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A Simulation-Based Methodology for the Analysis of Lean Principles on Manufacturing Efficiency: An Application in Aluminum Extrusion Die Production

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This paper addresses the challenges and innovations in die manufacturing with regards to integrating Industrial Systems Engineering principles for optimization of processes to enhance efficiency. By combining lean manufacturing principles, Value Stream Mapping (VSM), and simulation methodologies, this research identifies and reduces inefficiencies while improving resource allocation in aluminum extrusion die production. Data collection through performance measurements and process layout analysis identifies bottlenecks and non-value-added activities, especially in flat and backer part in die production. The current layout is evaluated and improved upon by a simulation model using ARENA software in resource utilization, workflow efficiency, and waste reduction. The study further explores how Industrial Systems Engineering concepts, such as process analysis, can be applied to die design and production workflow optimization. Findings have established that lean methodologies, working in conjunction with simulation and Industrial Systems Engineering, can provide a cheaper, more effective, and sustainable die manufacturing solution.
Keywords: Die manufacturing, Industrial Systems Engineering, Lean manufacturing, Value Stream Mapping (VSM), Simulation modeling, Resource optimization, Process efficiency.

1. Introduction

Industries today seek to enhance their competitive capabilities by integrating modern methodologies into production processes to simplify these processes and increase overall productivity (Davis et al. 2012), allowing them to stay ahead of competition, present products more effectively, and achieve a stronger position in the market, which also allows them to reduce waste, and create a more sustainable and cost-effective manufacturing environment (Gupta, 1995).

Lean manufacturing is a socio-technical system where future performance is benefited by optimized use of technologies as well as people making it a noble culture of enhancing production improvement. Starting with Toyota between the 1950s, lean manufacturing only rose to fame among industrial organizations turning out to be a crucial conceptual idea (Naciri et al., 2022). In its simplest terms, lean manufacturing is characterized by a specific aim at maximizing the elimination of waste in production processes with the intent of delivering customer goods at the right time and in exact customer specifications. This approach values the use of resources to achieve the organizational goals and to satisfy the needs of the customers.

Lean manufacturing transition requires a total organizational culture change (Inuwa and Rahim, 2020). A successful implementation strategy needs the involvement to personnel through creating an awareness of the changes to be made and establishing understanding of the anticipated changes by the management (Farrukh et al. 2022). While it is the case that earlier stages of this change process involve more attention to change management itself than actual implementation of lean tools and practices. Lean manufacturing is, therefore, much more than a set of tools; than an approach to supply chain management; as it is a socio-technical system that incorporates the various social and technical aspects in the organization of the production process for the achievement of greater efficiency and flexibility in modern manufacturing enterprise.

In any manufacturing firm, the primary role is to convert materials and components into final products. To make this transformation possible, the processes result from two different activities: activities that add value and activities that do not add value. Such operations are the activities and parts of this process that make these transformations and provide value added to the product from the customer rather than the manufacturer’s point of view (for example, tubing, stamping, welding, painting, etc.). The activities which do not create value from the customer’s perspective are called non-value-added activities; these include setting up, waiting for materials, and moving materials. It is noted that in the past, organizations mainly concentrated on value-added activities. The aim was to decrease the lead time for value-added activities and at the same time ignore non-value-adding activities. Lean manufacturing is primarily about waste elimination; its central objective is minimizing non-value-added work.

The main goal of lean manufacturing is the complete elimination of waste. Waste or (“muda” in Japanese) is anything that adds cost to the product without adding value. Wastes can be classified into eight categories: overproduction, waiting, transportation, processing, inventory, motion, defects, and underutilization of employees. Once the companies find the main sources of wastes, tools such as just-in-time, kanban system, quality at the source, flexible workforce, total preventive maintenance, autonomation, Kaizen, and others will help companies to take corrective actions to eliminate or reduce these wastes (Monden, 2011).

Value stream mapping (VSM) is a widely used quality tool that aims to eliminate waste. Waste in many processes can be as high as 60 percent (Krajewski and Malhotra, 2022). VSM is useful because it creates a visual "map" of each process involved in the flow of materials and information in a products value chain. These maps consist of a current state map, a future state map, and an implementation plan. A VSM spans the supply chain from a company's receipt of raw materials or components to the delivery of the finished product to the customer. As such, it tends to be broader in scope, showing much more information than a typical process map or flow chart used with Six Sigma process improvement efforts. Creating such a big-picture representation helps managers identify the value-added and non-value-adding activities.

