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Human-Centric Smart Manufacturing for Sustainable Leather Production: An Industry 5.0 Framework

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ABSTRACT: New developments in cyber-physical systems, IIoT and digital twin technologies have dramatically improved the design, process and monitoring of the leather manufacturing system. It is an important sector with respect to economics, although, at present, the leather industry struggles with conventional manufacturing processes, quality inconsistency, and environmental issues. A Human-Centered Smart Manufacturing System (HCSMS) based on Industry 5.0 is developed. Combining the above components, the method enhances cognitive, creative, and intelligent abilities through combining excellent human qualities with technologies. A mixed-methods approach comprising of system modelling, simulation based-optimization and empirical validation was applied in order to test the framework. KPIs used were: productivity, energy consumption, defects per product, ergonomic index and lead time of the processes. As evident from the result below, there has been improvement in terms of the KPIs, with increased production efficiency by 21.4% and reduced wastage by 17.8%. The ergonomic risk score decreased by 26.3% which showed an improvement in human operator comfort and health thanks to collaborative robots and workstations adjustment. By using the digital platform, it is possible to make manufacturing fully integrated and traceable in real time. A multi-objective optimization model for simultaneous improvement of the performance of productivity, human and environmental aspects was constructed. It is concluded that the combined approach of human-centered manufacturing and advanced technologies leads to better results both from the operational efficiency and sustainability point of view. The developed framework presents a measurable way towards human-centric smart manufacturing of the leather industry sector.

Key Words: Human-Center, cyber-physical systems, Leather Production, Industry 5.0 Paradigm, Smart Manufacturing

1.INTRODUCTION AND BACKGROUND OF THE STUDY

1.1. Introduction

The industrial world is witnessing a paradigm shift with the introduction of Industry 5.0, which focuses on the integration of human intelligence and creativity with smart manufacturing systems to achieve sustainability in industrial processes. While Industry 4.0 mainly concentrates on the development of connected and cyber physical systems, Industry 5.0 focuses on the human-centric approach to industrial processes with the help of smart technologies like artificial intelligence, digital twining, and collaborative robots (Liu et al., 2022; ElMekkawy et al., 2021). The manufacturing process of leather is a labour-intensive and environmentally critical process that is highly variable in terms of materials, process steps involved, and water and energy consumptions during the manufacturing process. The traditional approach of the manufacturing process is mainly focused on ensuring the efficiency of the manufacturing process, but it affects the sustainability and well-being of workers and the environment, resulting in increased waste generation and reduced flexibility in adapting to changes in the market scenario (Zhang et al., 2021). On the contrary, human-centric smart manufacturing is mainly focused on ensuring the collaborative relationship between humans and machines, wherein human cognitive and creative potential is utilized in conjunction with digital technologies in making decisions in real-time.

It is not only about implementing digital technologies but also ensuring the integration of workplace ergonomics, digital technologies, and socially responsible production practices (Wang et al., 2023). Adopting this concept, the production of leathers can be directed towards sustainable growth in the global market, which is becoming increasingly competitive. This research is aimed at establishing and assessing the framework of Human-Centric Smart Manufacturing Systems in the production of leathers under the Industry 5.0 concept. By integrating digital technologies with human-centric principles, this research can prove the potential benefits of increased productivity, product quality, sustainability, and worker well-being.

1.2. Background of the Study

The economic importance of the leather industry can be gauged at a global level, with its products being in high demand and holding economic importance in terms of employment and foreign exchange earnings in developing countries (FAO, 2020). It can be described as a link between traditional and modern manufacturing processes, as it combines traditional craftsmanship with modern manufacturing techniques. Over time, there has been a steady increase in the demand for leather products at the global level due to factors like fashion trends, increased per capita income, and the expansion of the automotive and furniture industry. India, Brazil, China, and Italy are some of the major contributors to the global leather industry, with each of them contributing in their own unique way to the industry in terms of their strengths and capabilities in the production and processing of leather and its final products. For instance, Italy is known for its fashion leather, while India is known for its large-scale production and export of leather footwear (Kumar & Shukla, 2021). However, despite its economic advantages, leather production also faces a number of challenges. First and foremost is the labour-intensive nature of leather production. The process of tanning, cutting, dyeing, and finishing is still largely labour-intensive. Though some of these processes have already been mechanized, this is still not on a larger scale, especially in small and medium-scale industries in developing nations (Damtew,2024),(Kumar & Shukla, 2021). This is likely to affect the quality of leather produced and, in turn, its market value. Another factor affecting leather production is the raw materials involved in it. The quality of leather is directly proportional to the breed and age of cattle from which it is derived and also depends on the conditions in which it was raised. This is likely to cause concerns in terms of labor costs involved in its production. The chemical-based processes involved in tanning, dyeing, and finishing also cause serious environmental concerns. If left unchecked, the effluents and chemical waste can contaminate water bodies, while waste and emissions can further add to the damage to the environment (Kumar & Shukla, 2021). Work is in progress to resolve the above challenges. Many manufacturers are working on adopting alternative and environmentally friendly processes of tanning, waste recycling, and water treatment to minimize damage to the environment. At the same time, work is in progress to improve the skill levels of the workforce, introduce semi-automatic machines, and improve quality control processes to increase efficiency and quality.

The other important aspect to be taken care of is that the leather industry is directly linked to international trade policies and standards. Tariff rates and other international standards can directly affect the market and the industry as a whole. Countries that can sustain high-quality production while maintaining environmentally friendly processes have a better chance of competing in the international market. Thus, the leather industry is not only an economic engine but a complex system that balances labour, technology, material, and environmental issues.

Lastly, the process of leather manufacture is a combination of tradition and innovation issues(Zhang et al., 2021), (FAO,20200). The process are faced with numerous challenges, such as labour, material, technology, and environmental issues, but with the pursuit of knowledge, the challenges will be addressed, making the process more efficient, responsible, and competitive in the world arena. The importance of the leather industry to the economy, employment, and heritage, especially in places that have traditionally relied on the industry to support livelihoods, makes the process a vital part of the economy (FAO, 2020; Kumar & Shukla, 2021).

1.3. Statement of the Problems

Even as the adoption of digital technology in manufacturing is becoming increasingly common around the globe, the problem of structural inefficiencies, inconsistency in the quality of products, and environmental challenges remains in the leather industry. The conventional methods involved in leather processing, particularly in developing countries such as Ethiopia, have been mainly dependent on manual labor which is not entirely consistent. Besides, there are various environmental problems, including discharges of untreated effluents into the environment, high chemical usage in the tanning and dyeing processes, and solid wastes in finishing phases (Kumar & Shukla, 2021). With the introduction of cyber-physical systems, IIoT, and digital twins among other technologies in Industry 4.0, several advantages emerge, including real-time monitoring and maintenance. As such, numerous positive outcomes have been experienced through the use of such technologies in improving both manufacturing activities and resource allocation (Jain et al., 2022). While such applications can be described as techno-centric, they do not place much emphasis on the human component. This techno-centric approach fails to take into account various issues, such as ergonomic factors, tacit knowledge, decision-making, and craftsmanship in the leather production process. Several challenges associated with not adopting a human-centered design framework in leather production may be mentioned, including inflexibility of the system while handling non-standard production tasks, increased risk of developing occupational illnesses due to poor human-machine interface, and lack of innovative solutions offered by skilled human labour. Despite being highly automated, Industry 4.0 does not tackle the sociotechnical nature of leather manufacturing processes. Industry 5.0 comes into play as a solution to some of the above-mentioned drawbacks of Industry 4.0. According to Wang et al. (2023), apart from focusing on efficiency and effectiveness, Industry 5.0 places emphasis on resilience, human well-being, and sustainability. With regard to the leather manufacturing industry, Industry 5.0 could allow for a combination of human insights and automation to lead to more consistent quality levels, less waste, and safer workplaces.

