FUPRE Journal

of

Scientific and Industrial Research

ISSN: 2579-1184(Print) ISSN: 2578-1129 (Online)

http://fupre.edu.ng/journal

Optimizing Manufacturing Processes through Advanced Process Engineering Techniques: A Case Study of Energy Efficiency, Waste Reduction, and Environmental Sustainability: Review

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ARTICLE INFO

Received: 15/06/2024

Accepted: 23/10/2024

Keywords

Biotechnology, Efficiency, Optimization, Simulation, Sustainable

ABSTRACT

Manufacturing processes has evolved over the last century with the incorporation of a lot of new concepts. The industry as today is faced with a growing demand for higher quality products, tailored to specifications, energy efficient processes, ecofriendly processes and increased process sophistication with fewer human operations and much reliance on artificial intelligence. Thus, there is so much reliance on technology, science, innovation, interdisciplinary research and development (R&D) to either develop advanced manufacturing processes or optimize the existing processes to achieve the desired goals. In this review study, emphasis is placed on the various advanced process engineering techniques for optimizing manufacturing processes. Advanced process engineering techniques encompass a range of methodologies and tools used to optimize and improve industrial processes across various fields, including chemical engineering, manufacturing, pharmaceuticals, and biotechnology. These techniques leverage on advanced computational methods, data analysis, optimization algorithms, and innovative approaches to enhance process efficiency, reduce costs, minimize waste, and ensure product quality. Optimizing energy use in industry contributes to sustainable engineering by conserving resources, reducing emissions, and promoting renewable usage, thus aligning with the global need for sustainable development. Thus, from studies reviewed, process simulation using Aspen HYSIS was adopted in optimizing the energy efficiency in SIBUR Petrochemical Company, and it resulted in the recovery of over 25% of the overall energy consumption, and an IRR greater than 25%. Other studies revealed that the implementation of Just-in-time inventory (JIT) methodology results in waste reduction. Lastly, a study shows that the adoption of eco-design strategies or characteristic in a manufacturing process, influences enterprise sustainability innovativeness.

1. INTRODUCTION

If we take a tour of some of the newly designed and built technologies in our contemporary time, especially in some of the basic sectors like petroleum refining and petrochemical, cement manufacturing, power generating, food processing, biotechnology, and automotive plants, we will observe relatively much larger capacities, novel concepts, process integration, and improved efficiencies when compared with similar, previously built plants. For instance, refineries of the 21st century, apart from using novel concepts

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like reactive distillation and membrane separation, also employ biotechnology to bring improvement in chemical conversion and efficiency (Barrientos, 2023). Moreso, major parts of these process plants were built decades before the knowledge and the technologies aimed at a better use of energy were available. There are new developments for efficiency improvement in power plant technology like combined cycle/once through boiler/supercritical technology and integrated coal gasification combined cycle (IGCC), which are all fallouts of successful development of advanced materials for higher duty (Beér, 2000). There have been tremendous successes in process and product development, starting from the basic idea, research and development, pilot scale and scale-up to final commissioning. These successes were made possible by accurate models, based on sound theory with process modeling tools which significantly reduce scale-up and marketing time and cost of new products/processes. Advances in computational technologies has also helped in improving the application of fundamental sciences. The most critical for the manufacturing process industry are process modeling, simulation, operations, optimizations and control. The static and dynamic modeling/simulation along with optimizers, achieves optimal design and operation (Liu *et al.,* 2021). Advances in computer hardware/software coupled with fundamental knowledge has changed the way process plants are designed and operated today. Thus, the use of computer software has become an indispensable part of process design, and now the current trend for meeting challenges of reactor design in complex plants of ever-growing size, involving advanced manufacturing methods and high-end stress analysis. Design software and codes such as heat transfer research incorporated (HTRI) and computational fluid dynamics (CFD) plays critical roles in enabling the optimization of heat exchanger sizes and material selection. It is worthy of note that the rapid development of advanced manufacturing process industries, also gave rise to multiple environmental issues. As a result, sustainability and life cycle analyses concepts, are also incorporated into industrial design, modelling, simulation and operations, for public acceptance of industrial facilities (Ramani *et al.,* 2010). Therefore, to achieve sustainable development, amounts to promoting sustainable chemical plant design, by eliminating toxic chemical usage, reducing waste and improving process operations.

