Enhancing Energy Efficiency in the Wood Furniture Sector Through Industry 4.0: Real-Time Implementation and Case Study

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This article presents a real-time solution designed to improve energy efficiency in the wood furniture industry by leveraging Industry 4.0 technologies. The proposed system integrates intelligent sensors, augmented reality, and AI-driven energy management, utilizing artificial neural networks to monitor and optimize energy-intensive processes, particularly heating and drying. After identifying critical energy use points through site visits and thermal imaging, the system is implemented and tested in the SEREX machining workshop in Québec. The solution prioritizes thermal comfort, material quality, and energy efficiency through hierarchical control logic. Experimental results demonstrate an 86% reduction in propane consumption and a 128.05 kWh decrease in energy use, resulting in $14.85 in cost savings over a 3 h operational period compared to an unassisted operation. This reduction is achieved using a 250 000 Btu h^{-1} Modine PDP250 heater in a 120 m^{2} workshop under standard winter conditions in Québec. These findings validate the system's potential to enhance energy performance and reduce emissions in small and medium-sized enterprises. The framework provides a scalable pathway for sustainable energy management applicable across various wood manufacturing.

Energy efficiency has become a strategic priority across industrial sectors, driven by rising energy costs, environmental concerns, and increasingly stringent regulations. In the wood industry, energy-intensive operations such as drying, machining, and climate control account for a substantial share of operating expenses and greenhouse gas (GHG) emissions.[3,4] Improving energy performance in these processes is crucial for enhancing competitiveness, minimizing environmental impact, and meeting regulatory requirements.[2]

Within the wood industry, the third transformation, furniture manufacturing, stands out for its reliance on engineered wood products, such as medium-density fiberboard (MDF) and melamine. These materials offer notable advantages in terms of dimensional stability, machinability, and affordability. However, preserving their quality throughout storage and processing requires stringent environmental control, particularly over temperature and humidity levels. This dual imperative, to ensure both thermal comfort for workers and optimal moisture content for materials, poses a complex energy management challenge.[4,5]

To address these challenges, the concept of Industry 4.0-enabled energy optimization has emerged as a promising extension of Industry 4.0, focusing specifically on digital energy management. Through smart sensors, real-time data analytics, and automated control systems, Industry 4.0-enabled energy optimization enables precise regulation of indoor conditions, improved process transparency, and adaptive energy optimization strategies.[6,7]

1. Introduction

The wood industry has traditionally relied on manual operations and limited automation, resulting in suboptimal energy use and constrained modernization. With the emergence of Industry 4.0, the sector now faces a transformative opportunity to integrate advanced technologies and enhance operational efficiency—particularly in the realm of energy management. Industry 4.0, encompassing data analytics, artificial intelligence (AI), and the Internet of Things (IoT), offers the potential to revolutionize production systems by enabling real-time monitoring, predictive control, and data-driven decision-making.[1,2]

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This study proposes a practical and replicable framework for implementing Industry 4.0 technologies to enhance energy efficiency in the furniture manufacturing segment of the wood industry. In contrast to previous work, which often centers on theoretical models or large-scale applications, this research presents a real-world case study tailored to the needs and constraints of small and medium-sized enterprises (SMEs).

By applying Industry 4.0 principles in a pilot implementation, the study evaluates the feasibility, scalability, and impact of AI-driven automation and sensor networks on energy consumption. It aims to bridge the gap between theoretical innovation and practical deployment, offering concrete evidence of energy savings and cost reductions. Given the limited number of empirical studies in this area, the work contributes valuable insights to guide the broader adoption of digital energy solutions in SME-scale manufacturing environments.[8]

2. Industry 4.0, Energy Efficiency, and the Wood Industry

Improving energy efficiency in wood manufacturing, particularly in thermally intensive processes, requires a shift toward more innovative, data-driven production models. This section examines how Industry 4.0 technologies can facilitate the optimization of energy use by enabling real-time monitoring, predictive control, and informed decision-making. A foundational step in this transformation is identifying and quantifying the key parameters that influence energy consumption in the sector.[6]

2.1. Industry 4.0 and Smart Manufacturing

Industry 4.0 refers to the digital transformation of manufacturing through the integration of cyber-physical systems, AI, the IoT, and real-time data analytics. The concept centers on the smart factory, where machines and systems communicate, learn, and adapt autonomously to optimize performance and resource use.[7]

Smart factories are equipped with advanced sensors, automation systems, and analytics platforms that enable continuous monitoring of production processes. These capabilities facilitate resource optimization, predictive maintenance, and real-time adjustments to improve energy performance. For example, IoT-connected devices track machine efficiency and environmental conditions, enabling timely interventions that reduce energy waste and enhance process control.[8]

In the wood manufacturing sector, adopting Industry 4.0 technologies presents substantial potential for improving productivity, product quality, and environmental performance. Through intelligent systems and automation, manufacturers can enhance decision-making, streamline operations, and reduce their energy footprint.[9] As illustrated in **Figure 1**, the transition to Industry 4.0 involves the convergence of digital and physical infrastructures into an integrated smart production environment.[10–12]

2.2. Energy Efficiency in Industrial Applications

According to the Québec Ministry of Energy and Natural Resources, energy efficiency is defined as the ability to maximize output while minimizing energy input.[13] In practice, this involves adopting energy-efficient technologies, implementing structured energy management systems (EMS), and eliminating unnecessary energy losses across production systems.[14,15]

Figure 1. Industry 4.0 and smart factories.[11]

In the wood industry, drying processes are particularly energy-intensive. Improving efficiency in these systems through enhanced insulation, intelligent control mechanisms, and optimized maintenance can lead to significant cost savings and a reduced environmental impact.[15,16] Energy management refers to the continuous process of monitoring, evaluating, and improving energy performance over time.[17] It involves integrating energy goals into overall production management while tracking performance metrics, typically represented as a ratio of useful output to energy input.[18]

2.3. Particularities of the Wood Furniture Industry

The furniture manufacturing segment, as part of the third transformation of wood, produces high-value goods, including cabinetry and office or residential furniture. This sector predominantly uses engineered wood products, such as MDF and melamine, which are chosen for their dimensional stability, ease of machining, and affordability.[19] However, the production of furniture also involves energy-intensive operations requiring significant inputs of electricity and thermal energy. In typical wood furniture companies, electrical energy accounts for ≈94% of total energy use, with major consumers being machining, lighting, and climate control systems (**Figure 2**).[15]

The industry faces dual pressures: on one side, increasing costs for materials and energy, and on the other, tightening environmental standards. These forces are pushing companies to adopt more efficient and sustainable production models.[20,21]

