AUTOMATION OF INDUSTRIAL PRODUCTION PROCESSES FOR MATERIAL AND ENERGY EFFICIENCY IN SUSTAINABLE DEVELOPMENT

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Abstract

During industrial production processes, the primary elements with the greatest impact are raw materials and energy. Throughout these processes, starting from the procurement of raw materials to the completion of production with the final products, waste is generated, representing both material and energy losses. This occurs mainly as a result of inefficient processes; therefore, there is a growing tendency for these anthropogenic processes to approach natural processes, which are considered more optimized. The reduction of material and energy losses in production processes enables the rational and efficient use of raw materials, contributes to the preservation of environmental resources over a longer period, supports environmental protection from pollution, and leads to improved economic outcomes, thereby moving closer to the objective of sustainable development. This can be most effectively achieved through the application of automation in production processes.

This paper examines the role of automation in production processes as a key factor in achieving sustainable development in modern industry. The increasing global demand for efficient resource utilization has intensified the need to reduce material waste and energy consumption while maintaining productivity and product quality. In this context, automation technologies such as sensor-based monitoring systems, programmable logic controllers (PLC), and real-time process control are essential for improving industrial sustainability.

The study presents a theoretical analysis of selected industrial cases where automation has contributed to achieving sustainability objectives, including reductions in material waste, energy consumption, and defect rates. Although automated systems require electrical energy for operation, they improve overall sustainability by reducing the need for reprocessing, minimizing machine idle time, and eliminating inefficient process conditions, thereby reducing the material and energy requirements per unit of production.

The results indicate that automation is a decisive factor in sustainable industrial development, particularly when integrated with intelligent monitoring and control systems.

Keywords: Sustainable development, industrial production processes, automation, material and energy efficiency

Introduction

Contemporary human activity is defined as dynamic, intensive and voluminous, being very efficient at exhausting and using up the means designed to maintain and uphold itself. Since the Industrial Revolution, this phenomenon has been exponentially more present, and considering the rate at which human numbers are increasing, and by extension, human industry is developing, this actuality is expected to intensify. In an attempt to satisfy consumer demands, ranging from basic necessities to recreational needs, all human industry, but specifically the manufacturing industry, has amplified its rate of production, striving to meet industry demands, oftentimes neglecting the environmentally detrimental byproducts and waste, generated with any production process which, if left unaddressed, inhibit society's ability to achieve a more sustainable approach towards consumer demands and economic, technological growth.

Manufacturing processes generally can be defined as transformation systems in which material and energy inputs are converted into useful products through controlled mechanical and thermal operations. However, these processes unavoidably generate material losses, as well as energy losses in the form of heat and other inefficiencies. (Kalpakjian & Schmid, 1989). Figure 1 presents a diagram of the elements of these transformative systems.

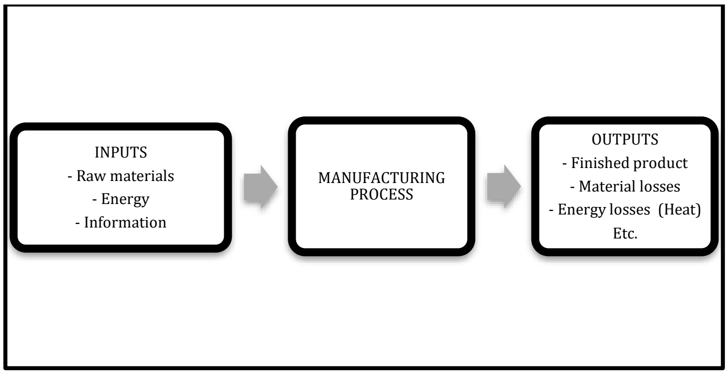

Figure 1. Diagram of manufacturing processes' elements

Addressing these losses in output methodically is imperative for achieving a sustainable approach to manufacturing, which serves not only an ecological purpose, but also achieves a more efficient, higher quality and inexpensive product.