2. RESEARCH METHODOLOGY

This review study was carried out by studying recent publications and materials on the optimization of manufacturing processes through advanced process engineering technique, aimed at energy efficiency, waste reduction, and environmental sustainability. The various techniques/tools adopted for such optimization where enumerated. The study also considered one or more manufacturing processes where an advanced process engineering technique, was adopted and the technique used was identified. The successes, challenges and limitations of the advanced process engineering technique were also emphasized.

2.1 Tools for Optimization and Improvement of Industrial Processes

Advanced process engineering techniques encompass a range of methodologies and tools used to optimize and improve industrial processes across various fields, including chemical engineering, manufacturing, pharmaceuticals, and biotechnology. These techniques leverage advanced computational methods, data analysis, optimization algorithms, and innovative approaches to enhance process efficiency, reduce costs, minimize waste, and ensure product quality (George & George, 2023). Here are some key advanced process engineering techniques:

(i) Computational Fluid Dynamics (CFD): CFD involves using numerical methods and algorithms to analyze and simulate fluid flow, heat transfer, and chemical reactions within process equipment such as reactors, heat exchangers, and pipelines (Raman *et al.*, 2018). It helps engineers optimize designs, troubleshoot problems, and improve performance without the need for physical prototypes.

(ii) Process Simulation: Process simulation software allows engineers to create virtual models of entire process plants or specific unit operations. These models can predict system behaviour under different operating conditions, identify bottlenecks, optimize parameters, and assess the impact of changes before implementation (Dimian *et al., 2014*).

(iii) Advanced Control Strategies: Advanced control techniques, such as model predictive control (MPC), adaptive control, and fuzzy logic control, enable tighter regulation of process variables, improved disturbance rejection, and better performance in the face of uncertainties (Kumar and Ahmad, 2012). These techniques can enhance process stability, increase throughput, and reduce energy consumption.

(iv) Optimization Algorithms: Optimization algorithms like genetic algorithms, simulated annealing, and particle swarm optimization are used to find optimal operating conditions, process configurations, and resource allocations. These algorithms can handle complex, nonlinear systems with multiple objectives and constraints, enabling engineers to identify the best solutions efficiently.

(v) Just-In-Time Inventory Management, also referred to as Lean manufacturing principles: JIT is a form of inventory management that requires working closely with suppliers so that raw materials arrive as production is scheduled to begin, but no sooner. The goal is to have the minimum amount of inventory on hand to meet demand. The JIT inventory methodology uses a variety of techniques to smooth operations. The lean method focuses on optimizing organization, paying attention to detail, having small lot sizes, increasing transparency, fostering cell manufacturing and using a pull (rather than push) approach (Kumar, 2010).

(vi) Quality by Design (QbD): QbD is a systematic approach to product and process development that focuses on understanding the relationship between process parameters and product quality attributes. By applying QbD principles, engineers can design robust processes that consistently meet product specifications and regulatory requirements while minimizing variability.

(vii) Data Analytics and Big Data: Advanced analytics techniques, including machine learning, statistical modeling, and data mining, are used to analyze large volumes of process data and extract valuable insights. These insights can help identify patterns, detect anomalies, optimize processes, and support decision-making in real-time (Qin and Chiang, 2019).

(viii) Advanced Materials and Catalysts: Developing and utilizing advanced materials and catalysts can significantly enhance process performance and product yields. Nanomaterials, composite materials, and tailored catalysts with specific properties can improve selectivity, reaction rates, and durability in various chemical and biochemical processes (Ocreto *et al.*, 2022).

(ix) Green Engineering Principles: Incorporating green engineering principles into process design and operation aims to minimize environmental impact and resource usage. Techniques include process optimization for energy efficiency, waste minimization, recycling, and the use of renewable feedstocks and alternative solvents (Ruiz-Mercado *et al.*, 2016).