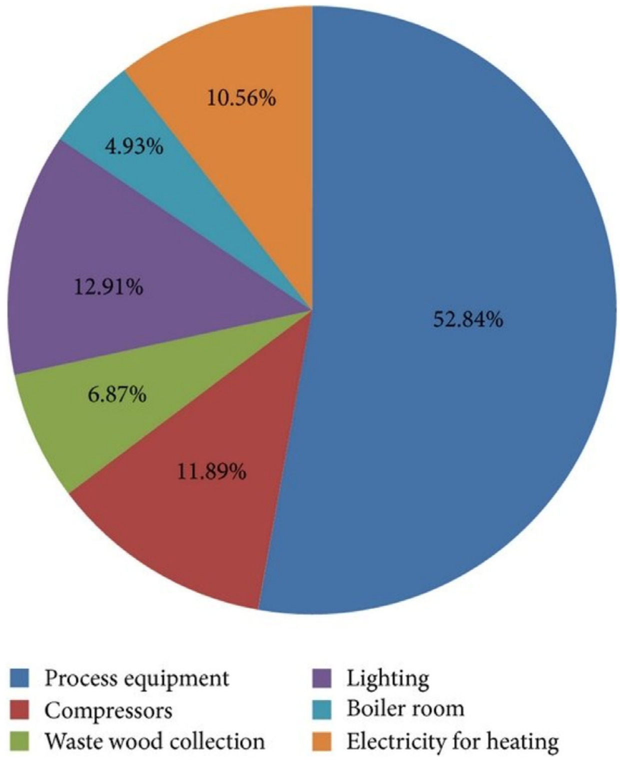

Figure 2. Distribution of energy consumption by process in a wood furniture manufacturing company.[15]

2.3.1. Energy Demand in Wood Processing

Wood processing entails several energy-intensive operations, including cutting, shaping, drying, and finishing.[1,3,22] Among these, drying is the most energy-demanding process, involving both electrical energy for fans, sensors, and control systems, as well as thermal energy, typically sourced from propane, natural gas, or biomass. The drying stage alone accounts for over 40% of total energy consumption in the wood manufacturing chain.[4]

Key variables influencing energy use include the efficiency of heating systems, airflow control, batch size, and the design of the drying cycle. Targeted improvements in these areas can yield considerable energy savings and improve overall system performance.

2.3.2. Raw Materials, Process Requirements, and Product Quality

Engineered wood products such as MDF and melamine require carefully managed environmental conditions to ensure consistent quality and mechanical performance. Maintaining the moisture content of raw materials between 8% and 12% is critical for machinability and dimensional stability.[5] Natural drying under the thermal comfort conditions remains a low-cost alternative to industrial drying, though it presents quality risks when environmental control is inadequate. Improper storage conditions can lead to material deformation, microbial growth, and higher rejection rates.[23]

2.3.3. Thermal Comfort in the Wood Industry

Beyond technical considerations, maintaining thermal comfort in manufacturing environments is essential for worker productivity and health. Standards from ANSI/ASHRAE define acceptable temperature and humidity levels for light industrial activities, as shown in **Figure 3**.[24] These environmental parameters must be balanced with the energy requirements for climate control, particularly in regions with significant seasonal variation.

Industry 4.0 tools, including IoT-based environmental sensors and AI-driven climate management systems, allow manufacturers to maintain compliance with comfort standards while minimizing energy use. These systems provide real-time feedback and adaptive control, adjusting energy inputs based on external conditions and internal process demands.

The integration of Industry 4.0 in the wood furniture industry represents a promising avenue for achieving energy efficiency without compromising product quality or worker comfort. Through the deployment of smart sensors, advanced analytics, and automated control systems, manufacturers can reduce operational costs, enhance system responsiveness, and align with global sustainability objectives. The following sections present a case study that demonstrates these principles in practice, illustrating the feasibility and impact of a digital transition in a small-scale wood manufacturing context.

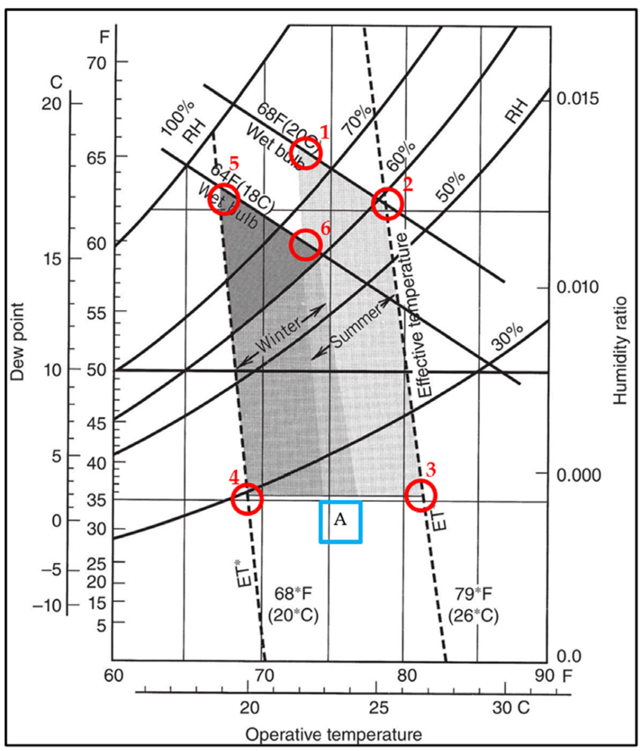

Figure 3. Acceptable ranges for temperature and humidity in industrial settings based on clothing and activity levels[24] Source: ASHRAE, www.ashrae.org (accessed on November 30, 2024). Addendum 55a-1995.

2.3.4. Energy Management System (EMS) in the Furniture Industry (Benchmark)

EMS provide a technological solution to monitor, analyze, and optimize energy consumption. **Table 1** compares EMS options available for furniture SMEs, emphasizing their suitability, cost-effectiveness, and functionality.

Unlike most off-the-shelf EMS solutions, which require significant upfront investment, specialized IT infrastructure, or advanced integration with existing automation, the proposed system is modular, low-cost, and designed to be deployed incrementally, making it particularly suitable for SMEs with limited resources but high energy-saving potential.

3. Implementation of Industry 4.0-Enabled Energy Optimization Solution

This section outlines the problem addressed, the proposed Industry 4.0-enabled energy optimization solution, and the methodology employed to implement and evaluate it. The approach integrates insights from recent literature,[1,3] industry practices, and a practical deployment at a real-world workshop.

Recent research has highlighted a significant gap in studies examining the intersection of Industry 4.0 and energy efficiency in the wood industry. While many investigations focus on applications in energy-intensive sectors such as metallurgy and automotive manufacturing,[1] there is limited exploration of its relevance to wood processing, particularly in SMEs.

For example, Podor et al.[23] examined the integration of Industrial IoT (IIoT) systems in two wood manufacturing plants, demonstrating potential for energy savings and operational optimization. Similarly, Seewald et al.[25] and Onu et al.[26] reported successful applications of Industry 4.0 in the automotive and renewable energy sectors, respectively. However, the lack of empirical studies tailored to the wood furniture industry underscores the need for practical case studies to fill this knowledge gap.

3.1. Problem Definition

Wood processing, especially in furniture manufacturing, involves several energy-intensive stages that are traditionally managed through manual or semi-automated control. Two processes stand out for their energy demands and optimization potential: 1) Drying operations: Drying is one of the most energy-consuming processes in wood production. Conventional systems often lack precise environmental control, resulting in excessive energy consumption and inconsistent product quality. By deploying IoT sensors and moisture content analyzers, it becomes possible to collect real-time data on wood properties and ambient conditions. AI-based EMS can then optimize drying cycles to balance energy use and material integrity.[27] A life cycle assessment (LCA) of the monitoring system components should be conducted to assess the overall sustainability impact; and 2) dust collection systems: Dust extraction in secondary and tertiary transformations also contributes significantly to energy consumption. Integrating smart control systems and real-time monitoring enables adjustment of motor speeds, flow rates, and filter operations based on actual demand. This leads to both energy savings and improved system longevity.[28]

In addition to these process-level inefficiencies, wood manufacturing environments must comply with two stringent requirements: 1) *Thermal comfort for workers*: Indoor temperature and humidity must comply with occupational health regulations, particularly in Québec, where industry standards mandate safe and comfortable working conditions; and 2) *material storage and processing conditions*: Engineered wood materials such as MDF and melamine must maintain a moisture content between 8% and 12% to preserve their dimensional stability and

Table 1. EMS solutions for SMEs in the furniture industry.