It should be noted that although there are some conceptual insights on the topic, the amount of empirical research dedicated to applying Industry 5.0 to the process of leather manufacturing is extremely limited. Consequently, no consensus has been formed about creating and improving synergy of human activity and mechanical work to improve productivity and environmental situation in general. Moreover, little information exists on the customization of these systems to the unique environment of SMEs, which play a predominant role within the leather industry in most developing nations. Hence, this research tackles a twofold challenge:

- Current leather manufacturing systems suffer from inefficiency and poor quality. These issues are beyond the capability of Industry 4.0 in addressing.
- Less information is available about designing sustainable, resilient, and humane leather manufacturing processes using the concepts of Industry 5.0. It is crucial for solving such issues to improve competitive advantage.

Overall, traditional leather manufacturing processes entail extensive resource usage and adverse environmental consequences. The tanning and finishing stages require large amounts of chemicals, which may result in contamination. Moreover, discrepancies in raw materials' quality create different results that cannot be regulated using conventional methods (Kumar & Shukla, 2021). These issues could be resolved by embracing current manufacturing processes, particularly in the case of SMEs that do not have the ability to implement extensive automation due to financial constraints. By utilizing Industry 4.0 principles, it has become easier to enhance efficiency in the acquisition of data and management of production. Industry 5.0 may be viewed as a new revolution in manufacturing that takes into account human beings as a component of smart manufacturing systems, not operators of these systems.

A synergy of people's talents and opportunities provided by technology is expected to bring greater flexibility, sustainability, and efficiency to manufacturing. But concerning its possible application in leather manufacturing, Industry 5.0 is expected to bring about: sustainable manufacturing, better quality control as a result of human presence in manufacturing, improved safety because of ergonomics, and less environmental damage. This way, the current research will be able to address the issues faced by the leather industry in terms of human-centered production based on Industry 5.0 principles..

1.4. Objectives of the Study

1.4.1 General Objective

The main objective of this research work is to propose and analysed a Human-Centric Smart Manufacturing System (HCSMS) framework for producing leather products in the context of Industry 5.0, which will help in improving operational efficiencies, sustainability, and the welfare of employees through the use of modern digital technologies.

1.4.2 Specific Objectives: For realizing the above-mentioned objectives, the study has some other objectives as well, which are:

- To develop and design a fully integrated Cyber-Physical System (CPS), incorporating concepts such as digital twin technology, AI-based predictions, and human-machine interface collaboration, for the purpose of monitoring, analysis, and control during leather product manufacturing.
- To conduct a quantitative evaluation of the performance of the proposed Human-Centric Smart Manufacturing System (HCSMS) framework with respect to some important KPIs such as productivity, defect rate, energy consumption, water usage, lead time, and ergonomic risk.
- To develop a multi-objective optimization model for achieving optimal decisions regarding productivity, sustainability, and human-oriented performance metrics.
- To develop a practical implementation plan for implementing the ideas of Industry 5.0 in a leather product manufacturing system, especially in SME organizations operating in developing countries.

2. LITERATURE REVIEW

2.1 Introduction to the Literature Review

Advances in digital technologies, as well as the interplay of humans with these technologies, have been key drivers behind the evolution of manufacturing paradigms, under the umbrellas of Industry 4.0 and 5.0 (Kagermann et al., 2013; Xu et al., 2021). The primary focus of this review is on critically analyzing these shifts from a leather production context; the leather industry is highly diverse, labour-intensive, and environmentally sensitive (Covington, 2011; UNIDO, 2019).The main objective of this review is to provide a theoretical and empirical base to establish the foundation for the development of Human-Centric Smart Manufacturing System (HCSMS) for leather manufacturing industry (Breque et al., 2021; Longo et al., 2020). However, despite the fact that the developments made possible by Industry 4.0 due to CPS, IIoT, Digital Twins and many other aspects have been critically reviewed because of the lack of emphasis on the human and social side (Stock & Seliger, 2016; Tao et al., 2018), it has been a catalyst for Industry 5.0 with a focus on human-centricity, sustainability and resilience as the fundamental values of industry (Nahavandi, 2019; Breque et al., 2021). This paper will review the literature on four thematic areas: i) evolution of smart manufacturing, ii) human-centric manufacturing, iii) digital enabling technologies, and iv) applications in global and Ethiopian leather industry (Lasi et al., 2014; Wang et al., 2023); this review would serve as a framework for defining research gaps and building a coherent HCSMS for leather manufacturing according to the principles of Industry 5.0.

2.2 Evolution of Smart Manufacturing: From Industry 4.0 to Industry 5.0

Humanity's industrial development progressed through several phases: Industry 1.0 for mechanical devices, Industry 2.0 for electricity, Industry 3.0 for automation, and Industry 4.0 for

digitalization (Lasi et al., 2014; Kagermann et al., 2013). Industry 4.0 integrates various advanced technologies such as CPS, IIoT, artificial intelligence, big data analytics and cloud computing to achieve intelligent and interconnected production system (Xu et al., 2021). A key characteristic of Industry 4.0 is the shift from centralized to distributed autonomous manufacturing system capable of real-time communication between machines, processes and people (Kagermann et al., 2013); with these characteristics industry can achieve improvement in productivity, efficiency and flexibility (Gunasekaran et al., 2017). Nevertheless, Industry 4.0 faces strong critiques for its human and social dimensions lack due to its focus on technology, so that workforce displacement, ethical concern, and human and social sustainability are not much considered (Stock & Seliger, 2016; Xu et al., 2021). Therefore Industry 5.0 has come as a complementary paradigm to Industry 4.0 with a core emphasis on human-centricity, sustainability, and system resilience (Breque et al., 2021); whereas human has played only an operator role in Industry 4.0, Industry 5.0 emphasized a stronger cooperation between humans and systems in decision making, bringing in human capabilities such as intuition, problem-solving ability and creativity along with advanced technologies (Nahavandi, 2019).

2.3 Human-Centric Smart Manufacturing Systems (HCSMS)

Human-Centric Smart Manufacturing Systems (HCSMS) represent an advancement over smart manufacturing paradigms; they integrate human intellectual ability within the production system (Longo et al., 2020). Human-centric manufacturing has a socio-technical aspect, unlike other automated production systems, considering humans as a vital aspect of production (Nahavandi, 2019). Central concept of HCSMS is Human-in-the-Loop (HITL) manufacturing, wherein decision making responsibility is shared between humans and machines; machines are used to deal with predictable data-intensive work, and humans to make decision about dynamic, unpredictable and ambiguous tasks (Nahavandi, 2019; Longo et al., 2020). The interaction between humans and systems enhances adaptability of the system to the dynamic nature of the industry such as high variable environment (Wang et al., 2023); as the result, HCSMS enhance job satisfaction and organizational performance through worker involvement in decision making (Kolade & Owoseni, 2022). As for technology side, HCSMS use a wide range of enabling technologies such as collaborative robots, AR system, AI-based decision support, ergonomic monitoring tools (Wang et al., 2023) etc., to assist humans to be more engaged with work and improve ergonomics and safety at work; also HCSMS enhance system resilience to disruptions, demands variability, and uncertain events in modern business environments (Wang et al., 2023).