In addition to lean manufacturing and VSM, computer simulation plays an important role in eliminate the waste (Zahraee, Rohani and Wong, 2018). Computer simulation is widely used today in various fields, including manufacturing, and logistics (Mourtzis et al., 2015). Simulation is the process of designing a model of a real system and conducting an experiment.

Combining computer simulation with VSM has many advantages, and they include but are not limited to the following, the process becomes more visible; processes are dynamic; improved decision making occurs in real-time (Mishra et al., (2020). Therefore, when the process flow is mapped out, and displayed in this manner, simulation allows the changes to be observed in real time, enabling users to make better decisions. The elements of flexibility in relation to testing suggest that selection of non-added value steps and bottlenecks can be identified more easily with the help of several tested scenarios. Also, by the simulation, variables can be measured in order to analyze the effect of changes on the VSM to facilitate decision making. Finally, it looks at how changes influence the utilization of resources hence improving on resource allocation.

Although there is wide research into simulation software and lean manufacturing in different industries across the world, there is a limited investigation of their joint application in the manufacturing industry. Consequently, further research is paramount to understand how the joining of these methodologies can better production processes and efficiency. Therefore, this paper attempts to explore the application of computer simulation and VSM in simulating, assessing, and enhancing the performance of a selected manufacturing company as a case study.

2. Methodology

This study was carried out at a factory that manufactures aluminum extrusion dies, which is part of a larger company specializing in aluminum products manufacturing. The factory mainly deals with the design and fabrication of dies used in aluminum extrusions. Dies are employed in the manufacturing to shape material, especially metals and plastics. In the aluminum extrusion, the die is the forming tool that create the desired cross-sectional shape of the extruded object. The operation environment is more or less a manufacturing line complemented by storage and office units with an emphasis on customer satisfaction and long-term development.

The extent to which die affect properties other than shaping the aluminum that dies control many properties of the final product in aluminum extrusion such as the mechanical properties and surface roughness. Hence, the precision in the die design directly impacts the success of the extrusion process, the quality of the resultant extruded product, and ultimately customer satisfaction. Specific to the manufacturing of the dies, it was expected that lead time reduction, waste minimization, and quality improvement in the manufacturing processes would be required.

The production of an aluminum extrusion die begins with designing the die in order to achieve the required profile. High-quality steel is then machined using CNC tools, followed by heat treatment for durability, polishing, and quality inspection before installation in the extrusion press to form the heated aluminum billet into the required profiles.

Figure 1 presents the research methodology used in this study as a roadmap, showing each phase of the research and highlighting the interconnections between them. The first stage involves data collection where general observations and measurements were conducted within the production facility. This includes the collection of main key performance indicators (KPIs), product and process layout, part arrival times, idle time, processing times, workforce allocation, and resource utilization through several site visits. These observations were essential for understanding the relationships among activities and workflows, detecting waste resources, developing plans, and proposing improvements.