1.1 Concept of "Sustainable Development" : One of the longest standing scientific and engineering approaches to any problem has been to draw inspiration from the natural systems and biological processes, this approach is called "Biomimicry". In many natural biological processes, a byproduct of a process which could be considered "waste", often serves a different purpose once it appears in the physical world, often times being reutilized to facilitate another biological process, this time as an input to the following process. This principle, which is observed in ecosystem cycles, reflects a high level of resource management efficiency and minimal accumulation of waste, and in turn provides a conceptual foundation for sustainable approaches in industrial systems, one of them being sustainable development in production industries.
Sustainable development is generally defined as development that meets the needs of modern generations, without compromising the ability of future generations to meet theirs. (World Commission on Environment and Development, 1987). In a manufacturing context, it is the attempt to minimize, any and all factors which impact a production processes material and energy efficiency, starting from the initial resources needed to initiate production, all the way until the finishing processes before the product hits the market. This approach to manufacturing, is done to ensure energy and material efficiency, resource preservation, lower manufacturing costs, punctual production, all while preserving product quality and consumer satisfaction.

1.2 Automation as a means of achieving sustainable development: As discussed above, biomimicry is an approach that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies. (Biomimicry Institute, 2006). Many biological systems in nature execute processes very efficiently, achieving desired outcomes while minimizing energy and resource consumption. This efficiency in said systems is enabled by built-in closed-loop control systems, in which sensory inputs, internal decision-making mechanisms, and actuating responses interact and communicate continuously. Through this feedback, the system controls relevant variables and respectively adjusts its behavior to ensure the most efficient response towards achieving the desired result. Good examples of these processes would be homeostasis in humans, or stomatal regulation in plants. This phenomenon in biological systems is why they present prime examples of sustainable systems, capable of fulfilling process needs efficiently with minimal waste generated.
In the pursuit of improved efficiency, consistency, control, and safety, engineering practices have increasingly adopted automation as a key approach in modern manufacturing. Beyond

these aforementioned advantages, automation can also be examined from a sustainability perspective. Through biomimicry, a conceptual parallel can be drawn between closed-loop control systems in manufacturing processes and similar feedback mechanisms found in living organisms. In both of these cases, continuous monitoring and adaptive response enable the system to achieve the most optimal outcome while minimizing inefficiencies and reducing the loss of material and energy resources.

This conceptual analogy is the foundation upon which the present research is based, as it attempts to quantify the extent to which automation benefits manufacturing processes in their pursuit of efficiency and ultimately of achieving sustainable development in industrial production processes. The following sections present the methodology used to assess the impact of automation, followed by an analysis of selected industrial case studies.

Analysis of automation in production processes for sustainable development

2.1 Sources of energy and material losses and their mitigation through automation: Having established the nature of manufacturing processes, it is understood that no such process occurs without the presence of material and energy losses throughout. The Law of Conservation of Energy states that energy cannot be created or lost, it only transforms from one form to another. In an ideal system, the entirety of energy going into a process should be converted into useful work and all materials in their entirety, should contribute directly to the output; when applied to the concept of manufacturing, this would mean that the total amount of any and all inputs going into the process should all be entirely useful to the process, with no input transforming into waste by the end of the process; the process should yield the desired output only, with no residue or energy inefficiency. In manufacturing processes, a portion of the energy input is dissipated as heat due to friction or other inefficiencies, while a part of the material input is lost as waste. As a result of this, any manufacturing processes inevitably produces undesired losses. This relationship can be expressed through an energy balance model:

$$E_{in} = E_{useful} + E_{loss} \quad (1)$$

which for metal-cutting processes can more specifically expanded as:

$$E_{in} = E_{cutting} + E_{friction} + E_{heat} + E_{idle} \quad (2)$$

The same logic and model can be applied to raw material waste, with losses in material as scrap, reworked parts, etc.