EMS solution/ Vendor	Type	Machine-level metering	PLC/SCADA integration	ISO 50 001 Support	Analytics & insights	Deployment time	Approximate cost range*	Best fit for furniture SMEs
Energy elephant	Cloud SaaS	Limited	No	Basic reporting	Dashboards, alerts, benchmarking	Weeks	Low ($1 k–5 k/ year)	Small SMEs needing a quick start, low-cost
Eniscope	Cloud SaaS + Hardware	Basic submeters	Limited	Limited	Energy visualization, alerts	Weeks	Low to medium ($5 k–10 k/year)	SMEs with some metering hardware
Schneider EcoStruxure	Industrial EMS/ SCADA	Full machine-level	Full (PLC, OPC-UA)	Yes (extensive)	Advanced analytics, AI, optimization	Months	High ($30 k+)	Medium to large SMEs with automation infrastructure
Siemens Desigo/ EnergyIP	Industrial EMS/ SCADA	Full machine-level	Full (PLC, OPC-UA)	Yes	Deep analytics, energy attribution	Months	High ($25 k+)	Larger SMEs with complex production systems
OpenEMS (Open-source)	Open-source/ Custom	Fully customizable	Custom development	Possible	Depends on setup	Variable	Low to medium (dev cost)	SMEs with internal IT and development skills
EnergyCAP	Cloud-based + On-premise	Asset-level (via hardware)	Limited	Yes	Reporting, compliance tracking	Weeks to months	Medium ($10 k+)	SMEs needing compliance and auditing support
Honeywell Energy Manager	Industrial EMS	Full machine-level	Full	Yes	Advanced monitoring & optimization	Months	High ($30 k+)	Large SMEs with multiple plants

machinability. Otherwise, quality defects will appear, such as fiber tearing, poor surface roughness, chipping of edges, or the formation of burrs.

Therefore, the challenge is to achieve these quality and safety requirements without excessive energy consumption, particularly as most factories rely on propane-fueled heating systems, which are both costly and carbon-intensive.

3.2. Proposed Solution

The Industry 4.0-enabled energy optimization solution consists of two integrated components: 1) *Hardware layer*–Sensors and Actuators: Smart sensors measure environmental variables such as air temperature, humidity, and material moisture content. Actuators (e.g., ventilation systems, heating units) are used to adjust operating conditions based on feedback; and 2) *software layer*–EMS: A centralized platform processes sensor data, employs AI-driven analytics, and communicates with actuators to maintain optimal conditions. The EMS ensures compliance with environmental and occupational standards while minimizing unnecessary energy use.

Figure 4 provides a schematic representation of the solution, illustrating the integration of Industry 4.0 technologies into the energy management framework.

A key innovation of the system is its hierarchical decision-making framework, which prioritizes system goals in the following order: 1) *Thermal comfort*: Ensures safe and comfortable working conditions for employees, as required by occupational health guidelines; 2) *material quality*: Maintains the necessary moisture content in panels (8%–12%) to preserve processing and product quality; and 3) *energy efficiency*: Optimizes energy usage only when the above two conditions are satisfied.

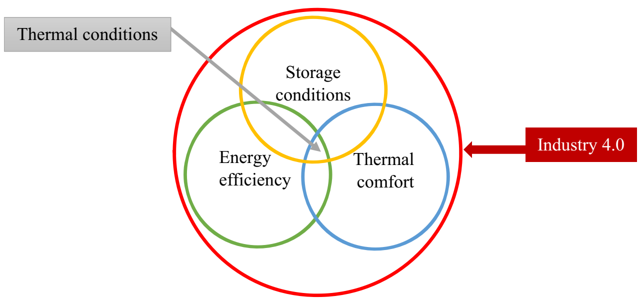

Figure 4. General illustration of the solution.

This structured logic prevents energy-saving measures from compromising worker safety or material integrity.

Notably, Haddouche et al.[3,4] showed that when MDF and melamine panels are stored within the ASHRAE thermal comfort zone, they gradually reach an equilibrium moisture content within the desired range. This correlation justifies the use of comfort standards as a proxy for material conditioning in storage and pre-processing environments.

3.3. Methodology

The implementation of the Industry 4.0-enabled energy optimization system follows a five-step methodology designed for replicability in SME-scale wood manufacturing environments: 1) *Identification of critical energy points*: Target energy-intensive operations (e.g., drying, dust extraction) where improvements would yield the highest energy and cost savings; 2) *sensor and actuator deployment*: Install IoT-enabled devices at critical process locations to capture real-time environmental and operational parameters; 3) *data extraction and analysis*: Use both historical datasets[1,3] and real-time data to define performance baselines and identify opportunities for intervention; 4) *development of user interface*: Build a real-time dashboard to visualize environmental variables, machine performance, and energy use. The interface also allows operators to adjust control settings as needed; and 5) *system evaluation*: Compare system performance with and without Industry 4.0-enabled energy optimization intervention, focusing on energy savings, process stability, and user feedback.

This methodology was tested at the SEREX machining workshop (**Figure 5**), a mid-sized facility representing typical conditions in Québec's wood furniture industry. The pilot installation enabled real-time monitoring and AI-based control of heating and humidity systems, validating the solution in a live industrial setting.

Figure 5. View of the experimental setup at the SEREX machining workshop.[32]

4. Case Study: Implementation at the SEREX Workshop

To explore the integration of Industry 4.0 concepts in enhancing energy efficiency within the wood manufacturing sector, an applied study was conducted based on site assessments and experimental validation. The approach combined exploratory field visits to active wood processing facilities with a pilot implementation in a controlled research environment.

4.1. Industrial Site Assessments

Preliminary investigations were carried out at three specialized wood transformation plants to: 1) Establish an accurate energy balance across operations; 2) identify the most energy-intensive processes and inefficiencies; and 3) determine suitable locations and technologies for deploying Industry 4.0 solutions.

The facilities visited were: 1) *Fabritec (Mont-Joli, Québec)*: A third-stage transformation plant specializing in kitchen and bathroom cabinetry. Fabritec processes MDF and melamine panels, making it a representative site for the furniture manufacturing segment; 2) *Bois BSL (Mont-Joli, Québec)*: A second-stage wood processing facility focusing on solid hardwood flooring. With its extensive drying operations, it presents an ideal opportunity for energy optimization strategies related to thermal processes; and 3) *Uniboard (Mont-Laurier, Québec)*: A large-scale producer of engineered wood panels, including MDF and melamine, operating with high-volume production and complex process integration.

These visits provided valuable insights into energy management challenges and illustrated the potential scalability of the proposed Industry 4.0-enabled energy optimization solution across various types of wood transformation processes. They also helped refine the system architecture to better suit the operational realities of SMEs in the wood sector.

