable energy share to 100%, eliminating non-renewable energy sources, optimizing machine efficiency, reducing energy consumption per unit, minimizing scrap and rework rates, streamlining cycle time, implementing energy-efficient technologies, improving process scheduling and resource allocation, enhancing quality control, focusing on sustainable initiatives, monitoring and minimizing emissions, and emphasizing training and continuous improvement.

In this study, it is evident that DES is an extremely useful methodology for modeling such complex production systems, allowing data-driven decision-making for improving energy efficiency, reducing environmental impact, and optimizing operating performance in the automotive industry, thus showing the areas that need to be improved in order to achieve high-quality results.

1. BACKGROUND

The automotive industry is one of the largest industries in the world, and its manufacturing process is very energy-consuming. Therefore, the production of brake discs is one of the most important portions in automobile manufacturing, which involves machining, assembly, and quality control. By definition, a brake disk is a type of brake that uses calipers to squeeze pairs of pads against a disc or "rotor" to create friction. This action retards the rotation of a shaft, such as a vehicle axle, either to reduce its rotational speed or to hold it stationary. The energy of motion is converted into waste heat which must be dispersed (Satyabrata Rout et al, 2023). With the current emphasis on environmental protection, there is an ever-growing need to reduce energy use, decrease waste, and lower carbon emissions in manufacturing processes. This study examines the manufacturing process for automobile brake discs, with an emphasis on potential sustainability improvements such as increased energy efficiency, a lower carbon footprint, and the use of renewable energy sources.

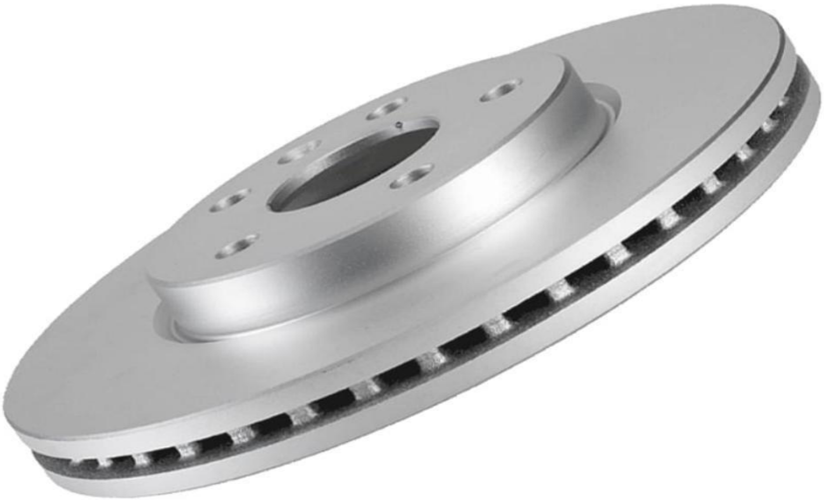

Figure 1- Brake Disk

1.1 Purpose of the Simulation

This simulation study aims to model and optimize the manufacturing process of brake discs to minimize their environmental impact, focusing primarily on reducing energy consumption, carbon emissions, and material waste. The study will explore potential improvements in both operational efficiency and sustainability using DES methodology. It will also identify key areas requiring urgent attention to improve system efficiency while minimizing CO2 emissions. The simulation will center on the critical stages of the manufacturing process, including machining, inspection, rework, packaging, and shipment, with an emphasis on enhancing energy use and reducing dependence on non-renewable energy sources.

1.2 Problem Statement

How does the introduction of renewable energy sources in the production of brake discs in the automotive industry pave the way for effectively reducing the carbon footprint without compromising production efficiency?

1.3 Literature Review

Energy Consumption in Automotive Manufacturing: It is well understood that automotive manufacturing, including the production of braking system is one of the most energy-intensive sectors. Sato and Nakata (2020) estimated the energy use in vehicle production to amount to 41.8 MJ/kg, depending on the materials and technological choice applied in production. Manufacturing processes for components such as brake calipers, discs, and pads involve energy-intensive machining and heat treatment steps. Optimization of energy use, in ways including the integration of renewable sources of energy, has been identified as one of the important strategies to increase sustainability. The International Energy Agency (IEA) in 2021, showed that over 30% of energy consumption in manufacturing could potentially be supplied by renewable sources of energy like solar, wind, and hydroelectric power to help reduce greenhouse gas emissions. Other reports have shown (e.g., Katchasuwanmanee et al., 2017) that industrial energy efficiency improvement through process technologies can make significant contributions toward the achievement of sustainability goals.

Carbon Footprint and Emissions in Manufacturing: The carbon footprint associated with manufacturing processes, including braking systems, is one of the major environmental concerns. According to Els (2021), the manufacturing activities of the automotive sector contribute between 20 and 30% of a vehicle's total GHG emissions. This is so because the majority of GHG emissions emanate from energy-intensive production of material commodities such as steel and aluminum apart from the assembly and logistic operations. According to Materi et al. (2021), the use of renewable sources of energy in all production processes could lead to a reduction in emissions as high as 25%. In a related vein, several articles call for an overall reduction in emissions from the mainstreaming of practices in a circular economy of recycling and reusing. Furthermore, Ghosh (2020) supports the transition to sustainable manufacturing processes using renewable energy to show huge potential for the reduction of emissions.