(x) Process Safety and Risk Assessment: Advanced techniques for process safety and risk assessment, such as hazard and operability studies (HAZOP), fault tree analysis (FTA), and process safety audits, are essential for identifying and mitigating potential hazards, ensuring personnel safety, and preventing accidents (Jain, 2007).

2.2 Application of Process Simulation for Achieving Energy Efficiency

A notable example of the application of process simulation for achieving energy efficiency is the research carried out by Dyudnev *et al.*, (2021); the research was on energy analysis and process simulation for the energy efficiency improvement of existing chemical plants, using SIBUR Petrochemical Company in Tobolsk, Russia, as a case study.

2.2.1 Background

There was need to optimize performance of the utility side of the plant; steam generation and utilization in SIBUR Petrochemical Company. There is only one steam generator system that feeds all the unit needing a hot duty, with high pressure (HP) steam (13 MPa) and medium pressure (MP) steam (1.3 MPa), depending on the requirement of the unit. After being used, the HP steam at the outlet of the given unit, is then sent to a MP steam collector and further used by other units. The steam generating system works in a closed loop configuration, makeup water is only provided in order to compensate for evaporation losses. Originally, the duty consumption occurs in sequence and no crossing streams matches present, which suggest that there is room for improvement by means of a proper energy analysis and with a deeper pipeline network understanding in order to consider possible integration between different plant sections as well.

2.2.2 Steps Involved in the energy analysis and process simulation

i. The first step towards the LPG section analysis and optimization is the generation of its digital twin on a process simulator, in this case Aspen HYSIS was used.

ii. After that a pinch analysis is performed according to the methodology discussed by Di Pretoro and Manenti (2020a, 2020b) by accounting for all the utility and process hot and cold streams of the plant, not only for the LPG section. This allowed for the identification of the enthalpic level of each stream and to detect all those cases in which the available energy was not effectively exploited, thereby determining the energy savings.

iii. The energy savings in then used to evaluate the reduction in terms of CO_2 equivalent emissions by means of the correlations proposed by Gadalla *et al.*, (2006).

iv. The introduction of new units for better heat recovery and a more proper steam usage.

v. Determination of the cost of the new units as well as the operating expenses related to the energy consumption through estimation by means of correlations proposed by Guthrie (1969,1974), Ulrich (1987) and Navarrete (2001).

vi. Selection of the most effective amongst the proposed modification enhancements to be added, instead of all the new units proposed by the analysis, for the purpose of practicability and cost saving. The economic analysis allows one to check the benefits of the possible modifications and to make a comparison between them, with the help of some economic performance indicators.

2.2.3 Outcome of the energy analysis and process simulation

From the energy analysis performed via the Aspen HYSIS simulation flowsheet two main measures were detected as having contributed to the recovery of more than 25 % of the overall energy consumption. The measures are namely: the installation of an additional heat exchanger in the LPG section and the installation of a new steam line connecting the Propane Dehydrogenation (PDH) section and the LPG section, as shown in Figure 1 and Figure 2 respectively.

The operational advantages, the energy savings and the economic improvements provided by each of these design solutions, were quite commendable. The economic indicators (i.e. Investment or Capital Expenditure (CAPEX), the Net Present Value (NPV), the Internal Rate of Return (IRR) and the Pay Back Period (PBP)), of implementing each of the design solutions were calculated using design and costing equations provided for in Brennan (2020). The IRRs of installing the heat exchanger and steam line, are 40.8% and 27.8% respectively. Thus, any of the design solutions can be implemented since their IRR are higher than 25 %, being the requirement by SIBUR Petrochemical Company for the justification of the plant revamp.

2.3 Application of Lean Manufacturing Principles for Achieving Waste Reduction

Lean manufacturing principles focus on eliminating waste, improving process efficiency, and maximizing value to customers. These principles not only enhance operational performance but also contribute to energy efficiency in manufacturing. Lean manufacturing emphasizes the identification and elimination of waste in all forms, including energy waste. By streamlining processes, reducing unnecessary movements, procuring only needed materials, and optimizing equipment utilization, manufacturers can minimize energy consumption, reduce waste, and improve overall efficiency. Lean manufacturing actually originated from the Toyota Production System (TPS) and was aimed at satisfying the customer needs in the most efficient way in which waste was minimized (Tuck *et al.*,, 2007; Mao and Zhang, 2008; Nordin *et al.*,, 2012). Thus, the review will be on Toyota Production System, as a case study.