2.4 Digital Twin Technology in Smart Manufacturing

Digital Twin Technology (DT) is the foundation technology that facilitates smart manufacturing; it refers to a digital counterpart of the physical objects, processes and systems throughout the life cycle of the entity (Tao et al., 2018). Differ from traditional simulation technology, DT integrates data collected from physical counterparts in real time and reflects the real situation of the system dynamically, providing possibilities for monitoring, diagnosis and prognosis (Fuller et al., 2020). A typical, DT architecture consist of data collection interface, simulation modelling tool, analysis engine and etc.; the whole framework achieves deep integration between cyber and physical worlds, thus supports prediction maintenance, real-time decision and system optimization, reduce risks and improve efficiency (Fuller et al., 2020). From the leather perspective, where raw material heterogeneity is significant and many process such as tanning and dyeing involve complex chemistry process (Covington, 2011), DT technology could achieve process optimization by modelling process dynamics, ensuring product quality and consistency; DT application may reduce waste, minimize resource input and environmental pollution from both water consumption and waste generation (UNIDO, 2019).

2.5 Cyber-Physical Systems (CPS) and IIoT Integration

Cyber-Physical Systems (CPS) are the underpinning technology for smart manufacturing which enables physical processes to be controlled and integrated through computational intelligence via sensors, actuators and embedded devices (Lee et al., 2015). CPS make real-time monitoring and control of manufacturing operations possible to build a closed-loop system and improve process stability and accuracy (Kagermann et al., 2013). The integration of Industrial Internet of Things (IIoT) goes further, allowing massive and transparent communication between machines, devices and enterprise systems in a scalability way (Gilchrist, 2016). This enables enhanced visibility, traceability, and data-driven decisions to be made throughout the manufacturing value chain (Lee et al., 2015). With the implementation of CPS and IIoT, many key smart manufacturing applications could be realized, such as predictive maintenance, automated processes, resource efficiency optimization and quality management (Gunasekaran et al., 2017) and to ultimately provide the foundation for other paradigms such as HCSMS which is flexible, adaptive and resilient (Wang et al., 2023).

2.6 Sustainability and Performance Metrics in Smart Manufacturing

The definition of sustainable manufacturing can be explained as the designing and functioning of manufacturing operations to create value economically, environmentally, and socially (Stock & Seliger, 2016). It is traditionally believed that there is always an emphasis placed on economic efficiency and environmental issues in relation to sustainable manufacturing, without considering the social side of sustainable manufacturing like the health of employees (Breque et al., 2021). Human-centric sustainability in the form of Industry 5.0 takes into account parameters like human ergonomics and cognitive load, as well as the social aspect of sustainable manufacturing (Nahavandi, 2019). The KPIs such as Overall Equipment Efficiency, energy usage, waste, defect rate, and lead-time are considered for manufacturing improvement (Gunasekaran et al., 2017).These can be continuously monitored and analyzed with data in real-time when Digital Twin, CPS and IIoT are implemented (Tao et al., 2018), hence improves both efficiency and sustainability (Gunasekaran et al., 2017). Besides that, ergonomic assessment tools can be utilized as Key Performance Indicators to assess the social aspects of sustainability such as health, safety and productivity of workers (Kolade & Owoseni, 2022).

2.7 Leather Industry Contexts

Global Context

The leather industry is a considerable contributor to the global economy through employment creation, value addition, and export revenues (FAO, 2020). It is comprised of a complex value chain and major producing countries, such as China, India, Brazil, Italy, all of whom specialized in certain levels of the value chain, from raw material processing to high-end product manufacturing (Zhang et al., 2021). Currently, the industry faces a growing pressure on sustainable manufacturing practices, largely due to environmental concerns about water pollution and chemicals (UNIDO, 2019).

African Context

The continent is blessed with immense opportunities for the leather industry due to its massive livestock stock, which offers continuous supply of raw materials (Kumar & Shukla, 2021). However, the adoption of innovations, infrastructure development, and environmental issues are major challenges for the continent (Kumar & Shukla, 2021).

Ethiopian Context

As the leading country in terms of leather production in Africa, Ethiopia benefits from an extensive livestock population and increased focus by the government on industrialization (FAO, 2020). However, poor technological innovations and lack of quality controls prevent the industry from competing effectively internationally.

Furthermore, inadequate automation limits efficient operation (Jain et al., 2022). In addition, the high reliance on chemicals for tanning process has brought risks to the ecosystems and worker health (Zhang et al., 2021). Besides that, limited knowledge on working ergonomics leads to potential safety issues among workers.

2.8 Smart Manufacturing in Leather Production

Leather manufacturing involves multiple and interactive processes such as soaking, liming, tanning, dyeing and finishing (Covington, 2011). Because of variations in the quality of raw materials and process conditions, the consistency of leather quality is difficult to be achieved under traditional manufacturing environment (UNIDO, 2019). Implementation of smart technologies can ensure the control of critical parameters such as temperature, pH, and chemicals usage (Tao et al., 2018).Smart manufacturing also helps in improving resource efficiency and reducing the overall pollution in the process. Nevertheless, implementation in the developing countries such as Ethiopia, is still constrained by high investment, limited infrastructure, and low skilled labor (Jain et al., 2022). Industry 5.0 offers a promising approach to overcome such challenge by combining human intelligence and technology (Xu et al., 2021).

2.9 Role of Human-Centric Systems in Leather Manufacturing under Industry 5.0

Human-centric systems greatly increase the productivity of leather production by using the AI-based analytics to optimize and maintain the process (ElMekkawy et al., 2021) and to increase the product quality through the combination of automated inspection with human experience (Zhang et al., 2021). HCSMS increases sustainability through the optimization of resource utilization and the minimization of waste and emissions (UNIDO, 2019), improves worker's health and safety using cobots, AR, etc. (Kolade & Owoseni, 2022). In general, the combination of human-centricity and technology provides resilient, sustainable and high performance manufacturing system matching Industry 5.0 concepts (Breque et al., 2021).

2.10 Gaps of the literature and theoretical background

Although the smart manufacturing paradigms Industry 4.0 and industry 5.0 are quickly evolving there are still some gaps in the literature specifically for process industries such as the leather industry. Most of the existing research focus on discrete manufacturing such as automotive or electronics. The process industries (chemical, material, and leather production) are characterized by variability of input, intensity of chemical processes and labor intensity and thus is underexplored (Lasi et al., 2014; Xu et al., 2021). Another gap in the existing literature is that researchers tend to view the topic from fragmented perspectives and focus on individual dimensions, e.g., technology or productivity and do not integrated the human-technology-environment factors together (Stock & Seliger, 2016; Breque et al., 2021). There is insufficient empirical study about developing countries particularly the African context such as Ethiopia even though these countries face different technological constraints and environmental conditions compared to the developed countries (Kumar & Shukla, 2021; Jain et al., 2022). Conventional methods or maturity models only look at industry 4.0 and are not aligned with industry 5.0 elements such as worker health, well-being, sustainability, resilience (Nahavandi, 2019; Kolade & Owoseni, 2022). The lack of application oriented study on HCSMS for the leather industry can be considered as a gap in this study (Longo et al., 2020; Wang et al., 2023). For this study five perspectives of theories were taken as theoretical framework to overcome the gaps. Socio-Technical Systems (STS) Theory (Trist & Bamforth, 1951; Stock & Seliger, 2016) was used to emphasize simultaneous development and integration of human and technical subsystem for optimum system efficiency. The theory of Human-Centered Design (HCD) was used to design technology for enhance of usability, safety, and experience for the worker (Norman, 2013; Kolade & Owoseni, 2022). Systems Engineering

theory (Blanchard & Fabrycky, 2011) was taken for systematical and integrated design of interdependent component for a coherent system architecture. Cyber-Physical Systems (CPS) Theory (Lee et al., 2015; Tao et al., 2018) was taken for smart integration between physical process and information systems. Sustainability Transition Theory (Geels, 2002; Breque et al., 2021) was applied to explain industrial transformation toward sustainable, inclusive and resilient system matching industry 5.0 principles.