Energy Impact of Manufacturing Defects: The rate of defects in manufacturing processes has a substantial effect on both energy consumption and the generation of material waste. Dhafr et al. (2006) expressed that defects increase energy consumption by 10-15% for rework, scrapping, and disposal. It is the quality of the products that determines the environmental impact of the manufacturing process. Advanced technologies like AI-based defect detection and predictive maintenance have already been proven to reduce defect rates and their associated environmental impacts. Javaid et al. (2022) reported that the application of AI in defect detection and quality control systems could help reduce waste generation and energy consumption, thereby increasing the sustainability of the entire manufacturing process.

Integration of Renewable Energy: There is a rising trend toward using renewable energy in manufacturing operations. The studies conducted by Usman et al. (2024) and VPIC Group (2024) have shown that integration of solar and wind energy in the manufacturing system can reduce GHG emissions substantially. Similarly, Usman et al. (2024) stated that when renewable energy contributed 50% of the production energy, a 40% emission reduction was achieved. VPIC Group (2024) further emphasized the fact that solar energy is feasible for industries located in regions that have abundant sunlight and that the advantages of renewable energy integration go beyond emissions reductions to lower long-term operating costs.

Material Efficiency and Circular Economy: The key to curbing the environmental footprint brought about by manufacturing lies with a move toward the aspect of a circular economy. According to Kayikci et al. (2021), increased material efficiency might give rise to large energy and material savings because of embracing better uses for raw materials and integrating recycling within the production process. In line with this, Omair et al. (2022) have found companies that adopt recycling programs to reduce their emissions of waste by up to 25% and cut raw material costs. In this aspect, the circular economy approach that emphasizes material reuse and waste minimization is crucial to enhancing overall sustainability in manufacturing operations.

Sustainability in Production: Much research emphasizes the requirement felt by many for sustainable manufacturing practices. According to Kumar et al. (2020), sustainable production involves the minimization of the consumption of natural resources, reduction in environmental pollution, and an increase in operational efficiency. The use of renewable energy coupled with the adoption of lean manufacturing practices goes a long way toward the simultaneous reduction of costs and environmental impacts. Another widely recognized measure to improve sustainability is the adoption of energy-efficient technologies that may include variable speed drives and energy-efficient motors. (Kumar et al., 2020; Dhafr et al., 2006).

2. METHODOLOGY

This section outlines the simulation methodology used to analyze sustainable manufacturing practices for brake discs in the automotive sector. The process includes defining the simulation approach, developing the model structure, making necessary assumptions, collecting data, and testing various scenarios. The simulation was conducted using the DES methodology in AnyLogic software, focusing on critical performance indicators such as energy consumption and carbon emissions at various stages of production. The goal was to identify opportunities for improving sustainability without compromising production efficiency

2.1 Why DES?

Firstly, DES is a computer-based operational research technique that models different systems as networks of queues and activities in order to assess, predict, and optimize a proposed or existing system, where changes occur at discrete epochs over time [13],[14],[15],[16],[18]. DES, also referred to as a time-to-event model, is ideal for complex problems [17]. DES is particularly effective for studying sustainable manufacturing practices in the automotive industry due to its ability to:

- *Model Complex Systems:* Represent manufacturing processes as sequences of discrete events.
- *Dynamic Analysis:* Monitor system performance over time, facilitating detailed analysis of throughput and delays.
- *Resource-Driven Modeling*: Simulate the allocation and utilization of resources like machinery, labor, and materials, which influence production outcomes.
- *Stochastic Representation:* Incorporate real-world uncertainties, such as defect rates, energy consumption, and delays, through statistical distributions.

2.2 Model Structure

The following are the main stages of the simulation model in the manufacturing of automotive brake discs:

Parts Arrival: This is where raw materials, such as steel or aluminum, enter the system and are prepared. This is a very important event that initiates the process, and its timing can be adjusted based on supply chain conditions.

Preparation: Parts are pre-treated to machining needs, which involve basic shaping, cutting, or pre-machining. Energy consumption in this stage sets the pace for the next operations. The energy usage is partly renewable-solar-and partly non-renewable.

Batch and Machine Preparation: Items are batched together and then subjected to various machining operations like drilling, turning, or grinding. The parts are then ungrouped and sent for inspection. This stage of machining is an energy-intensive process, and the energy usage at this stage is recorded.

Inspection and Rework: The parts are inspected for their quality, and the defective items are routed for either rework or scrapping. Rework operations increase energy consumption due to additional machining and handling. The defect rate impacts both the energy use and the environmental impact of the process.

Packaging and Shipping: The successfully processed parts are packaged, transported to storage and dispatched for delivery. This stage includes the logistical processes, and associated energy consumption is tracked.

An overall flowchart of the AnyLogic model of how all the stages are linked, and resources used by the stages, is shown in **Figure 2**. This provides an overall view of the manufacturing process and shows the major decision points such as quality checks and rework.