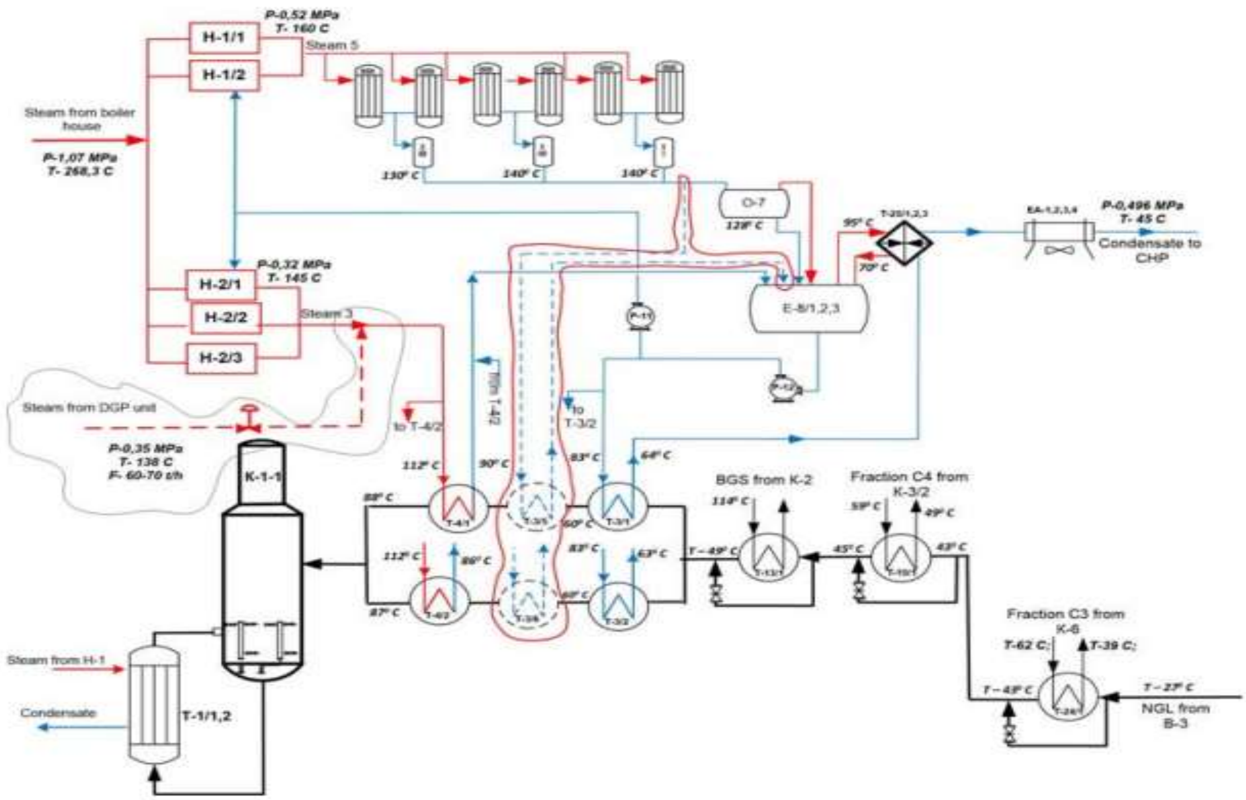

Figure 1: Process flowsheet showing the additional heat exchangers (Dyudnev *et al.*, 2021)