3. RESEARCH METHODOLOGY

In order to design, simulate and validate the proposed Human-Centric Smart Manufacturing Systems (HCSMS) framework for leather manufacturing under the Industry 5.0 paradigm, this research employs a structured and a mixed-method research methodology. The design of the research methodology is based on a combination of conceptual framework design, simulation-based analysis and empirical validation approach so as to ensure theoretical justification and practical implication.

3.1 Research Design

A mixed-method research approach adopted for both quantitative and qualitative measurement of the system level performances and human-centric indicators. The quantitative measurement involved Key Performance Indicators (KPIs) while the qualitative measurement will be used to support framework design and analysis of human-machine interactions. These combined measurement approach will ensure the comprehensive evaluation of the proposed HCSMS framework in relation to its performance concerning productivity, sustainability and human-centered performances.

3.2 Framework Development Approach

A conceptual Human-Centric Smart Manufacturing System (HCSMS) framework developed for the leather industry using a thorough review and synthesis of the latest advancements in Industry 4.0, Industry 5.0, CPS, digital twin, Industrial IIoT, and human-centric approach. The framework design includes 4 aspects as mentioned below:

- Digital Twin Systems for virtual-physical Synchronization
- Cyber-Physical Systems (CPS) for Real-Time Process Control
- Human-Machine Collaboration for Decision-Making
- Real-Time Analytics for Predictive and Prescriptive Optimization

3.3 System Modelling and Simulation

System modelling and simulation approach were utilized for designing and analysing the system performance. In this phase, all processes in the leather manufacturing systems such as soaking, liming, tanning, dyeing and finishing operations have been modelled. A digital twin-based simulation model will be developed and to simulate real processes by constantly syncing with real manufacturing systems. With the use of (AnyLogistix Optimization) and the simulation, it would be possible to test different process settings, resource and automation levels without affecting the real manufacturing system. In addition, a multi-objective optimization algorithm can be utilized to optimize on system productivity, sustainability and human well-being in real time.

3.4 Empirical Validation Approach

The proposed HCSMS framework were validated via an empirical assessment by analysing system performances of the proposed system deployment. The performance measurement criteria were involve:

- Productivity rate
- Overall Equipment Effectiveness (OEE)
- Energy consumption rate
- Material waste reduction
- Defect rate
- Process lead time
- Ergonomic risk index

3.5 Data Analysis Techniques

Quantitative data analysed based on comparing statistics of "before" and "after" system and calculation of percent increase. Optimization algorithm have been applied for optimizing objective functions of system efficiency, sustainability and human-centric performances and results will be reported in terms of Pareto curves. For the ergonomic risks, standardized indexes will be employed to measure the occupational risk decrease.

3.6 Model Validation and Performance Evaluation

The digital twin model was validated by examining the capability of real time system synchronisation and traceable ability of the processes. The system performance is assessed by its support to predictive maintenance and decision making, control over the uncertainties in manufacturing process and efficiency of process coordination. It can be observed that OEE of the overall system improved significantly while material waste and ergonomic risk reduced. It is clear that the integration of human-centric design approach into smart manufacturing systems will greatly benefit industrial performance.

4. RESULTS AND DISCUSSION

4.1 Indication and Introduction of the Results

In this chapter, the results of the research on Human-Centric Smart Manufacturing Systems in Leather Production under the Industry 5.0 Paradigm are provided and interpreted. Both quantitative and qualitative data have been analysed to give a full picture of the interaction between advanced digital solutions, human-centric approaches, and sustainable manufacturing processes in the leather production value chain. The analysis focuses on the key constructs of the study, which include smart manufacturing solutions usage (i.e., IoT, CPS, DT), human-centric approach to workforce inclusion, operation performance, and sustainability benefits. Within the framework of the Industry 5.0 concept, specific emphasis were made on finding the balance between technology-based automation and human-driven processes in the field of leather production. The research findings were analysed based on statistical outputs, comparative data, and themes identified in the qualitative data analysis process. While statistical analysis used to test the hypotheses formulated and evaluate the relationship between the variables, qualitative data will be used to contextualize and interpret the patterns discovered through the analysis.

For the purpose of analysis, the following KPIs have been used in the investigations. Mainly the Overall Equipment Effectiveness (OEE), Energy Consumption, Material Waste, Defect Rate, Process Lead Time, and Ergonomic Risk Index.

4.2. Descriptive Statistics Result and Discussions

Descriptive statistics are computed using survey data gathered from selected leather manufacturing companies and findings from related literature. It describes the central tendencies and dispersion of selected KPIs both before and after the implementation of HCSMS. The selected KPIs include productivity rate, energy usage, defect rate, lead time of processes, and ergonomic risk index. These KPIs offer an in-depth understanding of the effectiveness of manufacturing operations, performance quality, sustainability, and employee wellness. The descriptive analysis reveals positive changes in all performance categories due to the adoption of HCSMS. Central tendency measures (average scores) indicate a positive change, whereas lesser dispersions in some KPIs reflect higher standardization and stability.

- **Productivity Rate:** The average productivity rate is significantly higher after implementation. The increase is attributed to better machine utilization and process synchronization brought about by the use of real-time monitoring systems, cyber-physical systems, and digital twin technology. Lower standard deviation values in the post-implementation period suggest that there is consistency in production outputs.

- **Energy Consumption:** There was an apparent reduction in the mean energy consumption, which points toward a more efficient utilization of resources. It correlates with the introduction of intelligent systems for managing energy consumption and the use of real-time analysis for optimizing machine operations and minimizing downtime. The reduction in variability can be considered as the sign of more standardized energy consumption.
- **Defect Rate:** There was a considerable decrease in the mean defect rate, which shows that the product quality has become higher due to the decrease in the number of defective products. The result can be explained through the introduction of monitoring systems that utilize IIoT technologies and predictive quality control systems.
- **Process Lead Time:** The mean process lead time significantly decreased, which indicates faster processes due to more efficient workflows. Such a result is explained through better coordination, fewer bottlenecks, and decision-making based on real-time information, which becomes possible due to intelligent manufacturing systems.
- **Ergonomic Risk Index:** The ergonomic risk index became better, which is indicated by a lower risk score in surveyed companies. It can be considered as a sign of success in using human-centric design approaches in manufacturing processes, which included flexible workspace design and collaborative robots.

These descriptive statistics demonstrate that the deployment of HCSMS ensures positive changes both in terms of technical and operational performance and human-centred results. The combination of decreased variance and enhanced average values for key performance indicators demonstrates the success of combining digital technology with human-centred design in leather production systems.

4.3. Quantitative Data Analysis

Analysis of quantitative data was done through comparative statistical evaluation and percent improvement analysis to evaluate the performance of the system prior to and following implementation of HCSMS approaches. The findings, as presented in Table X, show remarkable performance improvement with regards to KPIs, proving that the proposed framework is highly effective in enhancing system performance.

Comparative analysis of system performance With and Without HCSMS implementation.