4.2. SEREX Workshop as a Pilot Implementation Site

To validate and operationalize the proposed Industry 4.0-enabled energy optimization solution, the machining workshop at SEREX (Service de Recherche et d'Expertise en Transformation des Produits Forestiers) was selected as the experimental site. SEREX is a Québec-based nonprofit organization founded in 1998, dedicated to supporting innovation and technology transfer in forest product processing.[29]

Located in Amqui, Québec, the SEREX machining workshop replicates the conditions of a typical SME-scale furniture manufacturing facility. It features standard processing equipment and environmental controls, offering an ideal platform for testing energy efficiency measures in a realistic yet manageable setting. A LCA of the monitoring system components should be conducted to assess the overall sustainability impact.

Key equipment available in the workshop includes (**Figure 6**): CNC 3-axis machine (Figure 6a): Brand: TOTAL CUT, Model: RTC, Machining surface: 60" × 144", Control interface: FlashCut, Tool magazine: $7 + 1$ tools.

Dust collector (Figure 6b): Brand: KING CANADA, Model: KC-4043, Dimensions: 55.5" × 23" × 99", Suction capacity: $2.28\ ft^3\ min^{-1}$, Motor: 3 HP.

Vacuum pump (Figure 6c): Brand: BUSCH, Model: MINK MM 1252 AV.

Storage area (Figure 6d): Panel rack dimensions: $30 \times 60\ cm^2$.

4.3. Implementation of the Solution Based on Industry 4.0-Enabled Energy Optimization

The solution based on Industry 4.0-enabled energy optimization was deployed at SEREX using a structured, three-phase approach that integrates hardware, software, and user interface development: 1) *Identification of heat sources*: Augmented Reality (AR) smart glasses were employed to detect and visualize heat signatures in the workshop. This technology facilitated the rapid identification of zones with excessive heat loss or thermal inefficiencies, providing valuable spatial data to guide the installation of sensors and insulation enhancements; 2) *real-time monitoring and control*: A network of smart sensors was installed to monitor key environmental and energy parameters, including: a) Air temperature and humidity; b) moisture content of stored materials; and c) energy consumption of heating and ventilation equipment.

The data was transmitted in real-time via Bluetooth to a custom-developed Energy Management 4.0 application. This application uses algorithmic logic to analyze the data and optimize control settings. In the reverse direction, the system can remotely actuate fans and heating elements to adjust temperature and airflow dynamically, based on environmental needs; and 3) *development of a human–machine interface*: A dedicated user interface was created to visualize environmental data, trigger alerts, and facilitate both manual and automatic adjustments. The interface features dashboards, historical trend visualizations, and programmable thresholds to facilitate informed operational decision-making.

This three-part integration of data acquisition, intelligent processing, and user feedback aligns with Industry 4.0 principles of automation, decentralization, and real-time adaptability, providing a replicable model for enhancing energy efficiency in the broader wood transformation sector.

4.3.1. Hardware Components of the Solution Based on Industry 4.0-Enabled Energy Optimization System

The hardware infrastructure for the Industry 4.0-enabled energy optimization solution is composed of two main categories: a) AR-based thermal diagnostics and b) a network of custom-designed IoT sensors and actuators. These components collectively enable real-time environmental monitoring, predictive maintenance, and automated control of heating and ventilation systems in wood processing environments **Figure 7**.

Augmented Reality (AR) Thermal Imaging for Diagnostic Analysis: To assess thermal conditions and identify inefficiencies in the workshop environment, an AR-based system was deployed. This includes (**Figure 8**): 1) AR smart glasses: SCIONE Metaverse model; and 2) thermal imaging camera: BLACKVIEW BV6600Pro smartphone with integrated FLIR thermal camera.

The combination provides an immersive visualization platform for detecting heat sources, enabling preventive diagnostics

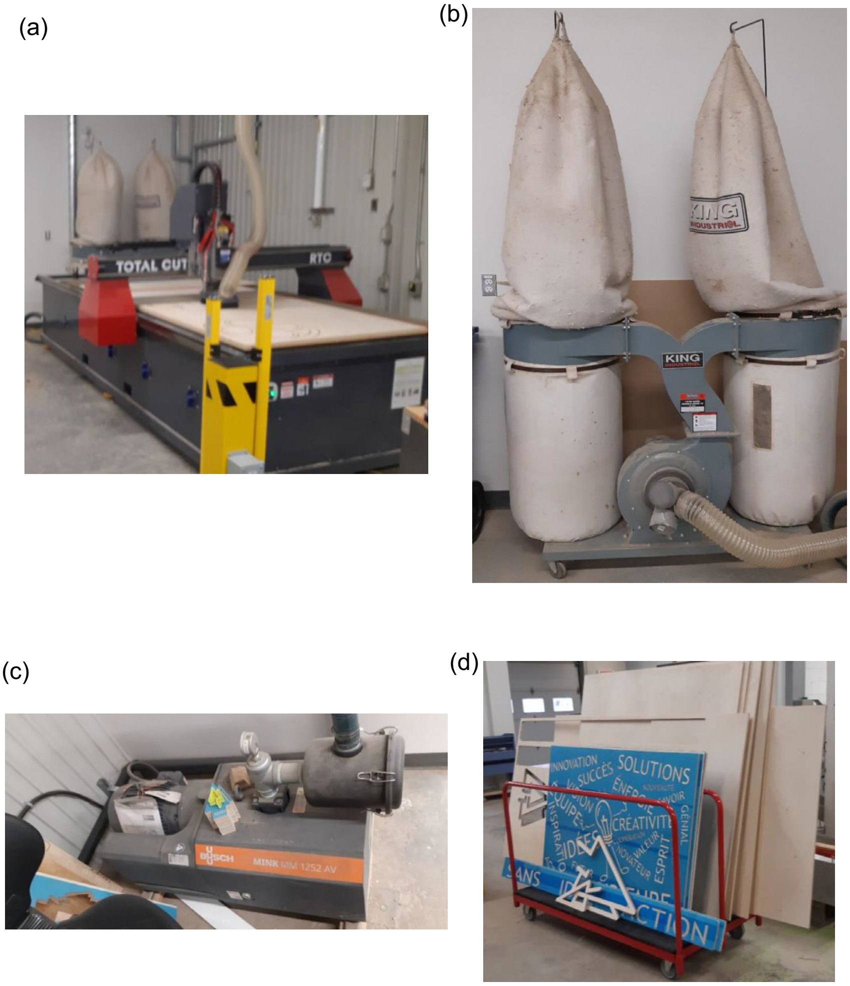

Figure 6. Tools and systems in the SEREX machining workshop.[32] a) CNC 3-axis Machine. b) Dust Collector. c) Vacuum Pump. d) Storage Area.

and accurate sensor placement. This method was essential for identifying key heat zones, such as motor units and duct systems, where energy losses or malfunctions are likely to occur. The key functions are: 1) Real-time thermal visualization; 2) anomaly detection (e.g., overheating, energy loss); and 3) informed sensor deployment decisions.

IoT-Based Smart Sensors and Actuators: Unlike conventional sensors connected to programmable logic controllers (PLCs), smart sensors used here integrate on-board processing, wireless communication, and self-calibration features. These components enable autonomous and energy-efficient operation, aligning with Industry 4.0 standards. The key features of the sensor network are: 1) Self-powered (no external power dependency); 2) auto-calibrating (ensures measurement accuracy); 3) local data processing; and 4) wireless data transmission via Bluetooth (HC-06).