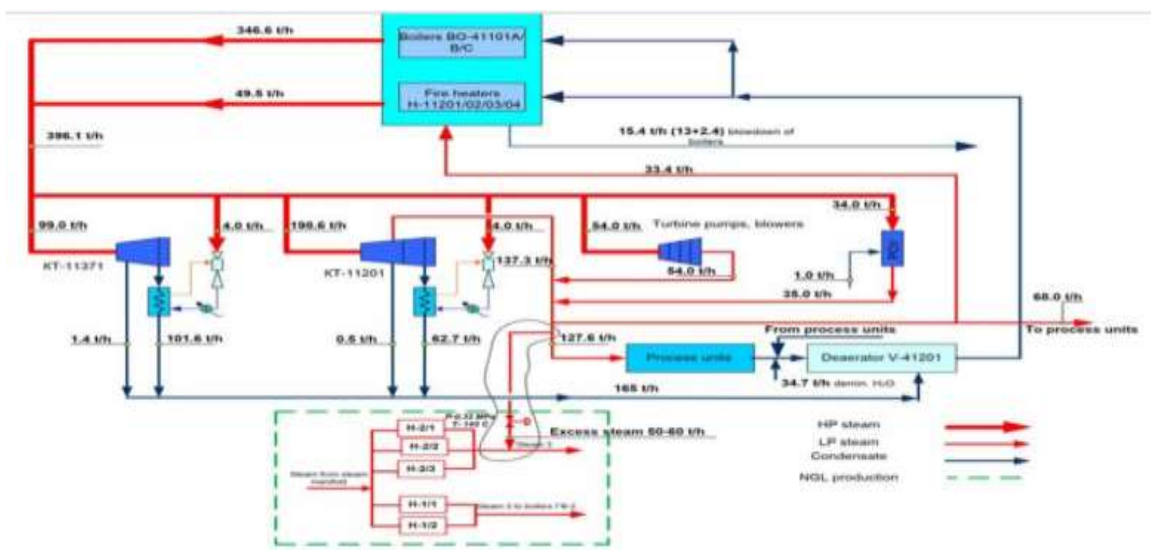

Figure 2: Process flowsheet showing new steam line connecting the two sections (Dyudnev *et al.*, 2021)

2.3.1 Background

In post-World War II Japan, car manufacturers faced shortages and were saddled with excessive, obsolete, defective and unsold inventories sitting in their warehouses. The Toyota Motor Company (TMC) then realized that U.S. carmakers of that era were outpacing their Japanese counterparts. There was therefore need to minimize resource consumption to survive and remain competitive. Eiji Toyoda and Taiichi Ohno, Japanese industrial engineers, then established the "Toyota Production System" (TPS) or just-in-time manufacturing (JIT), also refer to as Lean Manufacturing and closed the gap between 1945 and 1970. The underlying idea of just-in-time manufacturing is to minimize the consumption of resources that add no value to a product. JIT has continued to grow as a practice worldwide.

2.3.2 Techniques Involved in JIT Inventory Methodology

The JIT inventory methodology uses variety of techniques for its smooth operations. The lean method focuses on optimizing organization, paying attention to details, having small lot sizes, increasing transparency, fostering cell manufacturing and using a pull (rather than push) approach. The following management features were put in place as part of measures for the implementation of JIT in Toyota Motor Company:

i. Order: Maintaining a high level of physical and organizational discipline.
ii. Better Quality: Eliminating defects through attention to detail and continuous improvements.
iii. Reduced Setup Time: Creating flexible changeover approaches when setups need to adjust to meet customer demand.
iv. Small Lot Size: In JIT, one is the ideal lot size. The small size reduces in-process inventory, carrying costs, storage space, and makes for easier inspection and rework.
v. Load Uniformity: Leveling is a control mechanism that achieves a stable, level daily schedule.
vi. Flow Balance: Flow scheduling organizes throughput for even distribution of energy and labour.
vii. Diversified Skills: Cross-trained workers can be deployed to different areas to keep production moving.
viii. Visibility for Control: Using appropriate communication tools, keeps the entire team informed of inventory levels.
ix. Ongoing Maintenance: Ongoing oversight and focus on detail, including the machinery and tools the business uses every day, helps maintain a low defect, low problem environment.
x. Use Fitness: JIT spaces designed to fit each process speeds up production. One workstation pulls output from the one before it, as needed,

based on a master schedule or customer demand.

xi. Logical Plant Layout: Product-oriented design makes assembly easier and more efficient.

xii. Strong Supplier Network: Strong relationships with vendors make JIT inventory most effective.

xiii. Worker Immersion: Every team member should be dedicated to the process and colleagues to achieve JIT goals.

xiv. Cell Manufacturing: Create an environment where groups can work as quickly as possible to make as many products as they can and limit the waste they create.

xv. Pull System: The process of only replacing products once they've been used in production.