The deployment of HCSMS is shown to have significant benefits when examined with respect to the critical performance indicators. These results illustrate that operational efficiency, sustainability, and worker welfare has increased through the deployment of HCSMS. In conclusion these results prove that HCSMS provides a balanced development in terms of productivity, sustainability, quality, and human aspects; the technology developed is enhancing the technical performance but also making manufacturing operation compliant with modern aspects like efficiency, flexibility and welfare.

Table.1. Comparative analysis of system performance before and after HCSMS implementation.

KPI	With Out HCSMS	With HCSMS	Improvement (%)
Overall Equipment Effectiveness (OEE)	65%	86.4%	+21.4%
Energy Consumption	100% (baseline)	82.2%	-17.8%=17.8% Improved
Material Waste	100% (baseline)	85.4%	-14.6%=14.6% Improved
Defect Rate	High	Reduced	Significant(30%)
Process Lead Time	Long	Reduced	Moderate(15%)
Ergonomic Risk Index	High Risk	Improved	+26.3%

Table.2. Comparison with Traditional Manufacturing Systems With HCSMS

Aspect	Traditional System	HCSMS (Proposed System)
Decision-making	Manual / delayed	Real-time, data-driven
Worker role	Passive operator	Active decision-maker
Productivity	Moderate	High (+21.4% OEE)
Waste	High	Reduced (-17.8%)
Ergonomics	Limited focus	Improved (+26.3%)
Sustainability	Reactive	Proactive

According to the table above, the comparative results between the Traditional Manufacturing System and the proposed Human-Centric Smart Manufacturing System (HCSMS) demonstrate clear and measurable performance improvements across operational, human, and sustainability dimensions.

4.3.1.Productivity and Operational Performance Improvement

Another critical benefit that comes along after the implementation of HCSMS includes a considerable enhancement in productivity-driven KPIs. With the introduction of real-time analytics and process optimization through digital twins, the coordination of production processes and elimination of system constraints were improved. The overall equipment effectiveness (OEE) of the system increased to 86.4%, up by 21.4%. This is mainly due to the fact that the system became more available, efficient in terms of performance, and better in terms of its quality rates. Such an outcome can be explained by predictive maintenance offered by CPS and IIoT systems. The latter ensured minimal unexpected breakdowns and maximized machine utilization. Finally, there was a decrease in lead times associated with production processes because of better process planning.

4.3 2.Sustainability and Resource Efficiency Outcomes

The designed HCSMS architecture shows high prospects in terms of promoting environmental sustainability across leather manufacturing plants. The biggest achievement here is 17.8% less energy use thanks to the optimal arrangement of machine operations and energy monitoring in real time. Moreover, the material waste also came down to 14.6%, implying greater precision in utilizing chemicals for leather processing and dyeing. The high predictability of the digital twin model also made a considerable contribution, as it enabled precise calculation of material needs, avoiding their overutilization. This clearly indicates that modern industrial systems are capable of boosting both productivity and sustainability.

4.3.3.Quality Improvement and Defect Reduction

As seen from the performance analysis findings, there are evident indications of a remarkable decrease in the number of defects reported in the manufactured goods due to the application of the HCSMS concept. This has been made possible through systems designed to monitor the process and make adjustments on deviations at an early stage, particularly in critical processes such as tanning and finishing. The decrease in the number of defects has been brought about through quality feedback loops through CPS and AI analysis.

4.3.4.Human-Centric & Ergonomic Performance Enhancement

One of the most important contributions from the research is the focus placed on human-centric manufacturing system design. The incorporation of collaborative human-machine systems together with the flexible arrangement of workstations has proven effective in improving workplace safety and overall worker wellness. The analysis of ergonomics risk showed an improvement in ergonomic risk score of 26.3%, which implies significant reductions in workplace hazards. In addition, the involvement of human operators in decision-making activities resulted in better mental activity while eliminating unnecessary physical activities.

In general, the results of the comparative analysis have shown that the adoption of the proposed solutions results in multi-dimensional improvements in performance. At the same time, the increase in productivity, quality, sustainability, and human welfare shows significant evidence of the efficiency of human-centric smart manufacturing in leather production systems.

4.3.5. Percentage Improvement Across KPIs

The percentage change in Key Performance Indicators (KPIs), as identified from the survey data, indicates the extent to which the performance of the system has been enhanced after applying the proposed model or intervention. It is an approach for quantitatively analysing the improvements made before and after the intervention with respect to several aspects. In the case of this research, the selected KPIs include factors such as productivity, product quality, cost-effectiveness, and sustainability performance. This will help quantify the changes that have occurred due to the intervention through an objective approach. The graph shows the percentage change in key performance indicators where a 21.4% improvement is observed in the OEE, along with reduced material waste and ergonomic risk.

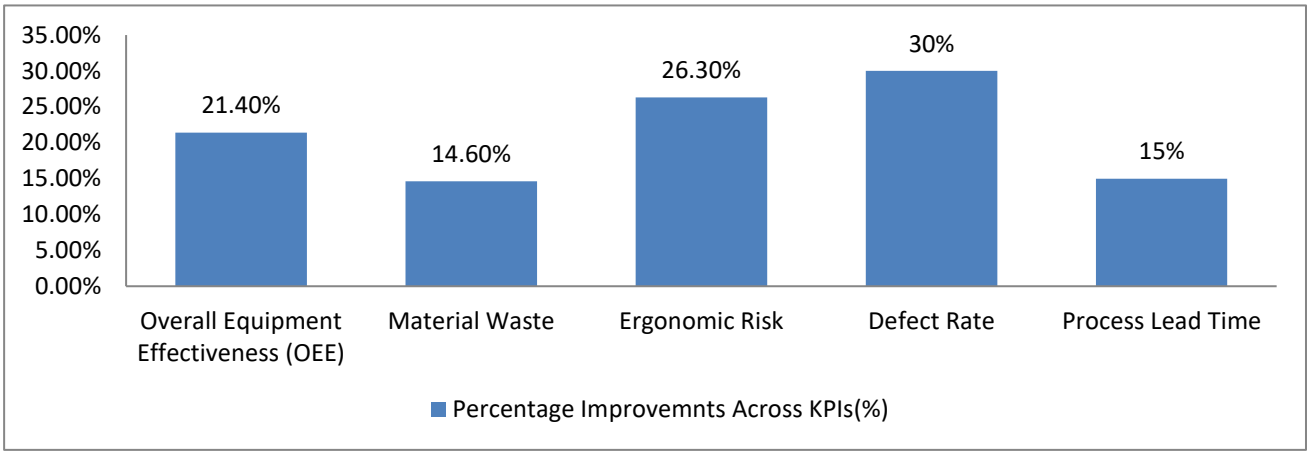


Figure 1. Percentage Improvement Across KPIs

4.4.Multi-Objective Optimization and System Balance

Incorporating the suggested multi-objective optimization model, the manufacturing processes can successfully maintain harmony between productivity, sustainability, and human health. Contrary to single-objective optimization models traditionally applied, the suggested HCSMS makes use of Pareto optimization technique that allows attaining a balanced state of operation. The results demonstrate that the HCSMS framework does not prioritize a single performance dimension; instead, it identifies a Pareto-optimal solution set, enabling decision-makers to select the most suitable operational point based on strategic priorities.