The system is based on an Arduino Uno R3 microcontroller, which serves as the hub for environmental and equipment monitoring. Below is a breakdown of the main subsystems and their roles: 1) Environmental monitoring (**Figure 9**): a) Air temperature and humidity sensor (DHT22); b) temperature range: $-40\,°C$ to $+125\,°C$ ($\pm 0.5\,°C$ accuracy); c) humidity range: 0% to 100% ($\pm$2%–5% accuracy); and d) positioned near operator zones for representative readings. 2) Moisture Sensor for MDF/Melamine Panels (**Figure 10**): a) Based on electrical conductivity; b) dual-mode output: analog (AO) and digital (DO); c) custom-calibrated for engineered wood material; and d) operates at 3.3–5 V, compact design. 3) Temperature monitoring of key machinery (**Figure 11**): a) CNC spindle motor (DS18B20); b) main heat source during machining; and c) direct contact mounting for real-time temperature tracking. 4) Dust collector (DS18B20 $\times$ 2) (**Figure 12**): a) Mounted on both the motor housing and the filtration bag and b) used to prevent overheating and identify airflow inefficiencies. 5) Vacuum pump (DS18B20 $\times$ 2) (**Figure 13**): Sensor 1: on motor casing and Sensor 2: on the hot air exhaust outlet. 6) Heating and ventilation actuation system (**Figure 14**): a) Fan-heater system; b) controlled by relay interface (5 V 1 A input, switching: AC250V 10 A or DC30V 10 A); c) connected to Arduino UNO with HC-06 Bluetooth for wireless control; and d) allows for dynamic adjustments of airflow and heat intensity based on environmental sensor input.

System Selection Justification: This modular and low-cost hardware configuration was selected for its: a) Flexibility in adapting

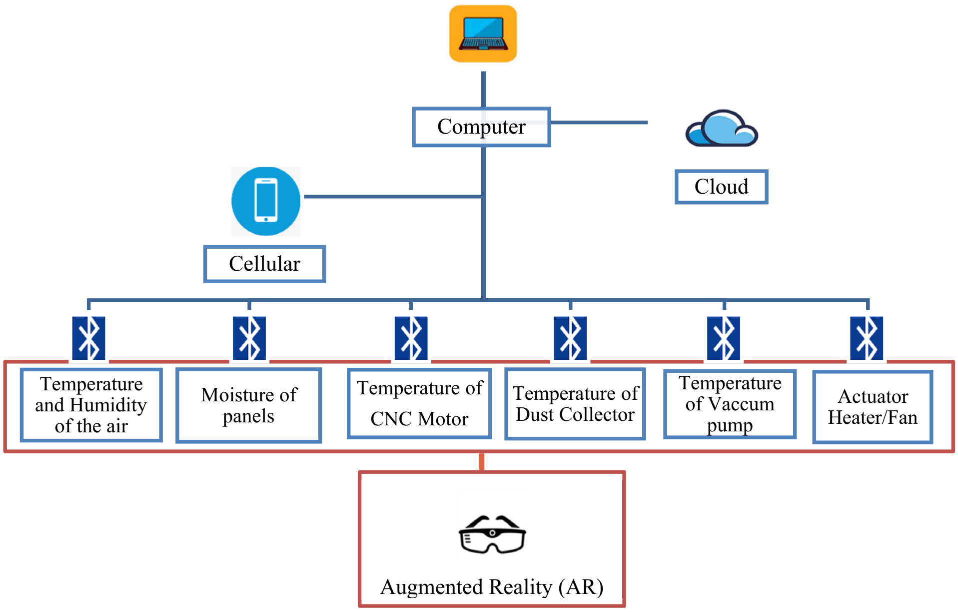

Figure 7. Physical system diagram showing sensor nodes, communication protocols, and actuator control paths in the implementation of the Industry 4.0-enabled energy optimization solution.

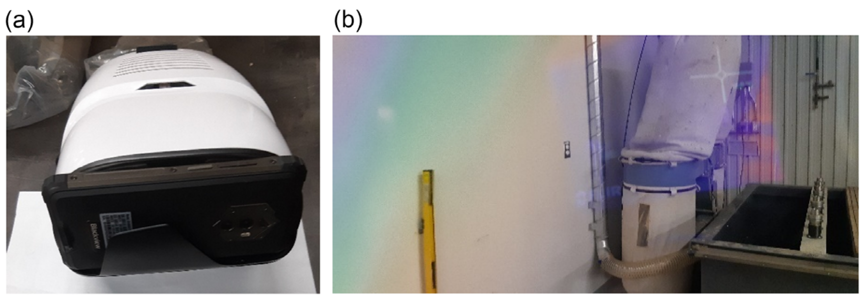

Figure 8. Assembly AR-FLIR. a) Devices. b) Image.

to diverse industrial setups; b) high availability in the market; c) favorable price-to-performance ratio; and 4) ease of maintenance and scalability.

These features make the system particularly suitable for SMEs seeking affordable yet advanced energy monitoring and control solutions.

4.3.2. Software and Energy Management

The software component of the Industry 4.0-enabled energy optimization solution comprises a custom-built energy management application that processes real-time data from smart sensors, applies priority-based control logic using embedded algorithms, and communicates with actuators to optimize energy usage. This component ensures that system decisions are data-driven, adaptive, and aligned with industrial performance and sustainability objectives.

The decision-making logic of the software follows a structured hierarchy: 1) Thermal comfort: Maintains air temperature and humidity within occupational health norms, ensuring safe working conditions; 2) panel quality preservation: Regulates moisture content in MDF and melamine panels within the ideal range of 8%–12%, critical for processing and product durability; and 3) energy efficiency: Adjusts heating and ventilation based on sensor feedback to minimize energy consumption, but only after the two higher-priority conditions are satisfied.

Algorithmic Logic and Data Flow: The core of the application is governed by an embedded decision algorithm, as illustrated in **Figure 15**, which determines system behavior in real-time by interpreting sensor input and triggering corresponding actuator outputs. Key variables used in the algorithm are defined in **Table 2**.

User Interface and System Control Dashboard: The desktop application interface (**Figure 16**) is designed to ensure intuitive control and monitoring of the system. It is divided into three functional zones: 1) *Device connectivity panel*: Allows simultaneous Bluetooth connection to up to six devices, including environmental sensors and motor temperature monitors;