The sustainable approach to manufacturing processes is to utilize methods and technologies which minimize said energy losses and material waste, by removing any part of the process which creates energy inefficiencies or causes the generation of raw material losses. The processes analyzed in the actual research are processes pertaining to the metalworking industry of manufacturing, and as such the main issues which lead to inefficiencies in these processes are:

Inconsistency in production – In manual or semi- manual production there is variability in the cutting speed, feed rate, temperature control and operator decisions throughout the work process. This leads to material waste, unsatisfactory product quality, the need for reworking parts etc. (Kalpakjian & Schmid, 1989)

Inefficient machine operation – The machines are operated at non-optimal loads and are sometimes idled unnecessarily, generating heat losses and causing excessive energy consumption. (Groover, 2020)

Lack of real-time process control – In the absence of process control, traditional manufacturing systems cannot react quickly to deviations, cannot perform real time process inspection and control, which results in errors being detected late. This causes energy and material waste. (Åström & Murray, 2008)

Human error – Human involvement oftentimes causes measurement errors, incorrect inputs of parameters and settings, inconsistencies in repetitive work processes etc.; all contributing towards material losses and energy efficiencies. (Khatib & Sicilano, 2008)

Introducing automation to manufacturing processes the mitigates these issues by replacing open, operator-dependent processes with closed-loop control systems, where sensors continuously monitor process variables and gather data, controllers process said data, and actuators adjust machine behavior accordingly for maximum efficiency.

Automation enables precise regulation of parameters such as speed, feed rate, temperature, and force, significantly reducing variability between production cycles throughout the production process. Furthermore, automated systems enhance energy efficiency by optimizing machine operation, minimizing idle time, and ensuring that equipment operates only under conditions that are considered productive, thereby reducing unnecessary energy loss. The use of robotics and programmable systems also eliminates many forms of human caused inconsistencies, improving repeatability and reducing defect rates. In addition, real-time monitoring allows immediate detection and correction of deviations during the process, preventing the accumulation of errors that would otherwise result in large-scale material waste.

Collectively, these mechanisms enable the transformation of manufacturing from a reactive process—where defects are often identified in conclusion of the production process —into a proactive and adaptive system that continuously optimizes itself. As a result, automation significantly reduces both material and energy losses while simultaneously improving productivity and aligning industrial operations more closely with the objectives of sustainable development.

Having discussed the advantages of automation in reducing material losses and energy inefficiencies in theory, the degree to which these improvements introduced by automation translate into measurable, quantifiable outcomes in real industrial environments remains dependent on analyzing specific instances where automation technologies and processes have actually been implemented. Therefore, it is necessary to move beyond mere descriptions and examine the actual impact of these effects in practice.

This research looks into this aspect by analyzing three selected industrial case studies in which automation technologies have been implemented in production systems. The objective is to identify and compare quantifiable improvements in terms of material waste reduction, energy efficiency, and overall process optimization. Through this comparative analysis, the study aims to evaluate the practical impact of automation and assess its effectiveness as a tool for advancing sustainable development in industrial manufacturing.

2.2 Energy optimization in CNC machining through intelligent process control: One of the clearest examples of automation contributing to sustainable manufacturing can be found in the study conducted by Johnatan Cardona Jiménez and colleagues, where the energy consumption behavior of CNC machining centers was analyzed and optimized using advanced computational control methods. The objective of the study was to determine how automated optimization of machining parameters could reduce electrical energy consumption while maintaining acceptable machining quality, specifically surface finish.

The experimental study was conducted using two industrial CNC vertical machining centers: the Haas UMC-750 and the Leadwell V-40iT. Both of these machines were used to perform controlled metal cutting experiments under different machining conditions. The researchers focused on three controllable machining variables that significantly influence machining performance and power consumption:

Depth of cut (mm) – the thickness of material removed in a single pass

Feed rate (mm/min) – the speed at which the cutting tool advances through the material
Spindle speed (rpm) – rotational speed of the cutting spindle
These variables were selected because they directly affect cutting force, tool- work piece interaction, machining time, and consequently the total electrical energy consumption.
To better visualize the relationship between machining parameters and energy consumption in CNC operations, a nonlinear model was developed to generate a surface graph of the process:

$$E(f,n) = k1n^2 + \frac{k2}{f} + k3f + k4n + E_{base} \quad (3)$$

The model inputs spindle speed and feed rate as the primary controllable machining variables affecting total energy demand, while also accounting for the baseline machine energy consumption, needed to simply keep the machine operational. Unlike a linear approximation, this model incorporates both quadratic and reciprocal terms to better represent real machining behavior. The quadratic spindle-speed term accounts for increasing rotational and frictional losses which appear at higher spindle speeds, while the reciprocal and linear feed-rate terms represent the energy penalties that are associated with both very low feed rates, which result in longer machining times and very high feed rates, which result in increased cutting loads. The coefficients used in the energy model follow empirical machining energy models described by (Diaz, Helu, Jarboe, & Dornfeld, 2011). As a result, the model produces a nonlinear energy surface containing a minimum energy region, highlighting optimal machining conditions.