2.3.3 JIT Process diagram

The JIT inventory methodology is usually an ongoing process, requiring regular evaluation of the results and adjustments, where necessary. The JIT process diagram is shown Figure 3.0 below.

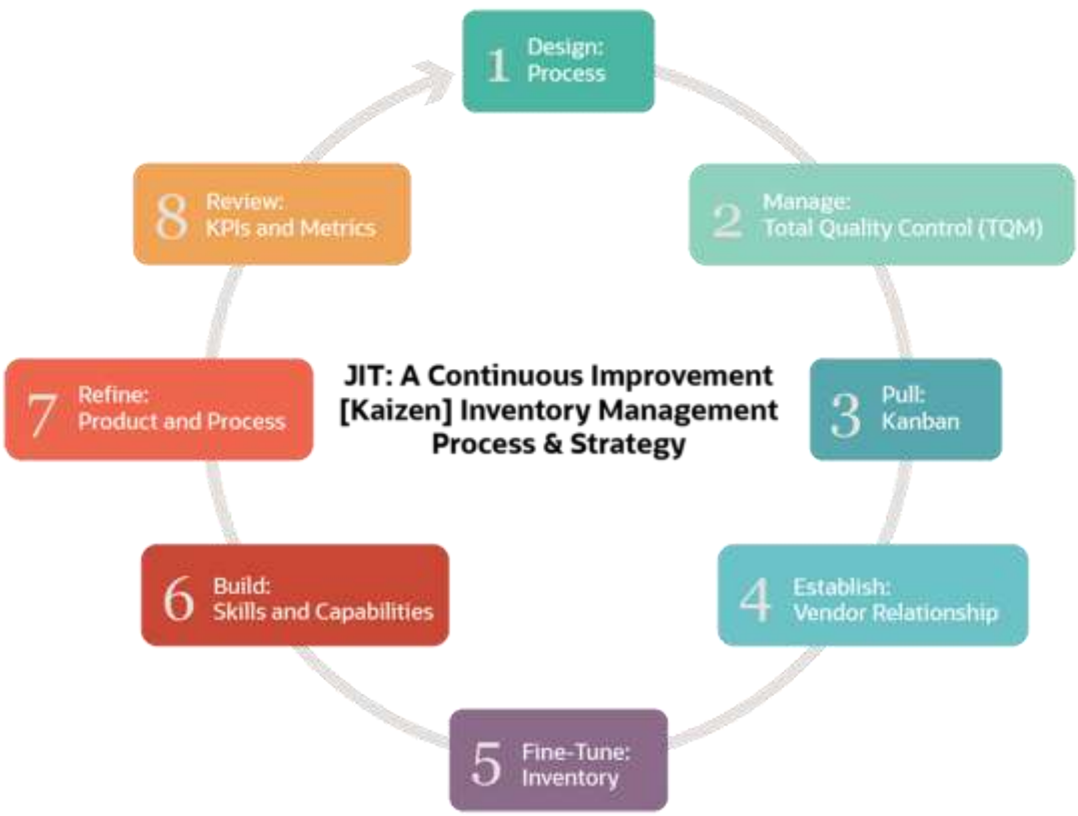

Figure 3: The graphic shows the Just-in-time (JIT) Inventory cycle (Abby, 2023)

There is bound to be variations from one organization to the other as to how the JIT is being implemented, but the general steps are the same. This diagram shows how the cycle of continuous improvement works in JIT inventory management.