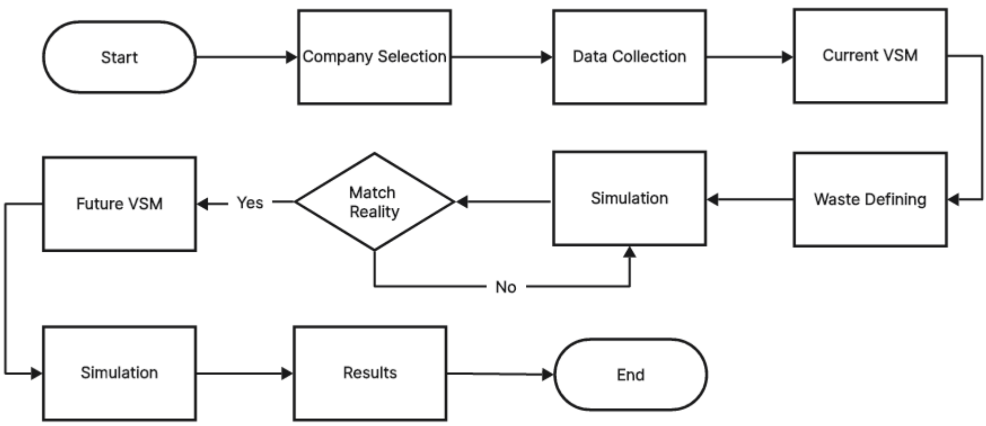
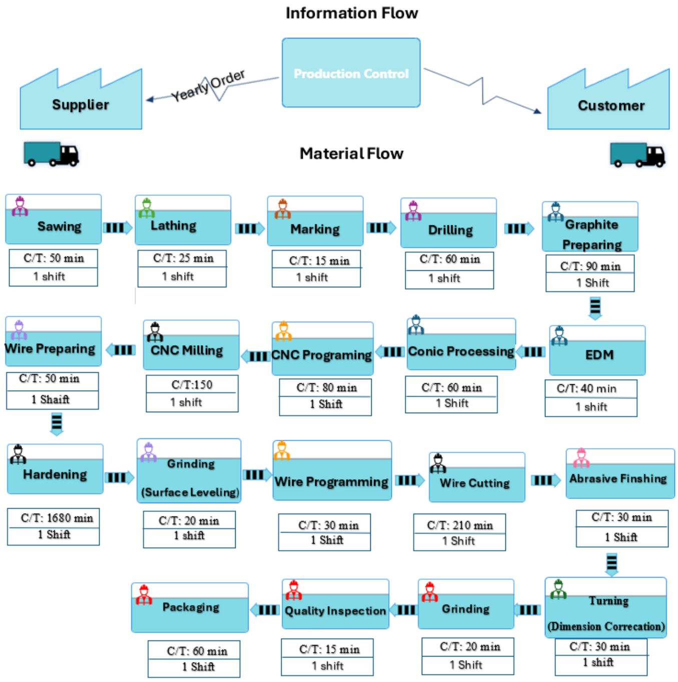


Figure 1 Schematic presentation of the Research Methodology.

Information for drawing the material and information flows were gathered from the shop floor by several site visits. This includes the data related to each process, such as cycle time (C/T), number of people required to operate the process, and the number of shifts. The collected data were analyzed using VSM to identify the waste in the production process. The current production process consists of 19 workstations for flat part and 12 for backer part responsible



for the various activities.

Figure **2** and 3 illustrate the current process maps for the flat part and backer part, respectively, for the flat die production system.

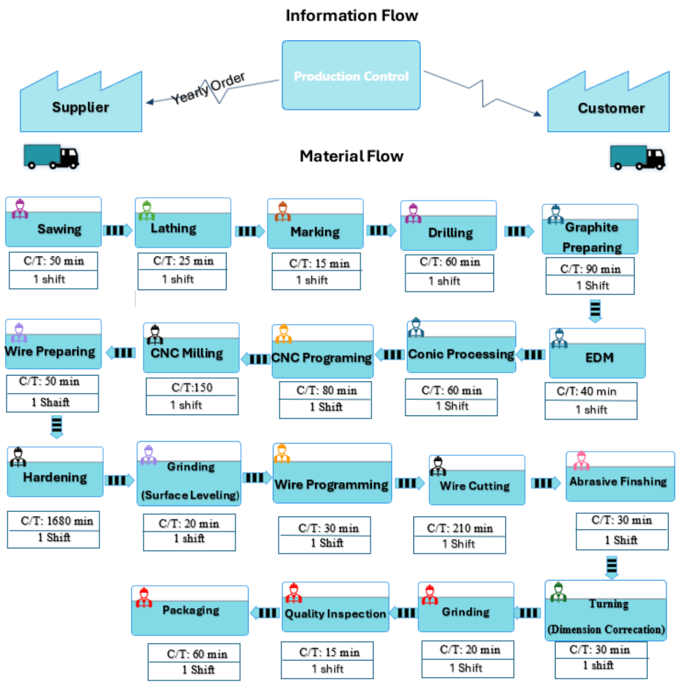


Figure 2 Value Stream Mapping (VSM) of the current production processes for producing the flat part in the flat die.