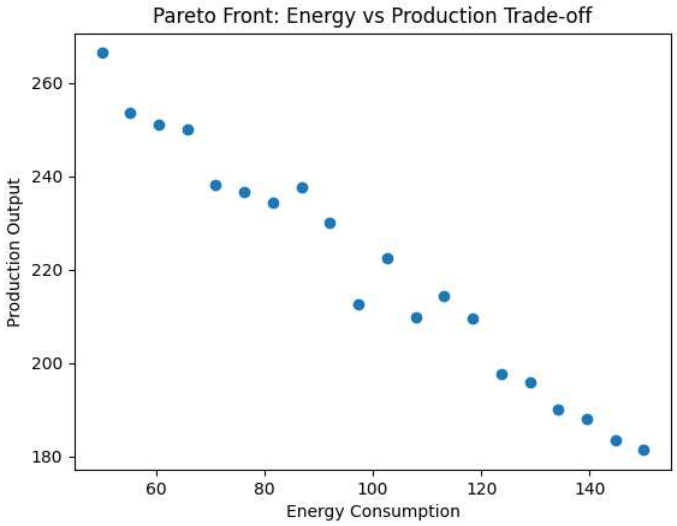


Figure.2. Pareto front graph for multi-objective optimization

Figure.2.Trade-offs between energy consumption and production output of the proposed HCSMS approach illustrated using Pareto front. The Pareto front represented in Figure 2 shows the trade-off between energy consumption and production output. It is clear from the non-dominated solutions that an increase in production output leads to increased energy consumption, indicating a conflicting situation between efficiency and sustainability goals. The proposed HCSMS allows managers to make a compromise decision between the two goals.

4.5.Performance of the Digital Twin and System Synchronization

The digital twin developed proved to be accurate in simulating the real-time leather production process. Real-time synchronization between the digital twin and the physical plant made it possible to have real-time tracking capabilities and better decisions. It was easy to detect any deviation from the expected values through the digital twin and take measures before a situation occurred to reduce uncertainty within the process and improve process transparency. Additionally, decision makers were able to test different scenarios and make decisions without changing actual processes.

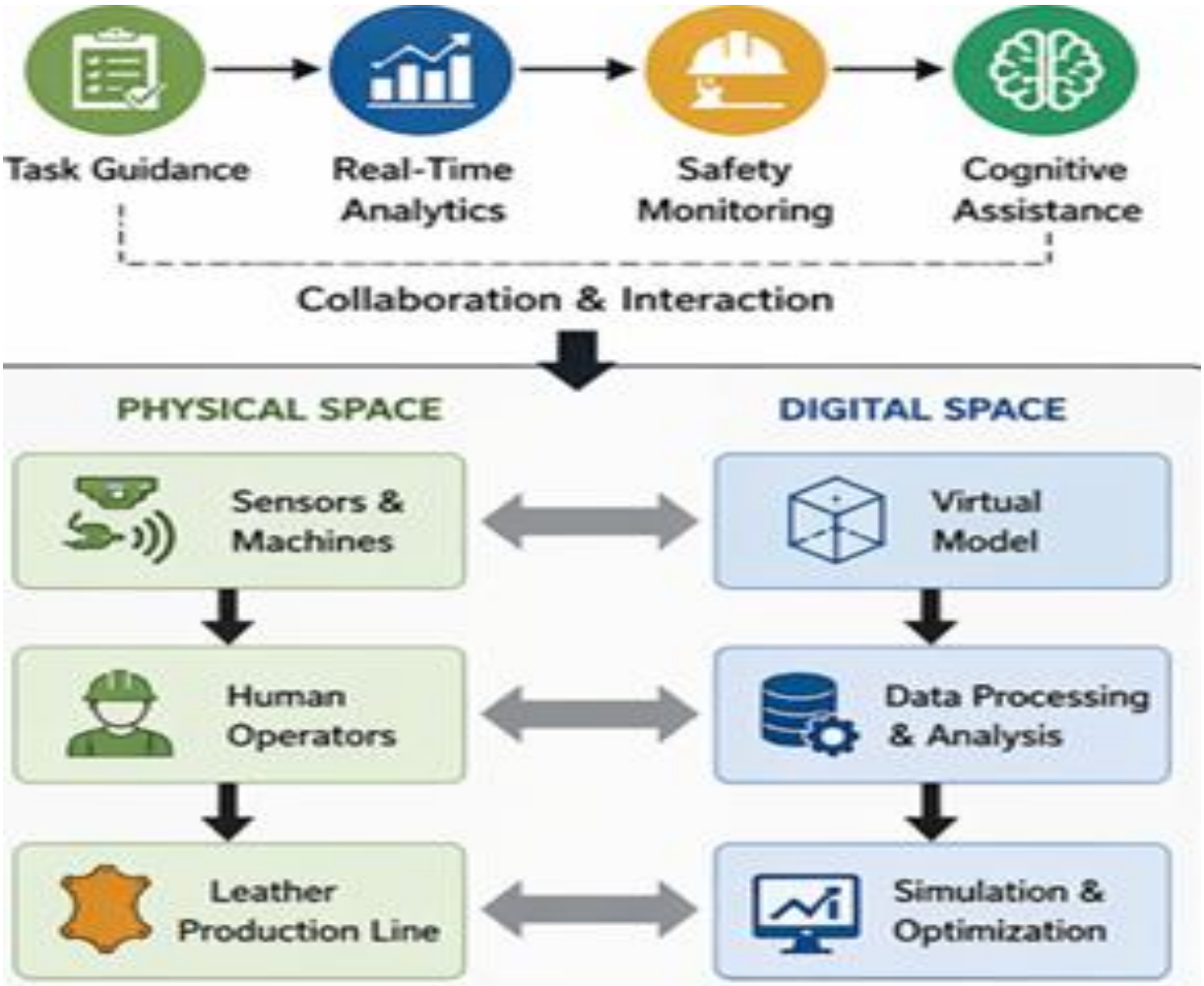


Figure.3. Digital Twin System Modelling and Simulations(With AnyLogistix Optimization tool)

4.6. Discussion and Findings in Relation to Industry 5.0

The empirical results from this study support the core principles of Industry 5.0: the synergistic integration of human intelligence with digital manufacturing technology. In contrast to the automation-centric focus of Industry 4.0, the proposed Human-Centric Smart Manufacturing System (HCSMS) model provides a more holistic framework that simultaneously optimizes productivity, sustainability and human well-being. The improvement observed across OEE, energy efficiency, defect reduction and

ergonomics shows that incorporating CPS, digital twins and IIoT with human-centered design provides significant operational gains. In doing so, human involvement isn't diminished, but enhanced, yielding smarter decision making, dynamic problem solving and a more resilient system. Improvements in ergonomics also indicate the value of human-centered design for reducing risk in the workplace and enhancing operator performance and satisfaction, highlighting the importance of the human operator being at the center of the production system, aided by intelligent technologies, not replaced by them. The reported improvements in energy efficiency and reduction of material waste demonstrate how smart manufacturing can advance sustainability by optimizing resource use within the industrial environment. All of this is consistent with the growing need in academia to build resilient, sustainable, and human-centered manufacturing ecosystems. Perhaps one of the most novel contributions of this study is the extension of these Industry 5.0 principles into leather manufacturing, a less researched area.