2.3.4 Steps in cycle of continuous improvement for JIT inventory

i. Design: The JIT process begins with a review of the essential manufacturing building blocks: product design, process design, personnel and manufacturing planning. Then plans are put into place to eliminate disruption, minimize waste and build a flexible system.
ii. Manage: A *Total Quality Management (TQM)* review ensures there is continuous improvement throughout the process. A management review defines workers' roles and responsibilities, defines and measures statistical quality control, stabilizes schedules, and checks out load and capacity schedules and levels.
iii. Pull: Educate the team on production and withdrawal methods using signaling methods like Kanban. Review lot size policies and reduce lot sizes.
iv. Establish: Vendor relationships are vital to the success of JIT. Review vendor lists. Settle on preferred suppliers, negotiate contracts, discuss lead times, delivery expectations and usage metrics and measures. Learn how to make the most of them in the supply chain.
v. Fine-tune: Determine inventory needs, policies, controls and reduce inventory movements.
vi. Build: Inform your team about the skills and capabilities it needs to complete its work and conduct team education and empowerment sessions to educate them.
vii. Refine: Reduce the number of parts and steps in production by refining, standardizing and reviewing the entire process.
viii. Review**:** Define and implement quality measures and metrics and conduct a root cause analysis of any problems. Emphasize improvements and track trends to improve every aspect of JIT.

2.3.5 Outcome of the JIT implementation in Toyota Motor Company

JIT inventory management boosts the return on investment (ROI) of TMC by lowering inventory carrying costs, increasing efficiency, increasing productivity, decreasing waste, and ensuring sustainability. The JIT also promoted major improvements in quality and productivity, as well as increased worker responsibility and commitment.

2.4 Eco-Design Principles for Product Lifecycle Sustainability

The modern manufacturing processes are faced with the need to carry out their operations with utmost consideration of the environment and to meet the United Nation Sustainable Development Goals (SDG). Hence, it is necessary to perform green design and manufacturing interventions. The green design, also referred to as eco-design principles, integrates environmental considerations into product development and design of processes to minimize environmental impact throughout the product lifecycle.

2.4.1 Strategies for implementing eco-design

The following strategies are required of manufacturers in implementing green design:

i. Material Selection: Choosing environmentally preferable materials with lower environmental impact, such as recycled, renewable, or biodegradable materials, reduces the ecological footprint of products (Okogwu *et al.*, 2023). Manufacturers can conduct life cycle assessments (LCAs) to evaluate the environmental impacts of different material choices.

ii. Energy-Efficient Design: Designing products for energy efficiency by optimizing energy consumption during manufacturing, use, and end-of-life phases reduces energy-related emissions and operating costs. Energy-efficient design features may include light weighting, aerodynamics, and energy-efficient components (Seow *et al.*, 2016).

iii. Design for Disassembly and Recycling: Designing products for disassembly and recyclability facilitates the recovery and reuse of materials at the end of their life. By using standardized components, labeling materials for easy identification, and designing for material separation, manufacturers can simplify the recycling process and maximize resource recovery (Yadav *et al.*, 2018).

A case study is on the work carried out by Jnr *et al.* (2018), in which a model was developed based on diffusion of innovation theory and sustainable life cycle process identified through a literature review; then, a survey method was employed (Gao *et al.*, 2021). The results revealed that the internal and external characteristics influenced enterprise sustainability innovativeness (Anthony, 2020). These characteristics are the strategies for implementing eco-design process in manufacturing system.

3. CONCLUSION

The review work has concisely explained some tools for optimization and improvement of industrial processes for increased efficiency, profitability, and sustainability. The case that was considered as an example of plant revamp, involve the application of process simulation for achieving energy efficiency in SIBUR Petrochemical Company. The study shows that through process simulation and energy analysis, improvement in the energy saving of an existing LPG section of the SIBUR Petrochemical Company facility could be achieved, by modifications and installation of a few pieces of equipment. There was a recovery of more than 25 % of the overall energy consumption, which is a good justification for implementing the possible modifications. Other studies revealed that the JIT implementation results in waste reduction. Lastly, a study shows that the adoption of eco-design strategies or characteristic in a manufacturing process, influences enterprise sustainability innovativeness.

4. Recommendation

Optimizing energy use in manufacturing industries contributes to sustainable engineering by conserving resources, reducing emissions, and promoting renewable usage, thereby aligning with the global need for sustainable development. Therefore, ccontinuous improvement and collaboration among stakeholders, is recommended for realizing the full potential of the suggested approaches (process simulation and revamp, JIT inventory and eco-design) in driving positive changes towards a more sustainable manufacturing industry.

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