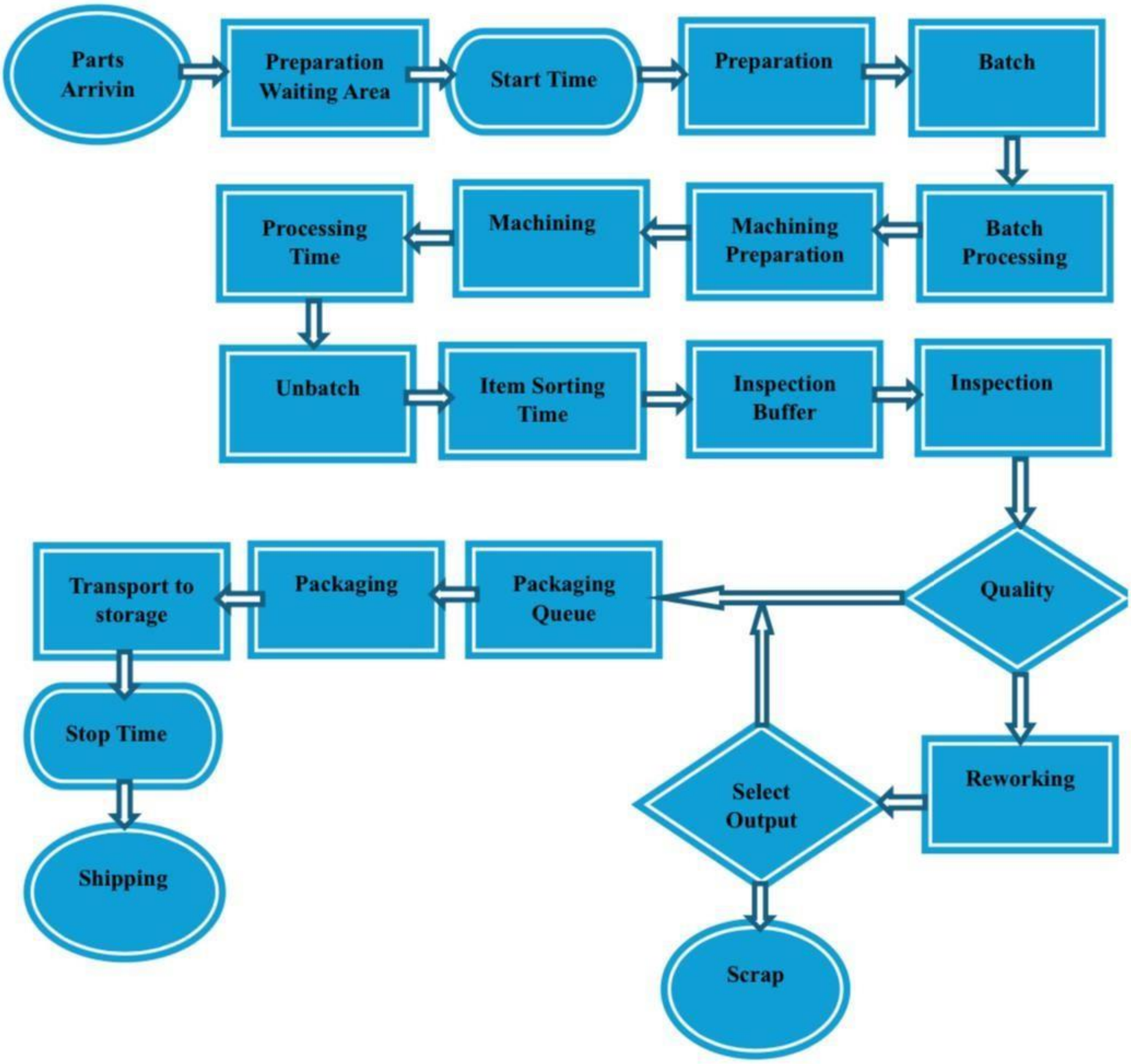

Figure 2 - Flow Chart of Model Stages.

2.3. Main Variables and Parameters

Key variables were tracked in the model for energy consumption, carbon emissions, defect rates, and throughput to track the sustainability of the manufacturing process.

Energy Use Per Unit (EnergyUsePerUnit): A measure of total energy consumed by producing one unit of brake disc. Units: kWh/unit.

Assumption: Each stage is separately tracking how much energy has been used to provide the summation into total energy use.

> ***totalEnergy***: This is the total energy consumption in kWh track for each process.
> Formula: *totalEnergy += energyUsePerUnit;*
> Purpose: It describes overall energy usage, both renewable and non-renewable energy.

renewableEnergy: Energy use from renewable sources in kWh.
Formula: *renewableEnergy = totalEnergy * renewableShare;*
Purpose: It measures energy from renewable sources, such as solar input, to evaluate sustainability.

nonRenewableEnergy: Energy use from non-renewable sources in kWh.
Formula: *nonRenewableEnergy = totalEnergy * (1 - renewableShare);*
Purpose: Represents energy consumption from fossil fuels, impacting carbon emissions.

carbonFootprint: Calculates CO_2 emissions based on non-renewable energy usage.
Formula: *carbonFootprint = nonRenewableEnergy * carbonPerKWh;*
Purpose: Tracks the carbon emissions generated from fossil fuel energy consumption.

totalCarbon:Cumulative This variable calculates the total carbon emissions over time on the energy mix renewable and non-renewable energy .
Formula: *totalCarbon += carbonFootprint;*
Purpose: Accumulates total carbon emissions for the entire manufacturing process.

Data Sets for Tracking

- *energyDataSet:* Tracks total energy consumption over time.
- *carbonDataSet:* Records cumulative carbon footprint over time.
- *renewableEnergyDataSet:* Stores energy from renewable sources over time.
- *nonRenewableEnergyDataSet:* Stores energy from non-renewable sources over time.

Defect Rate : Probability of a product being defective in each quality check.

- Units: Ratio (0-1)
- Assumption: 10% defect rate at the initial check, and 5% at the final quality check.

Production Throughput: This variable identifies how many units of brake disc are being produced and their qualities.Units: Units produced/day

Renewable Energy Usage: Renewable energy consumed, such as from solar. Units: kWh

Non-Renewable Energy Usage: Non-renewable energy consumed, sourced from sources such as fossil fuels.
Units: kWh

2.4 Assumptions

In this simulation model, the following assumptions are considered to simplify the analysis and focus on some key sustainability aspects in the automotive brake disc production process.