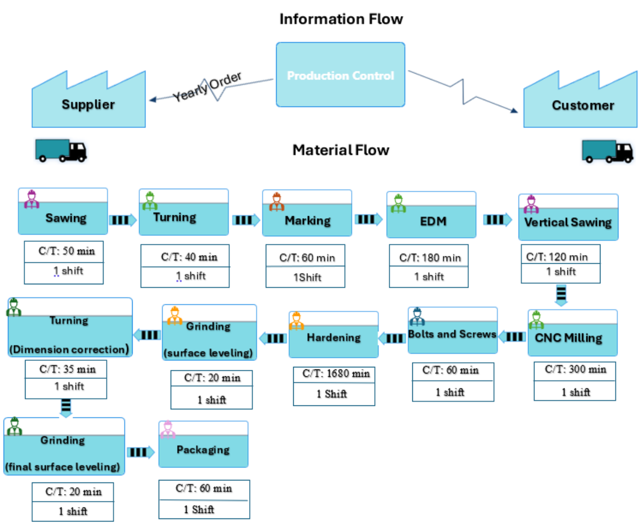


Figure 3 Value Stream Mapping (VSM) of the current production processes for producing the backer part in the flat die.

Following data analysis, the simulation modeling was conducted using ARENA software. A continuous-event simulation was performed for the production flow analysis. The technique of computational modeling simulates the behavior of complex systems that consist of independent entities interacting with each other. The simulation contained twenty-one important data modules, including entity data for part arrivals and resource data for tracking availability across workstations. A simulation of the current production layout was conducted first, followed by a simulation of the future layout aimed at improving resource utilization, enhancing workflow, reducing waste in motion, and improving process efficiency. Verification was performed to ensure the accuracy and reliability of the simulation by comparing the measured results with ARENA model outcomes. This included extensive debugging, output consistency checks, and the use of animations to visualize the operation of the system.

These steps are designed to improve processes. Proposed plans, which have been developed by adopting data analysis and simulation modeling, will be implemented to create an effective manufacturing setting. In the results section, the outcome of the VSM analysis and the simulation of productivity gains and wastes reduction with emphasizing the manufacturing strategies, utilization, and resources will be presented.

3. Results

This section outlines and analyzes the results of the investigation, covering in detail a comprehensive analysis of the aluminum extrusion dies fabrication process along with suggested improvements by using simulation and VSM. The analysis shows inadequacies in the existing system and gives examples of the effectiveness of the proposed changes in overcoming bottlenecks, increasing throughput, and smoothing out the use of resources.

A careful comparison between the current and the proposed improved processes to show how KPIs and resource allocation can be improved. The study highlights the deep impact of the recommended changes, displaying a systematic approach to identification and elimination of the main limitations in the present process. The results show how targeted interventions can substantially improve the organization's overall performance.

3.1 Analysis of the Current Process: Flat Part Manufacturing

The first analysis focuses on the aluminum extrusion die manufacturing for flat parts. The VSM depicted in Figure 2 gives a clear flow of the process from setup, machining, and inspection to the last stage in the production. The analysis found several areas where non-value-added activities were detracting from overall efficiency. Significant portions of the cycle time, approximately 40%, were consumed by transportation and waiting times. Such delays are caused by long time intervals of transition from one stage to another and inactivity intervals between them, which considerably affect the setting time of production and the system maximum productive performance.

Bottlenecks in the process mainly occur at the hardening stages. Lack of temporal synchronization among operations leads to significant inefficiencies. The overall process effectiveness was thus estimated at 60%, indicating that the process only had value-added activities for 60% of the total production time while the rest, a 40%, accounted for non-productive time. These observations proved vital in developing the suggested interventions based on reorganizing work sequences, minimizing unnecessary moving distances, and overcoming disturbances that hinder smooth operations of the production line.

The analysis underlines the need for optimization of the process in the workflow of flat part manufacturing. More concretely, the improvements should concern delays elimination, task synchronization enhancement, and creation of smooth transitions between operations. Handling such inefficiencies makes it possible to bring an increase in overall throughput and a decrease in downtime, hence going for a more efficient production system.