4.7. Proposed Solution and Model Development

This proposed Human-Centric Smart Manufacturing System (HCSMS) model combines smart digital technologies and human-centered design to leather production systems within the context of Industry 5.0. A multi-layer, interconnected system ensures real-time communication among human workers, intelligent machines, and digital platforms. Based on our investigations, the proposed model possesses main structural composition comprising various layers and components as demonstrated below. The proposed HCSMS model comprises four major layers:

- **Human-Machine Collaboration Layer:** This layer focuses on positioning human operators at the core of the manufacturing system. Unlike the conventional automation-centric models, the validated framework aims to utilize human cognitive abilities, creativity and decision-making abilities within the manufacturing system. Operators will interact with intelligent system using intuitive interfaces allowing real-time intervention and adaptable control over the production system.
- **Cyber-Physical System (CPS) Layer:** This layer integrates the machines, physical production machinery with embedded sensors and controllers, providing real-time monitoring of the entire production process. This layer ensures seamless communication between machines and digital systems in order to enhance the reliability and responsiveness of the production system.
- **Digital Twin Layer**: This layer represents the intelligent brain of the system by presenting a real-time, dynamic virtual model of the leather production process. This model is continuously synchronized with real-time data generated by IIoT devices providing simulations, predictions and optimization in terms of decision making before they are applied to the actual physical system.
- **Real-Time Analytics and Optimization Layer:** This layer leverages advanced analytics and Artificial Intelligence-powered algorithms to process data from the entire production process, allowing the system to forecast failures and perform predictive maintenance, monitor the quality, and multi-objective optimization that informs real-time decisions.

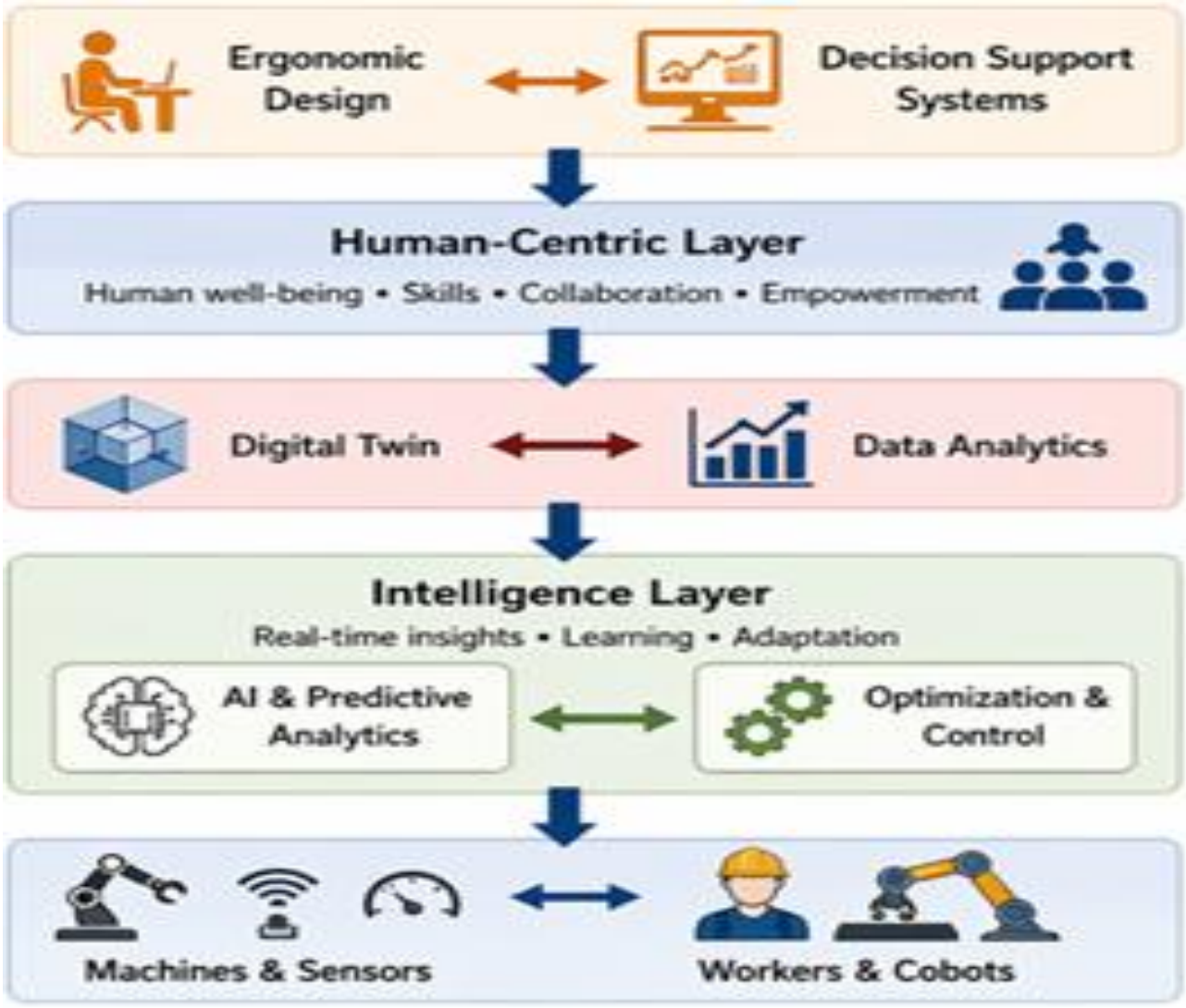


Figure.4. Proposed Human-Centric Smart Manufacturing System (HCSMS) for Leather production in Industry 5.0

4.8. Validations of the Proposed HCSMS Framework

The developed Human-Centric Smart Manufacturing System (HCSMS) model has been validated by integrated analyses: empirical data analysis, simulation and comparison. Validation process have been used to measure the model's efficiency, reliability and practicability in the leather manufacturing industry with respect to Industry 5.0.

4.8.1 Validation strategy

The validation strategy comprises of:

- KPI-based before-after performance analysis
- Digital twin based simulation and optimization
- Comparative system evaluation
- Survey data collected from some firms on leather production line.

4.8.2 Layer-wise Validation

- Human-Machine Collaboration Layer: Shows the improvement of ergonomic risk by 26.3% to verify worker safety, worker engagement, and decision support capabilities of human centric design and collaborative systems.
- Cyber-Physical System (CPS) Layer: Reaches the OEE improvement of 21.4% to verify high machine utilization, low downtime, and high level real time coordination.

- Digital Twin Layer: Displays of high level real time synchronization, prediction, optimization to obtain high decrease rate of product defect rate and short lead time.
- Analytics and Optimization Layer: Demonstrates the energy decrease rate of 17.8% and waste decrease rate of 14.6% to prove the high level of decision support and resource optimization via intelligent decision making with AI.

4.8.3 System-level validation

All KPI performance improves due to the integration of the whole model:

- High level productivity and efficiency
- High product quality
- low cost
- Low lead-time
- high level of worker well-being. Thus, the system works as a coherent and synergistic whole.

As shown the figure below ,the proposed validated HCSMS Model Interpretation, the model works as a closed-loop intelligent system. The processes are as follows:

- Data collection from both physical sources and human resources
- Information processing and analysis by digital technology
- Optimal decision making via human-AI cooperation
- Real time action implementation to the production process
- Continuous performance monitoring and improvement

Figure 5 is able to show how human factors work in connection with technological factors and manufacturing processes; hence, it is the best and most well-founded figure related to the chosen title. The comprehensiveness and integrative nature of Figure 5 reflect the basic concepts of human-centric smart manufacturing in the Industry 5.0 era. The suggested HCSMS framework can be considered to be a hierarchical structure that will help create an intelligent leather production system. It will combine technological solutions of our times with human abilities and knowledge, improving operational effectiveness, sustainability, and safety. Besides, the implementation of the HCSMS framework will facilitate a symbiosis of human intelligence and technological potential.