Energy Consumption:

- Renewable Energy: Initially, renewable energy sources, like solar power, provide 70% of the total energy consumption. The remaining amount (30%) is provided by non-renewable energy sources, mainly obtained from fossil fuel.

- Energy Consumption per Unit: For every part, there is a fixed amount of energy consumed in the different manufacturing stages, and for each stage, the amount of energy consumed is specified.

Emission Factors:

- Non-Renewable Energy: In this analysis, it has been assumed that the non-renewable or conventional source of energy-the source derived from fossil fuels-emits 0.25 kg CO_2/kWh.
- Renewable Energy: The emission factor for renewable energy-solar-is assumed to be 0.05 kg CO_2/kWh, reflecting the fact that it is much cleaner. Defect Rates:

Intermediate Quality Check: 15% of the parts are assumed to be defective after the intermediate quality check. Final Quality Check: 5% of the parts are assumed to be defective after the final quality check.

The defective parts are either reworked or scrapped. For the sake of this simulation, consider that 95% of the defective parts are being reworked and the rest 5% are scrapped.

Rework and Waste:

- Rework: The defective parts which are sent to rework consume extra energy.
- Scrap: 5% of the defective parts are scrapped, which creates waste that cannot be reprocessed. The environmental impact of scrapped parts is not directly quantified in terms of energy usage in this model, but it contributes to overall material waste.

Distribution Delays:

- Machining Delays: A triangular distribution to show dispersion and predictability in the machining time. It takes into consideration three points of entry-minimum time, mode, and maximum time-that guarantee realistic values for the delay according to the historic delay analysis.

- Delays in Inspection and Quality Check: Modeled using a normal distribution, assuming the delays are symmetric around the mean, reflecting consistent variability due to quality inspections.

- Rework Delays: Uniformly distributed, to show the equality of different rework times, hence modeling variability in defect complexity.

Cycle Time:

- The average cycle time for the production process should be 5 units/hr. This will keep up the flow of parts in the system and balance the delays with throughput. Production Flow:

- Arrival of Parts: The raw materials are assumed to arrive at regular intervals and are staged for preparation.

- Batching and Machining: Parts are batched together, machined, and then separated for inspection. This flow is important in assessing energy consumption and carbon emissions.

- Packaging, Transport To Storage and Shipping: After parts have passed the inspection stage-whether that be after rework or without defects-they are packaged, Transport To Storage and shipped. Energy consumption during packaging and shipping is considered but is minimal compared to the energy used in earlier stages.

Energy Mix Scenarios:

- The simulation will consider different scenarios: a baseline scenario with 70% renewable energy and a high-renewable-energy-share scenario . The impact of renewable energy integration on energy consumption and carbon footprint is one of the major focuses of the analysis.
  :

- *No Assembly Stage:* The assembly stage is not simulated in this model; this model only simulates parts arrival, preparation, batching, machining, inspection, rework, packaging, and shipping. There is no assembly, which simplifies the model but still allows for a typical production cycle in the automotive industry.

  These assumptions are necessary for the simplification of the model, but they also guarantee that the simulation concentrates on the most critical factors of sustainability in automotive brake disc production: energy consumption, carbon emissions, and waste generation. The assumptions allow for the analysis of scenarios in order to assess how different configurations of renewable energy and defect rates can affect the overall sustainability of the manufacturing process.

2.5 Data Collection Process and Sources

Primary Data from Industry: Real-life operational data from VULKAN Group was used to determine the base performance measures of defect rates, cycle times, and energy consumption in producing the brake disc. This data will provide the basis for calibration and validation of the simulation models.

Energy Consumption Metrics: Data from the DISA Group was integrated to simulate energy use in the manufacture of brake discs. For example, vertical moulding processes, with energy consumption of 232 kWh/hour, and horizontal moulding, at 625 kWh/hour, were considered as alternatives to study energy efficiency opportunities.

Reports from Volkswagen Group, 2023, and ACEA were used to benchmark the trends in energy consumption in the automotive industry.

Defect Rates and Quality Control: Defect rates were verified using Six Sigma benchmarks-such as Level 4 defect rates of 6,210 PPM-from ISM World.

Quality control data from EINES provided pragmatic information on the types of defects and their implications for manufacturing efficiency.

Sustainability and Renewable Energy: Data from the IEA and reports from the MAT Foundry Group on integrating renewable energy into manufacturing processes were used to model scenarios for enhanced sustainability.

Simulation Input Validation: Observations from production processes and stakeholder feedback complemented quantitative data to make sure that the representation in the simulation is comprehensive and as realistic as possible.

Sources of Data

- Primary Data: VULKAN Group
- Secondary Sources: DISA Group, Volkswagen Group, ACEA, MAT Foundry Group, IEA.
- Quality Control and Defect Rates: EINES, ISM World.

Data for the simulation was sourced from credible and relevant literature to ensure accuracy and reliability. Energy consumption data, measured at 41.8 MJ/kg, was obtained from Sato and Nakata (2020). Carbon emissions were modeled using emission factors derived from sustainability reports by Schillmoeller (2023). Defect rates, ranging from 10% to 15% for first-pass quality control, were referenced from Dhafr et al. (2006). Cycle times, spanning 18 to 35 hours per vehicle, were based on the findings of Els (2021). These data points were integrated into the simulation to model real-world production environments and validate the outcomes effectively.

2.6 Scenarios to Be Tested

In order to analyze the potential impacts of different operational and sustainability strategies in automotive brake disc manufacturing, a series of scenarios will be run. These scenarios are built around energy consumption optimization, carbon footprint reduction, and increasing production efficiency. In each scenario, key variables change regarding energy sources, defect rates, and production throughput.