3.2 Analysis of the Current Process: Backer Part Manufacturing

Similarly, detailed investigation was made for backer part manufacturing process shown in Figure 3. This analysis showed several areas lead to inefficiencies in the systems especially on the aspects of idle times. The major sources of constraint were found in the material handling and transfer processes especially between assembly and inspection cycles. These gaps are the relationships and the critical stages in the reducing layout and refining the role of the job expressed as the sequences of the tasks required to complete the task.

Implementing a new layout of the work environment in addition to the optimization of tasks flow were suggested as critical interventions. The elements such as product layouts redesign and workstation redesign were identified to be crucial levers towards optimizing material flow and minimizing unnecessary motions. If transport distances can be kept to a minimum and where possible the arrangement of workstations located, then the process can be made more efficient in terms of both resource use and business practices.

The results of the backer part analysis have emphasized the necessity of maximizing layouts and the task flow to reduce time wastage, as well as enhance material flows. The changes thus proposed should afford better coordination of the several tasks and processes involved so that transitions between operations are smooth, thereby improving throughput and overall cycle time in a major way.

3.3 Simulation Model Validation

To validate the simulation model used in the study, real-world factory data was applied for calibration purposes, and the results from the simulation were compared with the actual metrics observed on the production floor. The simulation was conducted for flat and backer parts in single layout with different sequences that illustrated in Figures 2 and 3 for both of them. Figure 4 presents a model for current process for the flat part that would validate through comparison results between real data and model.

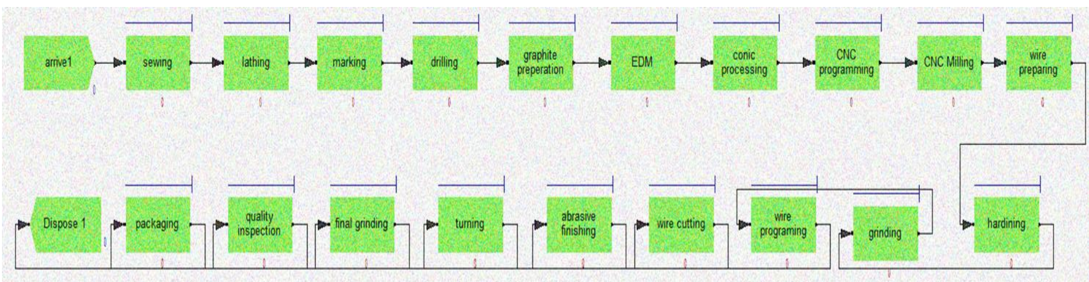


Figure 4: model using ARENA of the current production processes for producing the flat part in the flat die.

Thus, the comparison of the simulation model with real factory data proved that the model is an accurate representation of the current production system. This forms a vital step in the validation process since any variables proposed for changes by the model will produce consistent results when solved, provides a better decision making ground before the changes are to be implemented on the shop floor. The realistic and accurate one for making predictions makes the simulation a useful mechanism for evaluating the various purported modifications to the process as well as estimating the favorable outcome of the change.

3.4 Proposed Process: Future State Value Stream Map

The future state of the manufacturing system described in the Figure 5 highlights extensive improvements designed to minimize nonproductive activities. One of the critical changes proposed is the combination of processes for producing flat and backer parts into a common process layout. This integration drives the efficiency, eliminates many forms of waste, and conforms to lean manufacturing systems.