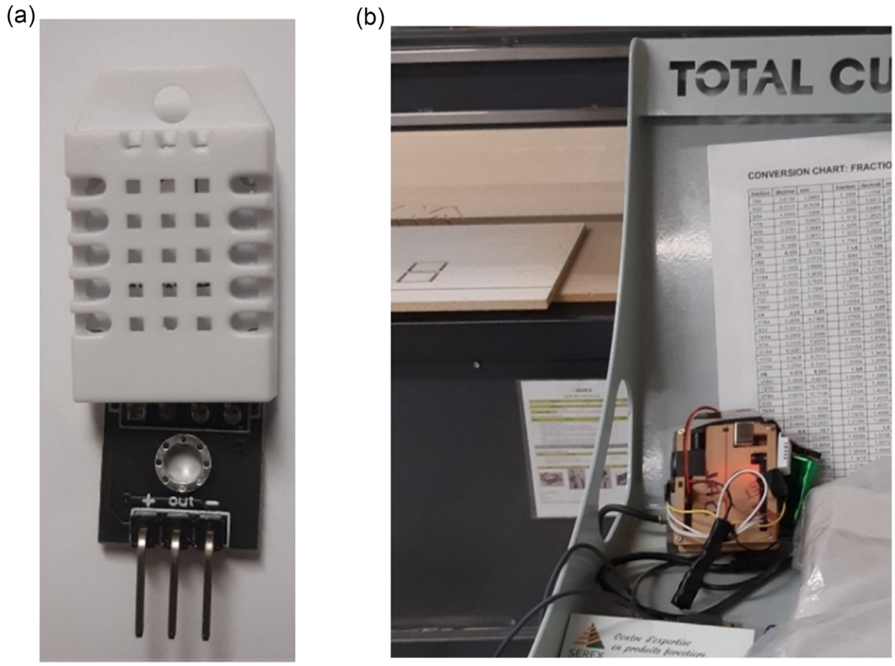

Figure 9. Temperature and humidity sensor DHT22: a) sensor unit. b) fully assembled monitoring system.

Figure 10. Moisture sensor used for monitoring panel drying conditions.

2) *command and control panel:* Provides user commands to: a) Start/stop data recording; b) view live data in tabular format; c) export data to an Excel file; and d) synchronize and store data to Google Cloud; and 3) *Data storage system:* a) Excel files are saved locally for offline access and b) Cloud integration enables remote data access and backup via a Google user account (**Figure 17**).

Mobile Interface: A simplified mobile interface (**Figure 18**) enables remote monitoring but does not allow manual control. It operates at two levels: 1) Level 1: Establishes Bluetooth communication between the smartphone and connected devices and 2) Level 2: Displays live sensor data (temperature, humidity, etc.) in real-time.

This dual-interface software architecture supports real-time decision-making, remote accessibility, and data-driven automation, which are key pillars of Industry 4.0 energy management. The system's layered control logic and integration with both local and cloud-based platforms ensure versatility, scalability, and user-friendly operation across a range of industrial environments.

5. Results

To assess the performance of the proposed Industry 4.0-enabled energy optimization solution, a controlled experimental simulation was carried out in the SEREX workshop. The implementation involved real-time data collection from a network of IoT sensors monitoring temperature, humidity, and equipment conditions. The results are presented by comparing two operational modes: 1) *Unassisted mode*: Conventional operation based on manual adjustments and 2) *assisted mode*: Data-driven control using the Industry 4.0-enabled energy optimization application.

This comparison highlights the effectiveness of smart energy management in reducing fuel consumption while maintaining environmental conditions within defined quality and comfort standards.

5.1. Temperature and Humidity Analysis

Sensor deployment and monitoring began at 08:46:10 AM, with workshop machinery activated at 09:04:10 AM and turned off at

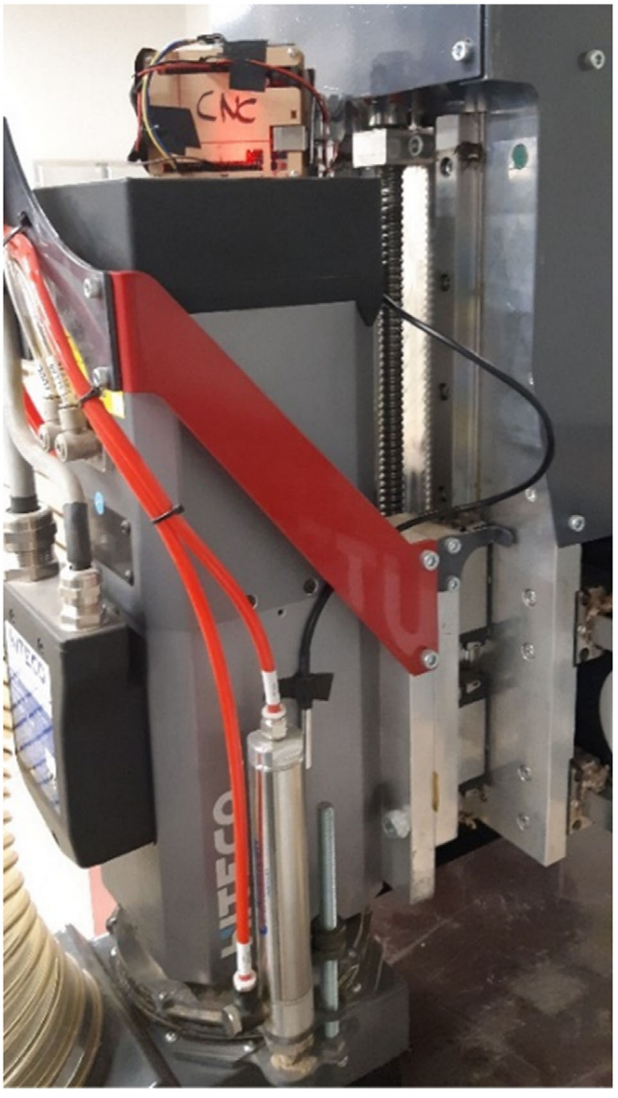

Figure 11. Temperature sensor mounted on CNC spindle motor.

11:46:10 AM. The thermal response of key devices is presented in **Figure 19**, illustrating temperature fluctuations during machining activities. These variations validate the relevance of targeted thermal monitoring for equipment operating under variable load conditions.

Simultaneously, the ambient relative humidity and the moisture content of melamine and MDF panels were continuously tracked by the sensors (**Figure 20**). The assisted mode maintained environmental parameters within optimal thresholds, ensuring thermal comfort for workers and preserving the integrity of the panel. Thermal comfort was assessed based on ASHRAE 55 standards, and panel moisture content was monitored to remain within the 8%–12% optimal range. This range is crucial to guarantee the quality of the panel after machining, as explained in sections 2.3.2 and 3.1.

5.2. Comparison of Energy Consumption Between Modes

The comparative analysis between assisted and unassisted modes (**Figure 21**) reveals a marked difference in the efficiency of heating operations. In unassisted mode, heating decisions were made manually based on the operator's judgment, often resulting in excessive energy consumption. Conversely, the Industry 4.0-enabled energy optimization system enabled intelligent control based on real-time environmental data.

As shown in Figure 21, the assisted mode achieved a progressive and controlled temperature increase, staying within the thermal comfort zone while minimizing unnecessary heating.

5.3. Fuel Consumption and Cost Analysis

To quantify the energy savings, propane consumption was estimated using the characteristics of the Modine PDP250 heater (250 000 Btu h^{-1}, 83% thermal efficiency). The analysis accounted for total operating time, energy delivered, and propane used in each scenario.

After extensive testing over one month in the autumn season (from November 15th to December 15th). A representative day is selected, and the results are presented in **Table 3**.

These results confirm that the Industry 4.0-enabled energy optimization-assisted mode led to: 1) A reduction of 128.05 kWh in energy consumption; 2) a savings of 17.47 liters of propane; and 3) a cost reduction of 14.85 CAD over a 3 h experimental period from one representative day in a month-long test. While these results validate the concept, long-term evaluations across seasons and varying operational loads are necessary for broader conclusions.