Scenario 1 - Increased Participation of Renewable Energy:
This is a scenario that investigates the impact of increasing the renewable energy share in the production process from 70% to 90%. The possible reduction in carbon emissions and energy consumption that could be associated with increased renewable energy use are estimated.

Scenario 2 - Reduced Defect Rates through Process Optimization:
For such analysis, the following scenario reduces the defect rates by improving either the defect-detecting or quality control technology. The intermediate defect rates decrease from 10 percent to 5 percent; thus, final defect rates from 5 percent to 2 percent. This scenario investigates, within this context, their feasibility in reducing rework energy usage or emission totals.

Scenario 3 - Process Delay Reduction:
This case emulates the impact of reduced delays during machining and rework. This scenario will reduce the delays in the case of machining and rework, while calculating its impact on production throughput and energy consumption per unit.

Scenario 4 - Lean Manufacturing Practice Implementation:
Lean manufacturing practices are introduced in this scenario to reduce waste and improve production flow. The expected outcomes include a 15% reduction in energy consumption and a 10% increase in throughput, enhancing both energy efficiency and production capacity.

Scenario 5 - Increased Production Throughput:
This is the scenario that tests the effect of increasing production throughput per day. It is supposed to determine whether higher production capacity increases energy consumption and defects, or if it results in higher efficiency.

Scenario 6 - Energy Efficiency Improvements in Machinery:

Scenario Description: Upgrade machinery to more energy-efficient models, which consume 15% less energy. This case will analyze the opportunity for energy consumption per unit while keeping the same production rate and defect rate.

Baseline Scenario: This scenario sets the current operational conditions using default energy consumption rates, defect rates, and renewable energy participation. This scenario serves as a benchmark to compare the efficacy of other scenarios.

Key Performance Indicators Used in All Scenarios:

Energy consumption per unit reflects the total energy consumed by each scenario during production. The carbon footprint measures the CO_2 emissions associated with end-use energy consumption, differentiating between renewable and non-renewable sources. Production throughput evaluates the number of units manufactured daily across various scenarios. Defect rates and rework gauge the efficiency of quality control interventions aimed at reducing defects and minimizing rework energy. This study provides valuable insights into the potential benefits of adopting energy and process optimization strategies for sustainable automotive brake disc manufacturing.

3. RESULTS

The results from the simulation provide insights into various performance indicators related to energy usage, production efficiency, and environmental impact in the simulated manufacturing process. Below is a breakdown of the key findings, supported by graphs and tables.