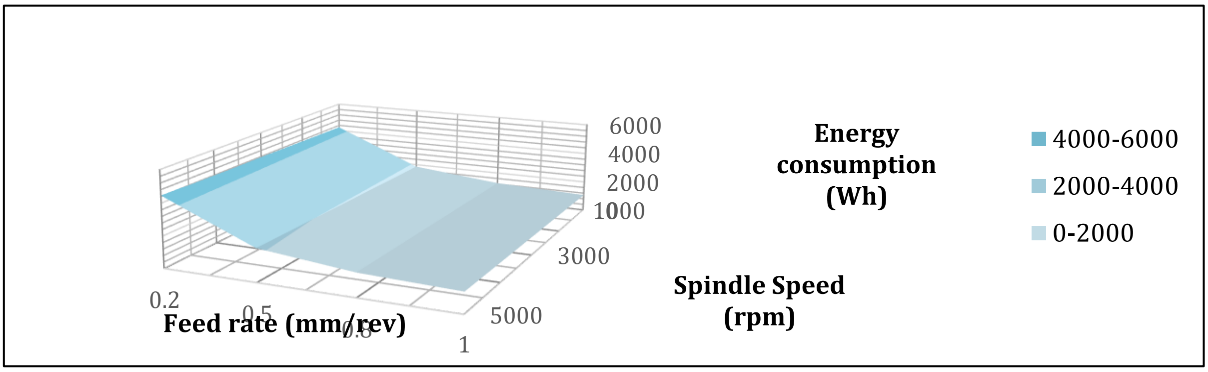

Figure 2. Nonlinear response surface of CNC machining energy consumption as a function of feed rate and spindle speed (model-based analysis)

In order to be able to quantify the relationship between these variables and machine performance, the researchers used a factorial experimental design, which is a method where multiple machining parameters are varied in different possible combinations instead of being tested one at a time, which allows the researchers to see, not only how each parameter in isolation affected the process, but also how the parameters interacted with one another. The factorial experimental design was combined with a Bayesian Seemingly Unrelated Regression (SUR) model. This model allows the simultaneous analysis of two outputs which are affected by the same input parameters; in this case these were parameters critical to the study, namely: Electrical power consumption (energy demand) and surface roughness (machining quality). This is important because simply minimizing energy is not sufficient if that causes the product quality to deteriorate. Therefore, both outputs had to be optimized together, hence the simultaneous analysis.
After developing predictive models for both machining centers, the researchers implemented an automated optimization method using a genetic algorithm combined with quasi-Newton derivative optimization. These methods represent a form of intelligent automation, where the

system itself iteratively searches for machining conditions that minimize energy consumption while preserving surface quality.
The optimization process produced several important findings:
Feed rate was identified as the most influential variable affecting machine power consumption.
Depth of cut was found to have the strongest influence on the roughness of the surface.
The optimization algorithm narrowed down the best operating conditions after approximately 20 generations of iterative search. (Cardona Jiménez, et al., 2022)
The predictive accuracy of the optimized model was extremely high, with an error of less than:
0.01% for the Leadwell V-40iT
0.03% for the Haas UMC-750. (Cardona Jiménez, et al., 2022)
These results demonstrate that automation in the form of intelligent process control can accurately identify the most energy-efficient machining conditions without impacting production quality. Instead of operating under fixed or parameters selected by the operator, which often lead to excessive power usage, longer machining times, and unnecessary tool wear, the automated system continuously determines the most optimal cutting conditions based on process feedback and statistical prediction.
From a sustainability perspective, this has significant meaning, because by minimizing unnecessary spindle load, reducing inefficient cutting conditions, and shortening effective machining time, the automated system lowers the electrical energy used for each manufactured component. In large-scale industrial production, optimizations like these can help achieve substantial reductions in total energy consumption, lower carbon emissions, and more efficient use of industrial resources, directly supporting sustainable manufacturing objectives.