This proof-of-concept, although limited to a short-term simulation, provides strong support for the feasibility and scalability of the Industry 4.0-enabled energy optimization solution. For robust industrial validation, more extended deployment (e.g., over one year) in real-world factory conditions would be necessary to confirm performance consistency and allow for

Figure 12. Sensor integration on dust collector: a) filtration bag, b) motor unit, and c) complete system view.

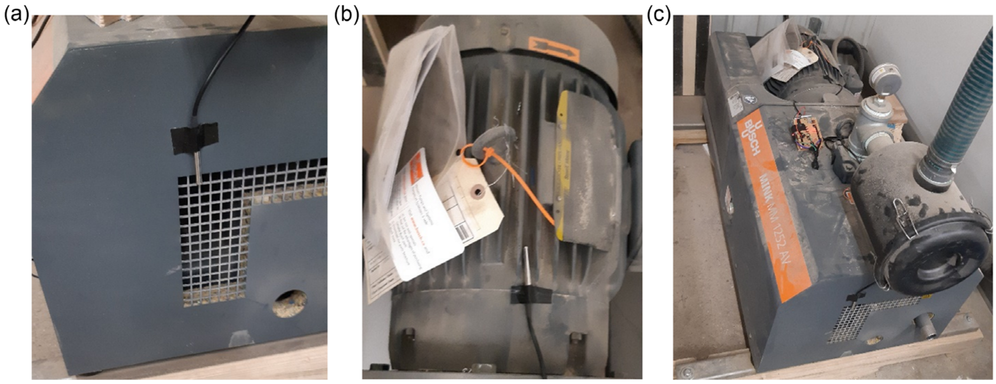

Figure 13. Vacuum pump sensors: a) exhaust outlet, b) motor, and c) complete assembly.

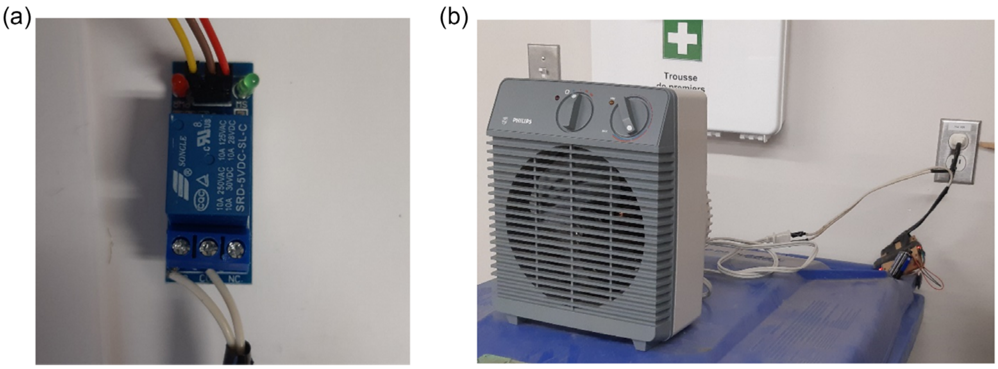

Figure 14. Actuation system: a) Relay board and b) integrated actuator for fan-heater system.

extrapolation. Future work should include statistical analysis and repeated trials to enhance reliability.

6. Implications and Challenges

The implementation of the Industry 4.0-enabled energy optimization solution in a real-world setting demonstrated tangible benefits for energy management and operational performance in wood processing environments. Key achievements include: 1) *Improved environmental control*: Ambient air temperature and relative humidity were maintained within the thermal comfort range, supporting worker well-being and regulatory compliance; 2) *enhanced material quality*: Real-time monitoring enabled precise control of panel moisture content, ensuring that melamine and MDF panels remained within the optimal 8%–12% range necessary for machining and product durability; and 3) *energy and cost savings*: The system enabled substantial reductions in energy consumption, GHG emissions, and associated operational costs.

Despite these benefits, several implementation challenges and limitations were identified, along with recommendations for improvement.

6.1. Data Management and Infrastructure Needs

The volume of data generated by prolonged monitoring of environmental and operational parameters can quickly overwhelm basic IT infrastructure. While the system performed effectively in short-duration tests, scaling up to continuous or long-term monitoring would require: 1) Robust data storage solutions, whether local servers or cloud-based platforms, 2) efficient data processing pipelines capable of handling high-frequency updates; and 3) adequate computational power tailored to the expected data load and analytics requirements.

Therefore, a thorough assessment of IT infrastructure requirements is crucial before implementing full-scale deployment.

6.2. Cybersecurity Considerations

As with any connected industrial system, cybersecurity represents a significant concern. Industry 4.0 frameworks rely on real-time communication between industrial control systems (ICS), IIoT devices, and cloud interfaces, making them vulnerable to security threats. Practical implementation should include measures like encrypted communication, two-factor authentication, and intrusion detection systemss 1) Data breaches; 2) System sabotage; and 3) operational disruptions.

To ensure operational integrity, cybersecurity protocols must be embedded in the system architecture. This includes: 1) Secure authentication layers and data encryption: Devices and users should authenticate and encrypt communications at all times (e.g., using Blockchain); 2) Firewall and anti-intrusion mechanisms that comply with energy cybersecurity standards (e.g., NERC CIP); and 3) periodic risk assessments and software