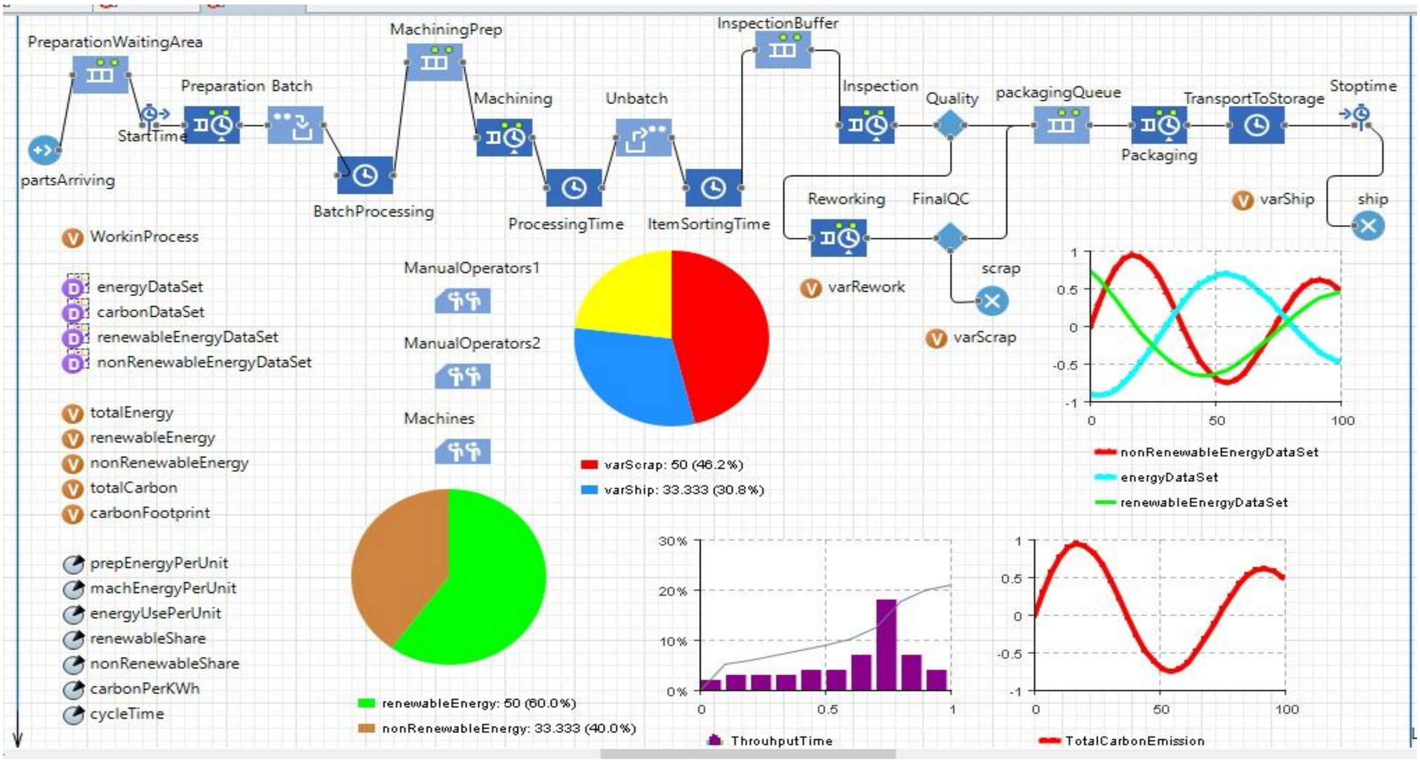

Figure 3 - The system before running the simulation

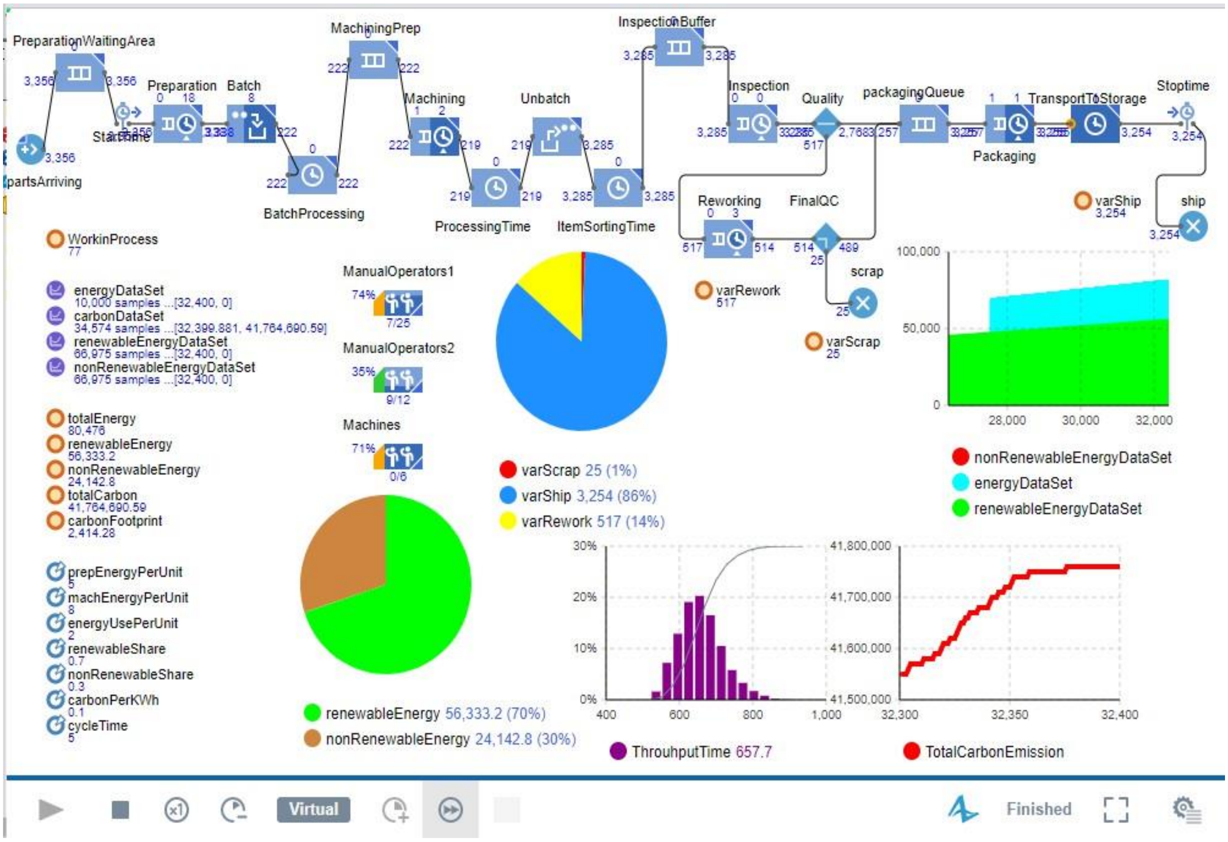

Figure 4 - The system after running the simulation

1. Energy Consumption Overview.
The simulation recorded a total energy consumption of 80,476 kWh, with renewable energy accounting for 70% (56,333.2 kWh) and non-renewable energy comprising the remaining 30% (24,142.8 kWh). The resulting carbon emissions from this energy usage were calculated to be 41,764.50 kg. These findings are visually represented in a pie chart, which highlights the proportional contributions of renewable and non-renewable energy sources to the overall energy mix.

2. Scrap and Rework Rates.
The production process yielded a significant success rate, with 85% of the units produced (3,254 units) successfully shipped. However, 14% of the units (517 units) required rework due to failing initial quality checks. Additionally, a minimal 1% of the items (25 units) were scrapped entirely, reflecting a small portion of total waste.

3. Throughput Time Distribution.
The histogram provided in the results shows the distribution of throughput times across all completed items. The average throughput time was measured at 657.7 seconds, with a noticeable clustering in the range of 400 to 800 seconds.

4. Process Efficiency and Utilization.
Manual Operator 1 was utilized 74% of the time, while Manual Operator 2 had a utilization rate of 35%. Additionally, machine utilization remained high at 71% throughout the simulation period. These metrics indicate the potential for reallocating resources or adjusting workflows to balance workloads.

5. Environmental Performance
The area chart depicting renewable and non-renewable energy datasets illustrates a consistent reliance on renewable energy, suggesting the process aligns with sustainability goals.