2.3 Energy reduction in CNC milling through automated toolpath optimization: A second example of automation contributing directly to sustainable manufacturing can be found in the study done by Ampara Aramcharoen and Paul T. Mativenga, which investigated the impact of machining strategy and toolpath selection on the energy consumption of CNC milling operations. The objective of this research was to identify how machine-tool energy consumption changes under different automated machining conditions and to determine whether optimization of the tool movement could reduce overall electrical energy consumption during metal cutting.
The study focused on CNC milling processes, where electrical energy is consumed not only during actual material removal, but also during non-cutting machine states such as spindle acceleration, axis movement, coolant circulation, tool repositioning, and standby operation. One of the most important findings of the study was that, in machining operations, a significant portion of total machine energy consumption does not come from cutting itself, but from these movements and non-productive machine activities. The authors note that in mechanical machining, more than 90% of environmental impact is associated with direct electrical energy demand of machine tools. (Aramcharoen & Mativenga, 2014)
To investigate this, the researchers developed a detailed energy demand model for CNC milling. The methodology involved separating machine energy consumption into different operational states:
Basic machine energy – energy required to keep the machine operational
Spindle energy – energy required for rotational motion of the spindle
Axis movement energy – energy used during linear tool movement
Cutting energy – energy directly involved in material removal
By isolating these energy demands, the researchers were able to identify which portions of the machining cycle contributed most to unnecessary energy consumption. (Aramcharoen & Mativenga, 2014)

The experimental phase involved analyzing multiple NC-programmed toolpaths for milling operations. Different machining trajectories were programmed and they were executed under identical cutting conditions, which allowed the authors to isolate the influence of toolpath geometry and machine movement on total power consumption. Parameters such as spindle speed, feed rate, cutting distance, rapid positioning movements and idle motion sequences were all evaluated.

The results demonstrated that toolpath used during the cutting process had a major influence on total machine energy demand. Toolpaths that contained excessive repositioning movements and unnecessary non-cutting motions, significantly increased the electrical consumption. Then, by applying optimized CNC toolpaths with the use of computer-aided manufacturing systems, the researchers identified major opportunities for energy demand reduction, primarily by minimizing non-cutting machine movement, reducing idle spindle operation, and shortening total machining cycle time. The study also identified that machine "ready-state" energy, which is the power required simply to keep the CNC machine operational, made up a large portion of overall energy demand, meaning that reductions in machining time directly reduced total energy usage. (Aramcharoen & Mativenga, 2014)

From an automation perspective, this study demonstrates that sustainability improvements are not achieved only by automating physical machine movement, but also by automating process planning and toolpath optimization; in essence, how the machine moves. Rather than relying on manually selected machining strategies, CAM-based automated path generation allows the system to determine the most energy-efficient movement patterns before machining even begins. This approach reduces unnecessary machine movement, lowers electrical consumption per component, which then improves the overall energy efficiency of production.

From a sustainable development perspective, these findings show that automation and optimization of the machining process in its entirety, can significantly reduce the environmental footprint of CNC machining by optimizing how energy is used across the entire production cycle, rather than focusing solely on the cutting process itself.

2.4 Optimization of a Robotic Spot Welding Manufacturing Line in Automotive Metal Production: A third example of automation contributing to manufacturing efficiency and sustainability can be found in the industrial study carried out by Lopes, Sikora, Schibelbain, & Molina, which investigated the optimization of a fully automated robotic spot welding line in an automotive manufacturing factory operated by Renault in Curitiba, Brazil.

The objective of this study was to determine whether intelligent automation and the balancing of the production-line could reduce inefficiencies caused by excessive robotic movement, uneven distribution of workloads, and non-productive machine time in large-scale sheet metal welding operations.