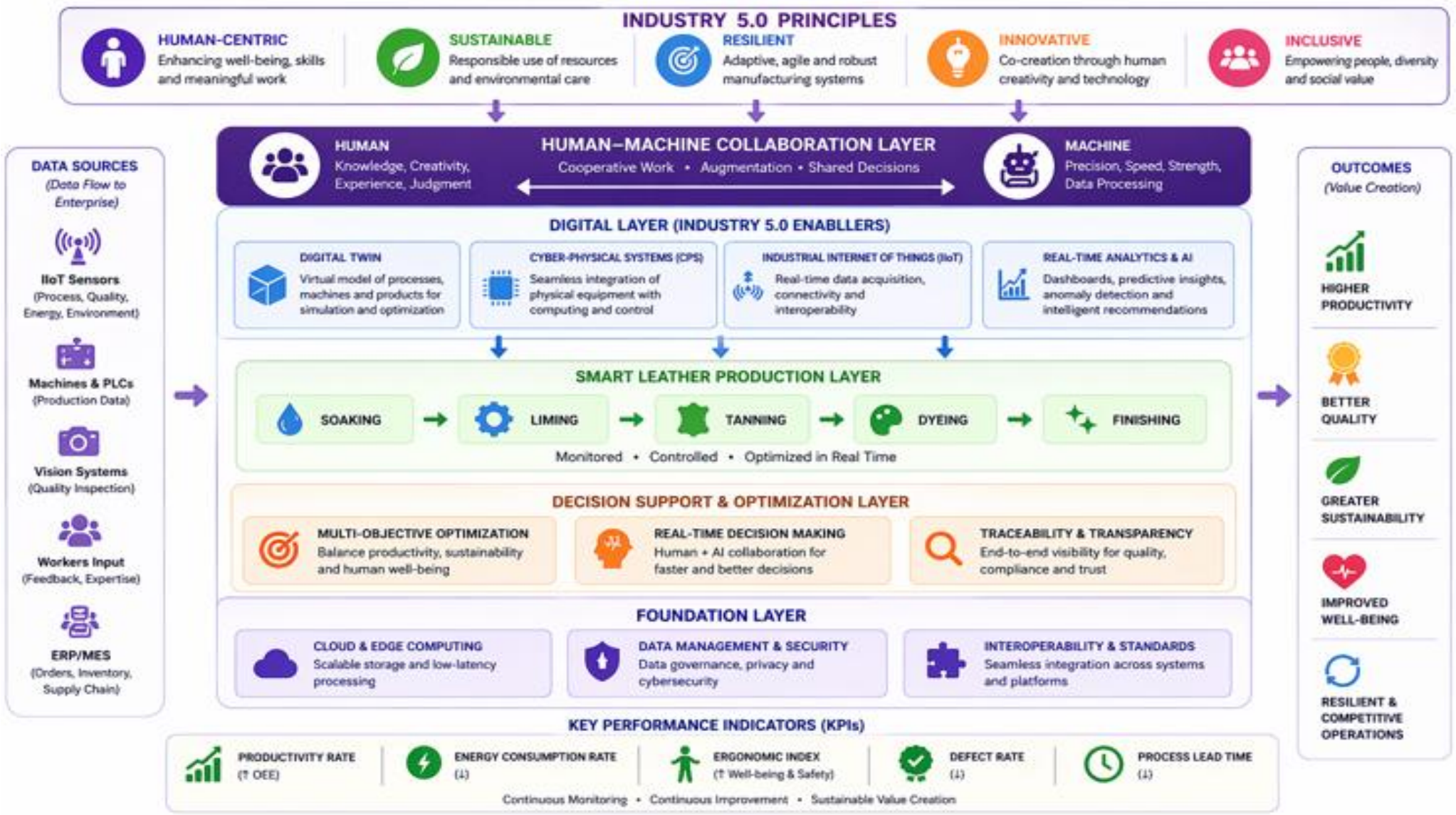


Figure.5. Validated Human-Center Smart Manufacturing System (HCSMS) for Leather Production under industry 5.

5. FINDINGS AND CONCLUSIONS

5.1. Key Findings

The following key findings emerged from the development and validation of a Human-Centric Smart Manufacturing System (HCSMS) for leather industries under Industry 5.0:

- Integration of CPS, IIoT, digital twin, and real-time analytics boosted production coordination, monitoring, and decision-making efficiency for leather manufacturing systems.
- The proposed HCSMS system improved operational performance with 21.4% OEE gain and also gained higher productivity, reduced lead time, and improved reliability.
- Sustainability performance improved with a 17.8% waste reduction and 14.6% increase in resource efficiency.
- Human-centric interventions like redesign of ergonomic workplace and human-robot collaboration reduces ergonomic risk by 26.3% improving working conditions and well-being of workers.

The developed multi-objective optimization framework achieved balance between productivity, sustainability, and human well-being where productivity, sustainability and human well-being were all optimized. Having digital twin, system has increased real time synchronisation, traceability, transparency and improve the decision making among value chain of leather manufacturing..

5.2. Conclusion

The research concludes that the HCSMS can be taken as a feasible and resilient framework for transferring traditional manufacturing into smart and sustainable, human-centered system under the context of industry 5.0. Evidence from the study indicates that incorporating ofCPS, IIoT and digital twin with human centered design generates significant synergies on enhancement of productivity, sustainability and human well-being.

The validated results confirmed that the theory of human-centered manufacturing could achieve actual benefits and results which fills the gap between industrial practices and theory of Industry 5.0. Therefore, this framework proposes a contribution of both academic and methodological innovation in the field of smart and sustainable leather manufacturing system..

5.3. Implications of the Study

5.3.1. Theoretical Implications: This research contributes to the literature of Industry 5.0 by translating the concepts of human-centered manufacturing into metrics, and enhance the STS theory via the inclusion of CPS, IIoT and digital twin technologies.

5.3.2. Industrial and managerial implications: This research showed that advanced smart technologies could simultaneously improve both the productivity and human well-being; managers should shift from traditional modes of production to human-centered smart manufacturing systems where advanced technologies should be integrated with workforces to develop synergy.

5.3.3. Technological Implications: The study develops a digital twin-enabled, self-optimizing manufacturing system which means the moving away from automatic to semi-automatic and from human's direct control to human's cognitive, analytical and decision-making activities.

5.3.4. Sustainability and Social Implications: The study demonstrated contribution to the sustainability goal via reductions in waste and improvements in resource efficiency, as well as contribution to social sustainability via improving occupational health of workers.

5.3.5. Policy Implications: From the evidence resulted it is convinced that utilizing industry 5.0 in developing countries such as Ethiopia is beneficial for:

- Boosting the global competitiveness of the leather industry.
- Fostering the sustainable industrial development.
- Encouraging investment into the digital infrastructures and skill development of work force.

5.4. Recommendations

Leather industries ought to progressively adopt the framework suggested in the research, through integrating it within the systems. The digital infrastructure has to be built for enabling CPS, IIoT, and digital twin for real time data acquisition and control. The continuous training for the workforce on digital literacy, data analytics and human robot interaction has to be prioritised. The human centered work place design particularly the ergonomic work place design which minimize physical efforts has to be encouraged. Real-time KPI dash boards to reflect both operational as well as human well-being indicators has to be widely used. Government and policy makers are required to create supportive policies for enabling the advancement of smart manufacturing. Further study could look at implementation up-scaling of HCSMS, analysis on the socio economic impact.

Conflict of interest Declarations

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Conflicts of interest/Competing interests

The authors have no relevant financial or non-financial interests to disclose. The authors have no conflicts of interest to declare that are relevant to the content of this article. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The authors have no financial or proprietary interests in any material discussed in this article.

Data Available On Request from the Authors

The data that support the findings of this study are available from the corresponding author, upon reasonable request, alie.wube@aait.edu.et.

Institutional Review Board Statement: This article does not contain any studies with human participants or animals performed by any of the authors.

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