6. Cumulative Trends.
The red line chart tracks the gradual increase in carbon emissions throughout the simulation, correlating with production activity. The energy consumption per unit demonstrates efficient resource use, with renewable energy providing the bulk of power requirements.

Tables and Graphical Summary

METRIC	VALUE
Total Energy (kWh)	80,476
Renewable Energy (%)	56,333.2 (70%)
Non-Renewable Energy (%)	24,142.8 (30%)
Total Carbon Footprint (kg)	41,764.50
Throughput Time (sec)	657.7 (avg)
Successful Outputs	3,254 (85%)
Reworked Units	517 (14%)
Scrapped Units	25 (1%)

4. INTERPRETATION AND DISCUSSION

The simulation results provide a comprehensive understanding of the manufacturing system's energy consumption, production efficiency, and environmental sustainability. Several key insights emerge from this analysis:

Energy Consumption and Environmental Impact: The system demonstrates a commendable commitment to sustainability by deriving 70% of its total energy consumption, amounting to 56,333.2 kWh, from renewable energy sources. This reliance reflects a strong alignment with environmental objectives. However, despite the high usage of renewable energy, the carbon footprint remains substantial at 41,764,690 kg, primarily due to the 30% dependency on non-renewable energy sources. This underscores a critical area for improvement, emphasizing the need to further reduce reliance on non-renewable energy to enhance environmental performance.

Production Performance: The system achieved an impressive success rate, with 85% of units produced being successfully shipped, reflecting an overall efficient production process. However, a 14% rework rate, involving 517 units, highlights an area for improvement in initial quality control to minimize inefficiencies and reduce costs associated with rework. On a positive note, the system achieved a minimal scrap rate of just 1% (25 units), demonstrating excellent resource efficiency and a strong commitment to minimizing material waste.

Throughput Time Analysis: The average throughput time of 657.7 seconds, with a clustering between 400 to 800 seconds, indicates a reasonably efficient process. However, reducing the upper range of throughput times could enhance overall productivity and consistency.

Resource Utilization: Manual Operator 1's high utilization rate of 74% suggests potential overuse, which could lead to fatigue or inefficiency over time. Conversely, Manual Operator 2's lower utilization rate of 35% indicates underutilization, presenting an opportunity for workload rebalancing. The machine utilization rate of 71% demonstrates consistent performance but leaves room for optimization to further maximize capacity.

Sustainability Performance: The steady reliance on renewable energy, as depicted in the energy datasets, reflects a positive trajectory towards sustainability goals. However, achieving a higher percentage of renewable energy usage will further reduce the carbon footprint.

Cumulative Trends: The gradual rise in carbon emissions aligns with production activity. This trend underscores the need for integrating more renewable energy sources or adopting energy-efficient technologies to mitigate environmental impact.

5. Recommendations

RECOMMENDATION	A BRIEF EXPLANATION
Improving Quality Control	Implementing advanced quality inspection systems, such as AI-powered defect detection, can significantly reduce the 14% rework rate and associated costs. By enabling early and accurate detection of defects during the production process, these systems can enhance first-pass yield rates, minimize inefficiencies, and improve overall operational efficiency. This proactive approach ensures higher quality standards while optimizing resource utilization.
Optimizing Resource Allocation	Redistributing tasks between Manual Operators 1 and 2 balances workloads, ensures effective utilization, and avoids overuse of any single resource. Investigating opportunities to increase machine utilization without compromising reliability, such as scheduling predictive maintenance during off-peak periods, enhances efficiency.
Reducing Throughput Time Variability	Analyzing process bottlenecks causing longer throughput times and implementing targeted improvements, such as automating repetitive tasks or refining workflow designs, can enhance efficiency. Monitoring throughput time trends ensures continued optimization.
Enhancing Sustainable Initiatives	Investing in technologies to increase renewable energy usage beyond the current 70%, such as solar panel installations or wind energy integration, is recommended. Additionally, phasing out non-renewable energy sources to achieve 100% reliance on renewables would further align with sustainability goals. Exploring energy storage solutions can help reduce reliance on non-renewable energy during high-demand periods.
Monitoring and Minimizing Emissions	Conducting regular audits of carbon emissions to identify high-impact areas and implement emission-reduction strategies, such as transitioning to low-carbon manufacturing processes or materials.
Training and Continuous Improvement	Providing targeted training for manual operators improves efficiency and ensures adaptability to new process enhancements. Fostering a culture of continuous improvement by involving staff in identifying areas for optimization further enhances overall performance.

6. CONCLUSION

The simulation provides a comprehensive analysis of the manufacturing system's performance, focusing on energy consumption, production efficiency, and environmental impact. Key findings indicate a strong reliance on renewable energy, with 70% of total energy usage coming from renewable sources, significantly contributing to sustainability goals. However, the system still faces challenges, such as a substantial carbon footprint of 41,764,690 kg, primarily due to the 30% reliance on non-renewable energy. Production efficiency is commendable, with 85% of units successfully shipped, but a 14% rework rate and a minimal scrap rate of 1% suggest areas for improvement in quality control and resource utilization.

Throughput time analysis shows an average of 657.7 seconds per unit, with a clustering between 400 to 800 seconds. While this reflects reasonable efficiency, reducing the variability in throughput times could further enhance productivity. The utilization of Manual Operator 1 is high at 74%, indicating potential overuse, while Manual Operator 2 is underutilized at 35%. This disparity presents an opportunity for workload rebalancing. Machine utilization remains strong at 71%, though there is room for further optimization.