The manufacturing line which was analyzed in this study was responsible for welding automotive body structures during the final body assembly stage. The production line consisted of: 42 industrial welding robots, which were distributed across 13 production stations, performing over 700 individual spot welds per vehicle body. Although the line was already automated, the researchers identified inefficiencies caused by uneven distribution of welding tasks between robots, unnecessary robotic travel distances between weld points, robot interference in multi-robot stations and extended cycle times caused by poor station balancing.

To address these issues, the researchers developed a Mixed Integer Linear Programming (MILP) optimization model. This model works by searching the most efficient outcome of the combination of different types of inputs or variables; one input of continuous value, such as time or energy and the other, whole number or yes/no values, such as robot assignments. This mathematical optimization model was designed to automatically reorganize welding tasks among the robots while also considering constraints throughout the process such as the

accessibility of the robots to the welding points, physical movement time between welding locations, possible collision/interference between adjacent robots, cycle-time requirements of the production line etc. (Lopes, Sikora, Schibelbain, & Molina, 2017)
The model was validated using empirical production data collected directly from the industrial welding line. After optimization, the system automatically generated better and improved task distributions and movement strategies for the robots and the results were significant:
Production cycle time was reduced by up to 6.6%
Workload balancing between robotic stations improved substantially
Non-productive robotic movement was minimized
Idle time between welding operations was reduced. (Lopes, Sikora, Schibelbain, & Molina, 2017)
These results demonstrate that automation can improve sustainability not only through direct machine control, but also through optimization of the production flow in its entirety. By reducing unnecessary robotic movement and shortening production cycle time, the total electrical energy consumed per welded component is reduced. Additionally, shorter cycle times increase machine utilization and reduce the energy consumed during standby states.

Table 1. Performance comparison of robotic welding line before and after optimization

Performance metric	Before optimization	After optimization	Improvement
Number of robots	42	42	—
Production stations	13	13	—
Cycle time	100%	93.4%	6.6% reduction
Robot idle time	100%	~85–90%*	Reduced
Task balance variance	High	Lower*	Improved
System utilization	Baseline	Increased*	Improved

** These qualitative metrics come from the paper's optimization objectives, even if exact public values are not always explicitly stated.*

From a sustainable development perspective, these improvements are highly relevant. In automotive metal manufacturing, where millions of welded components are produced each year, even a 6.6% reduction in cycle time translates into lower total electrical energy consumption, reduced operating costs, lower equipment wear, reduced indirect carbon emissions et cetera.
This case demonstrates that when automation is integrated with intelligent optimization algorithms it can significantly improve the efficiency of large-scale metalworking systems, bringing industrial manufacturing closer to sustainable production objectives. The study also reinforces an important conclusion for this research, that is automation does not only reduce losses at the process level, but can also optimize entire manufacturing ecosystems through intelligent coordination and feedback-based production planning.

Discussion of results and sustainability implications

The analysis of the three selected industrial case studies demonstrates that automation contributes to sustainable development at multiple levels of manufacturing, ranging from individual machining parameters to complete production-line coordination. Although each study investigated different manufacturing environments and applied different automation strategies, a common outcome emerges: the implementation of intelligent control systems consistently reduced operational inefficiencies, which leads to measurable reductions in energy consumption, non-productive machine activity, and process-related waste.

The first case study, involving automated optimization of CNC machining parameters, demonstrated that intelligent process control can identify optimal operating conditions that minimize machine power consumption while preserving machining quality. By continuously optimizing spindle speed, feed rate, and depth of cut through algorithmic control, the system eliminated inefficient cutting conditions that would otherwise result in excessive electrical consumption. This confirms that automation at the parameter-control level directly improves resource efficiency.

The second case study expanded this principle further to the process-planning level. Through automated toolpath optimization in CNC milling, unnecessary machine movements, idle spindle operation, and redundant positioning motions were minimized. The study reported energy-saving potential between approximately **30% and 67%**, depending on the machining strategy selected. These findings suggest that a substantial portion of industrial energy losses are originated not from the cutting process itself, but from inefficient planning and machine coordination—issues that automated CAM systems are capable of mitigating.