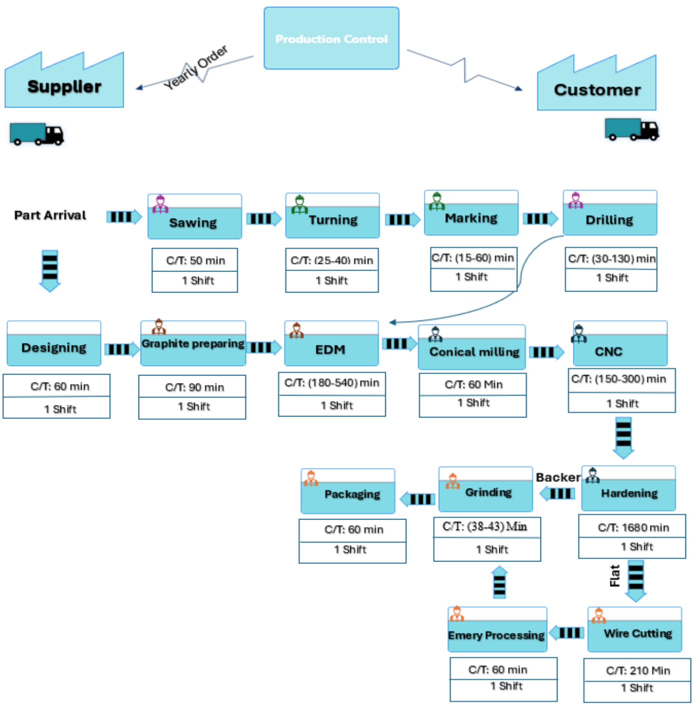


Figure 5: Future State Value Stream Map for the Proposed Process

Some of the significant improvement is the merging of the CNC coding function, wire cutting, and die design to form a single stage thus doing away with the issue of several handoffs and transitions. Also, the preparation of graphite columns, while requiring the participation of several operators in the past due to many stoppages in-between, has been molded into a continuous process totally managed by a single operator, as therefore improving continuity in work flow.

Processes that have previously been carried out in discrete steps on the same piece of equipment as the screw block preparation process have been combine into a single stage for procedural efficiency. Besides, the former three processes of final lathing, grinding and quality inspection have been integrated into one process called “final lathing and inspection”. This change disassembles the previous state in which operators were constrained by the conventional linear process order and hence, lead times will be shortened.

One of the largest positive changes of the workforce has been made by applying the one-worker, multiple-machines (OWMM) cell rule. Since most procedures necessarily involve positioning workpieces into machines, staff has been relocated according to skill and proficiency. These changes are carried out bearing in mind that the organization’s reallocation process promotes the use of people resources and stable productivity in every phase of operations.

It is expected that the proposed process improvements would increase the weighted average total process efficiency to 90% focusing on the increase of value-add activities of production. Most of the objectives that lead to reduction in the elapsed time include the redesigning of the organizational processes, dispensing with non-added activities and the lack of accumulation in between stages to work in a flow that is largely uninterrupted. Such improvements are expected to result in higher process flow, shorter time for a cycle, and optimal use of resources.

Through integration and reorganization of core processes, the proposed system will enhance an efficient and effective manufacturing system. These refinements contribute to superior task integration, diminished operational inefficiency, and increased effectiveness and efficiency and fulfilling the goal of process enhancement and resource management.

3.5 Processing Time Breakdown Analysis

Figure 6 shows the proposed process model including an arrival decision module as Decide 1 to split between design and cutting operations. In this same stage of development die design has to be done, CNC programming and wire cutting code preparation must begin at the same time as well as the preparation of the graphite for the die itself.

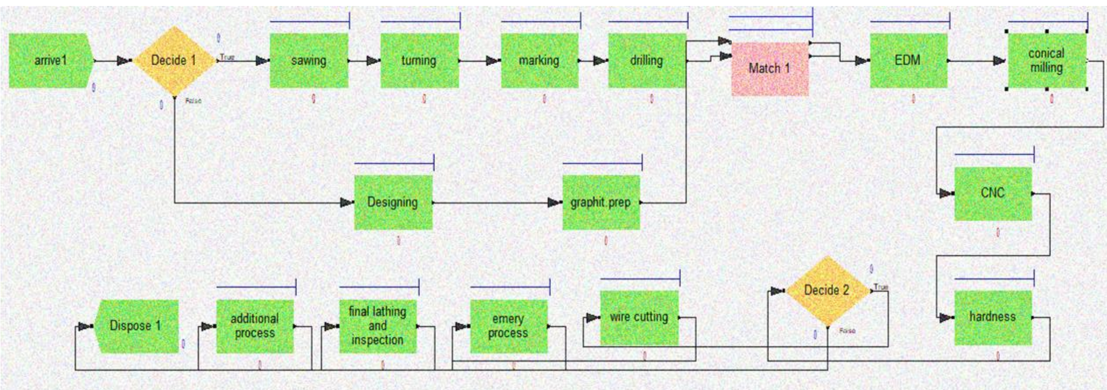


Figure 6: model for proposed process

Subsequently, the cutting process continues through the sequence and the match module confirms the EDM process only when drilling and graphite preparation are done. This alignment provides consistency and eliminates gaps between the successive phases of a process.