From a sustainability perspective, the system's steady use of renewable energy aligns with environmental goals, but increasing the share of renewable sources would further reduce the carbon footprint. The gradual rise in carbon emissions throughout the simulation highlights the need for additional renewable energy integration or the adoption of energy-efficient technologies.

In conclusion, the simulation reveals a manufacturing system that performs well in terms of energy efficiency, waste reduction, and production output. However, improvements in quality control, throughput time management, and resource allocation are needed to optimize overall efficiency. Enhancing sustainability through increased renewable energy use and reducing reliance on non-renewable sources would align the system more closely with long-term environmental and business objectives. By implementing the recommended strategies, the system can achieve greater operational efficiency, reduce costs, and further its commitment to sustainability, ensuring competitiveness in an eco-conscious market.

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8. APPENDICES

Appendix A - Energy Source Distribution.

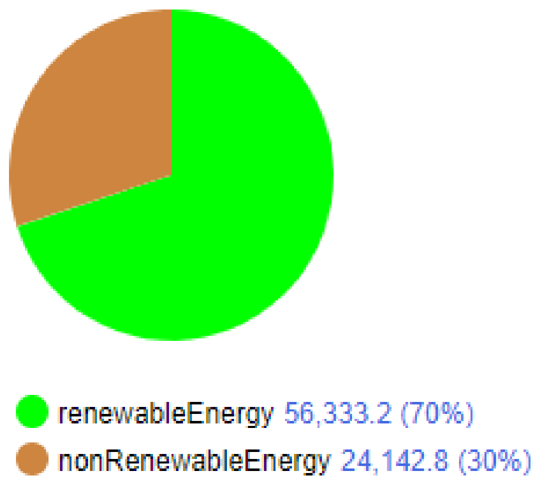

Figure 5 - Energy Source Distribution.

Appendix B – Throughput Time Distribution.

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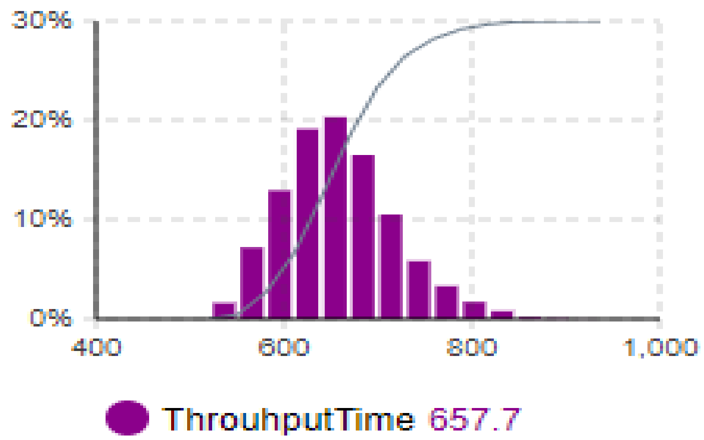

Figure 6 - Throughput Time Distribution.

Appendix C – Cumulative Carbon Emissions.

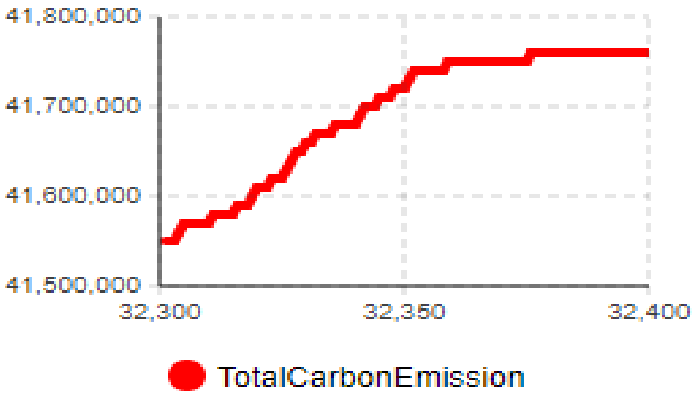

Figure 7 - Cumulative Carbon Emissions.

Appendix D – Scrap, Rework and Ship Ratio.

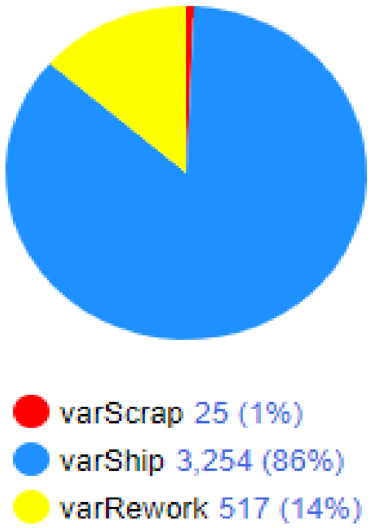

Figure 8 - Scrap, Rework and Ship Ratio.

Appendix E – Energy Consumption Breakdown Over Time.

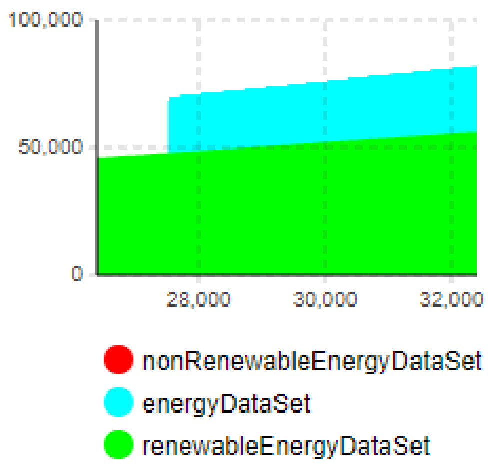

Figure 9 - Energy Consumption Breakdown Over Time.