The third case study demonstrated the impact of automation at the production-system level. Through the optimization of a robotic spot welding line consisting of 42 industrial robots, cycle time was reduced by **6.6%**, which directly improved robot utilization and decreased non-productive energy consumption across the manufacturing line. Although the percentage reduction appears smaller compared to the previous studies discussed, its industrial significance is a lot greater due to the scale of automotive production, where even small improvements transform into major long-term reductions in energy demand and operational cost.

To better evaluate the sustainability impact of these studies, the quantitative findings can be compared directly:

Table 2. Quantitative comparison of automation effects on manufacturing efficiency and sustainable production

Case study	Automation level	Measured improvement
CNC parameter optimization	Process parameter control	Prediction/optimization accuracy error <0.03%
CNC toolpath optimization	Process planning	30–67% energy reduction potential
Robotic welding optimization	Production-line control	6.6% cycle-time reduction

When comparing the results, it becomes evident that the scale of improvement depends on the level at which automation is implemented. Parameter-level automation improves process precision and eliminates smaller inefficiencies. Process-planning automation allows for larger direct energy savings by optimizing machine movement and cutting strategy. System-level automation achieves smaller percentage improvements, but its large-scale industrial application results in substantial sustainability benefits.

Based on these findings, automation can be considered a decisive technological driver of sustainable industrial development. By reducing energy demand, minimizing idle machine operation, lowering defect rates, and improving overall process stability, automated manufacturing systems reduce the material and energy footprint per unit of production. These improvements directly support the principles of sustainable development by enabling industrial growth while preserving material resources, lowering environmental impact, and improving long-term economic efficiency.

Conclusion

The objective of this research was to examine the role of automation in modern manufacturing processes and quantitatively evaluate its contribution toward minimizing material and energy losses in support of sustainable industrial development. Through the theoretical analysis of production systems and the examination of three industrial case studies in metalworking and automated manufacturing, the findings consistently demonstrate that automation represents far more than simply a method of increasing productivity or reducing dependency on human labor. Rather, automation is established as a critical engineering approach for improving the overall efficiency, stability, and sustainability of industrial production systems.

The analysis began from the understanding that all manufacturing systems operate as input–process–output structures, where raw materials and energy are transformed into finished products through a series of technological operations. As discussed, under real industrial conditions, these transformations are always accompanied by losses in the form of material waste, machine operation that is non-productive, process variability, and inefficient energy conversion. The research identified that many of these inefficiencies originate from inconsistent process control, human operational variability, inefficient machining strategies, and delayed correction when there are process deviations. These factors collectively increase energy consumption, they generate unnecessary scrap, and reduce the overall sustainability of production systems.

The selected case studies provide us with strong quantitative evidence that automation effectively addresses and mitigates these limitations at multiple levels of manufacturing. In the first case study that was presented, the intelligent optimization of CNC machining parameters demonstrated that automated control systems can identify the most efficient operating conditions while also maintaining machining quality, thus significantly reducing unnecessary energy demand during metal cutting. The second case study showed that process-planning automation through the generation of optimized CNC toolpaths can reduce machining energy demand by as much as **30% to 67%**, proving that substantial inefficiencies often originate in process planning rather than the material removal itself. The third case study demonstrated that system-level automation in robotic spot welding reduced production cycle time by **6.6%** across a large-scale industrial production line, improving robot efficiency and reducing non-productive energy consumption in high-volume automotive manufacturing.

When analyzed collectively, these results reveal an important engineering principle: the effectiveness of automation increases with the depth of integration within the manufacturing system. Although automated systems themselves require electrical energy for operation, the evidence presented in this research confirms that the reduction in wasted materials, machine idle time, defective production, and unnecessary energy waste significantly outweighs the energy required to operate the automation infrastructure itself.

From the perspective of sustainable development, these findings confirm that automation is not merely a technological advancement, but a strategic necessity for the future of industrial manufacturing. By reducing the material and energy footprint per unit of production, automated systems enable the most responsible use of natural resources, lower environmental impact, and improve economic competitiveness. Therefore, the integration of intelligent automation, real-time monitoring, and feedback-based control systems should be regarded as one of the most effective pathways toward achieving sustainable industrial development in modern manufacturing.

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