The process advances systematically until reaching a second decision module (Decide 2), which separates between the manufacturing workflows for backer and flat parts. The flat parts are routed to the wire cutting process, whereas the backer parts bypass this stage and proceed directly to the emery process. Subsequently, both part types rejoin the main process flow to complete the remaining operations as depicted in the figure.

A significant observation from the time breakdown analysis is the prolonged waiting time between the machining and inspection stages. This delay highlights a critical opportunity to enhance synchronization between these stages. Addressing this inefficiency could significantly reduce idle time, improving overall resource utilization and accelerating throughput.

These findings underscore the importance of optimizing machining and inspection stages to eliminate bottlenecks. The proposed model demonstrates potential for substantial improvements in process flow, providing a basis for targeted interventions to achieve a more streamlined and efficient manufacturing system.

3.6 Comparative Analysis: Current vs. Proposed Processes

Table 1 shows an increase in KPIs when there is a move from the current process to the future process. The manufacturing process efficiency increases by 30 and the numerical result is also 0.90 as shown below. This is an improvement of 50 percent, and shows that there was certainly some lack of synchronization in earlier production processes which have now been cut out.

Table 1 Comparison between the current and proposed processes

KPI	Current Process	Proposed Process
Efficiency	0.60	0.90
Utilization Rate	0.60	0.95
Output per Cycle	1 part	2.7 parts

Respectively, the measures similar in growing that utilization rate elevates from 0.60 to 0.95. This improvement however reveals efficiency in the distribution and utilization of resources, whereby near optimum production capacity has been achieved with minimal downtime. The output per cycle presents an impressive evolution from 1 part to 2,7 parts. This nearly threefold increase suggests that an even more efficient process layout that permits more output rates per running cycle will occur.

The changes recorded on these factors offer a good basis on the outcome of the change strategies proposed herein. The enhanced process also produces worthwhile improvements in production flow, outputs, and productivity overall as resource utilization becomes more efficient. These results indicate that process redesign is indeed essential for higher levels of operational performance, and highlight the possible advantages of installing the proposed future process in manufacturing environments.

3.7 Impact of Proposed Changes on Production Rate

As for the proposed improvements of the future process the increase in the production rate is shown in the figure 7 below. These improvements are due to shorter transition time and a better assignment of the tasks throughout the process stages. This organization of the production process helps to reduce time durations where production processes were blocked, waiting for upstream operations to complete, and thus ensuring productivity gains across the whole production line.

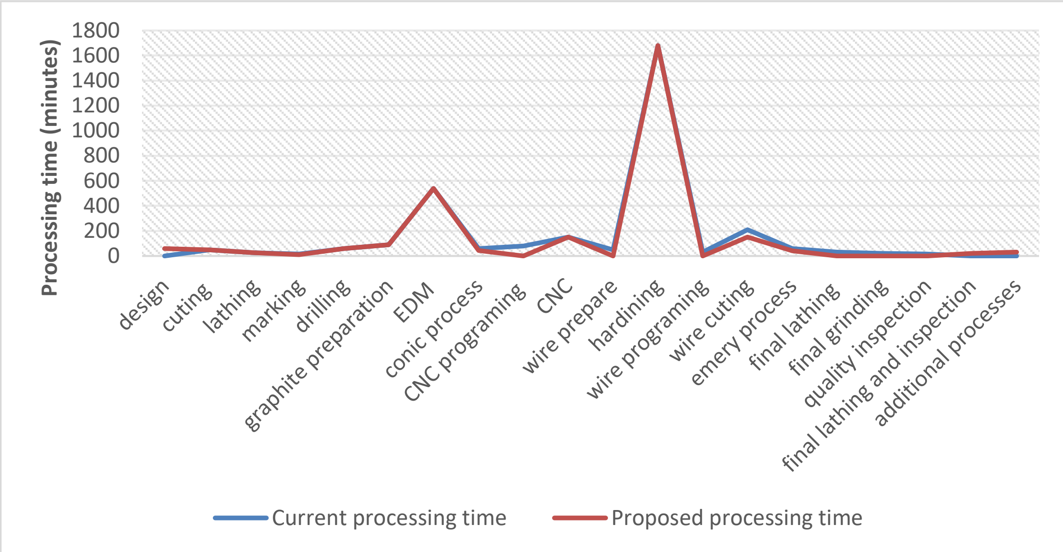


Figure 7: Processing Time Breakdown by Stage

The outcomes of the simulation can be considered as effective evidences confirming the efficiency of the proposed changes. They agree that changes to task orders and flow will increase production rate hence improving the efficiency of the system.

3.8 Utilization Rates: Current vs. Proposed Processes

The comparison of the rates of utilization between the current and proposed processes is depicted in the figure 8 below. In the current process, the use estimation ratio is only 0.6 meaning that labor and machinery are underutilized because the workflow does not run efficiently. On the other hand, the proposed process provides a much higher practical use ratio of 0.95 thereby maintaining proportionality between resource availability and production requirements. Some processes that have zero utilization rate since they were suggested for elimination from the proposed future process.

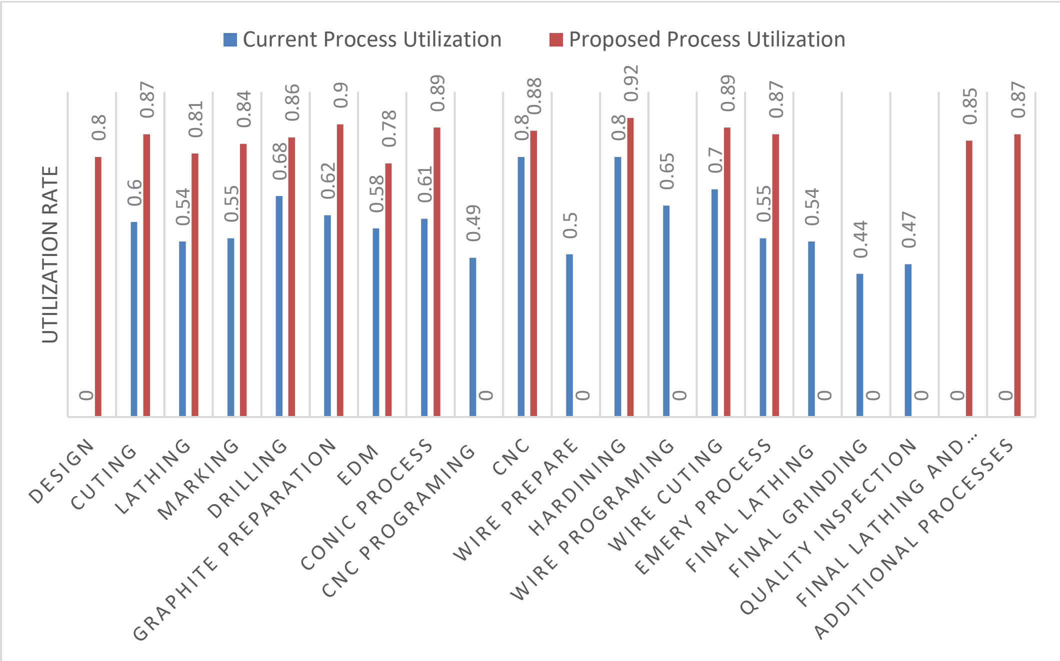


Figure 8: Utilization Rates Comparison

The proposed changes ensure that resources are employed much more efficiently; hereby enhances the general performance of the system and reducing downtime. The increase in utilization rates shows that with the proposed process, workers and machines are utilized in value-added activities for a greater proportion of the work cycle.

4. Conclusion

This paper is able to establish how VSM and computer simulation can be implemented to improve the manufacturing processes. Applying VSM in aluminum extrusion die manufacturing line, problems such as transportation time, waiting time and idle time were realized. Enhanced by simulation modeling employing ARENA software, these results confirmed some of recommendations and showcased their potential impacts on production performance through experimentation. The future state map for the proposed change and the subsequent further enhancements present many possibilities for increasing utilization of the resources, achieving faster cycle times, and eliminating non-value-added activities. The findings of this study therefore point to the efficiency of using a combination of lean and simulation techniques in order to design improved and more sustainable manufacturing systems. Subsequent studies should explore the applicability of these methodologies across various industries both to gain a better understanding of the universal applicability of such methods and to identify the best practices for their application for constant enhancement.

Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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