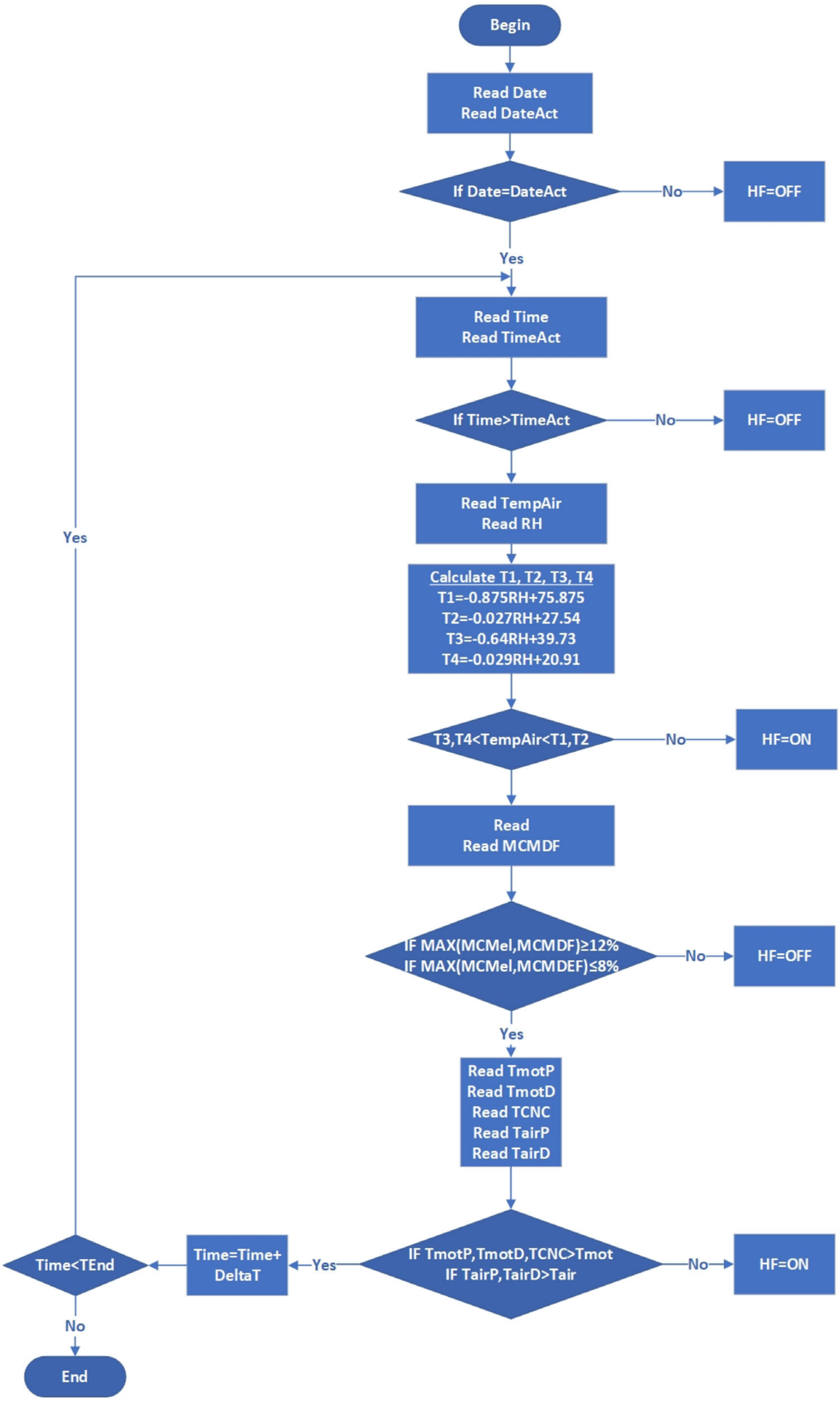

Figure 15. Algorithm flowchart for the Energy Management application.

Table 2. Significance of the variables in the algorithm of Figure 15.

Symbol	Significance
HF	Heater, fan
Date	Actual date (system)
DateAct	Activation date (Woodshop operation start date, ex: Monday, December 5th, 2022)
Time	Actual time (system)
TimeAct	Time of activation (Operation start time, ex: 8h00)
TempAir	Ambient air temperature
RH	Relative humidity in the ambient air
T1, T2, T3, T4	Limit temperature of the comfort zone (see the point position in Figure 3)
MCMel	Humidity rate of melamine
MCMDF	Humidity rate of the MDF
TmotP	Vacuum pump motor temperature
TmotD	Dust collector motor temperature
TairP	Vacuum pump exhaust air temperature
TairD	Dust collector exhaust air temperature
TCNC	CNC motor temperature
Tmot	Motor setpoint temperature
Tair	Outgoing air temperature setpoint

updates: Follow change management procedures to avoid downtime in critical systems.

Failing to address cybersecurity could lead to significant disruptions or loss of critical production and monitoring data.

6.3. Human Factors and Economic Barriers

Human factors and economic barriers could have a negative influence on the decision of SME leaders to invest in Industry 4.0, particularly in the energy sector.

First, the managers should have a clear strategy for the Industry 4.0-enabled energy optimization implementation and human reactions, e.g., workers' education level and implications, resources, training, and control.

Furthermore, the high initial costs of Industry 4.0 integration remain a significant barrier, particularly for SMEs. Budget constraints may hinder access to advanced solutions, even when long-term benefits are evident.

Recent literature highlights a notable gap in cost-benefit analyses: Maretto et al.[27] reported that only a limited number of studies have systematically evaluated the financial viability of Industry 4.0 investments. Addressing this gap is essential for informed decision-making by stakeholders.

A dedicated techno–economic assessment is recommended to: 1) Quantify the return on investment (ROI); 2) analyze

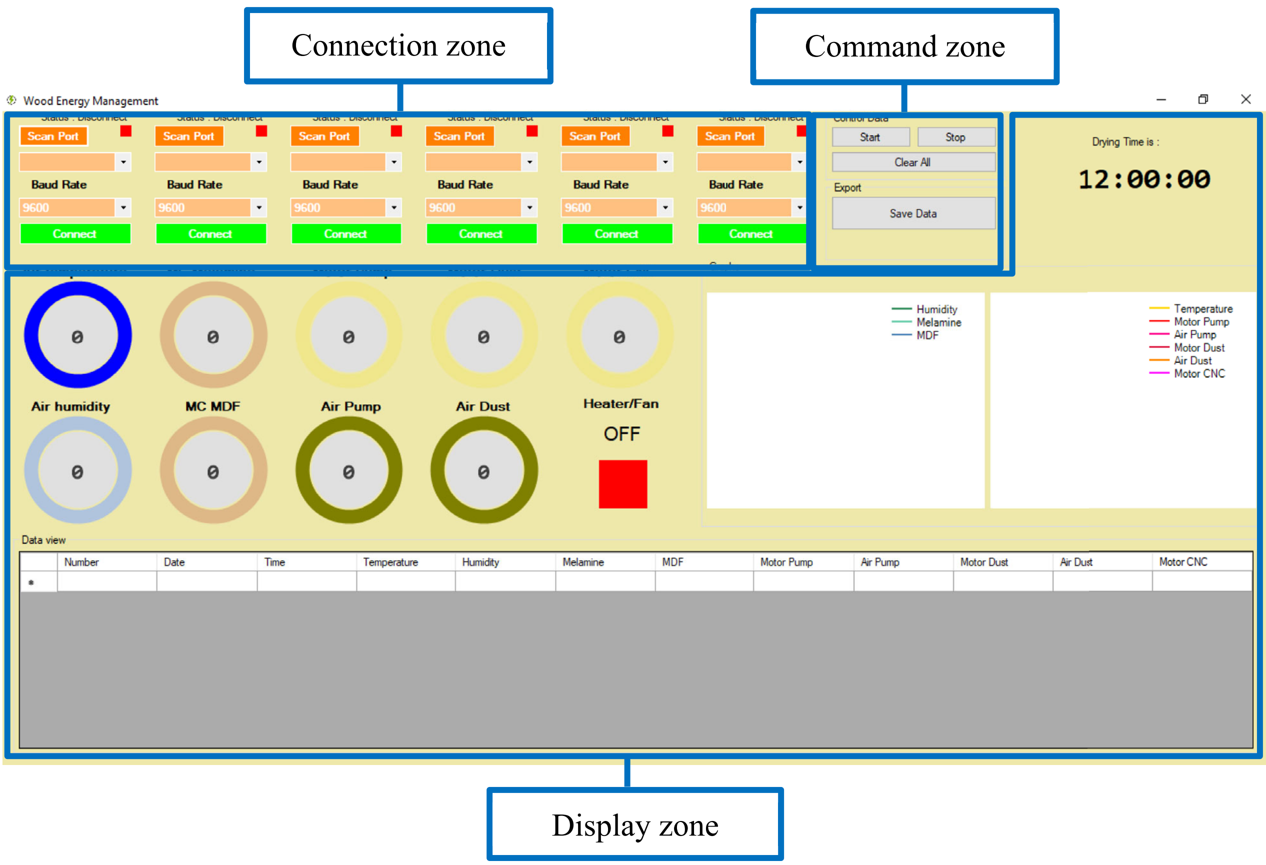

Figure 16. Desktop user interface for the Energy Management 4.0 system.

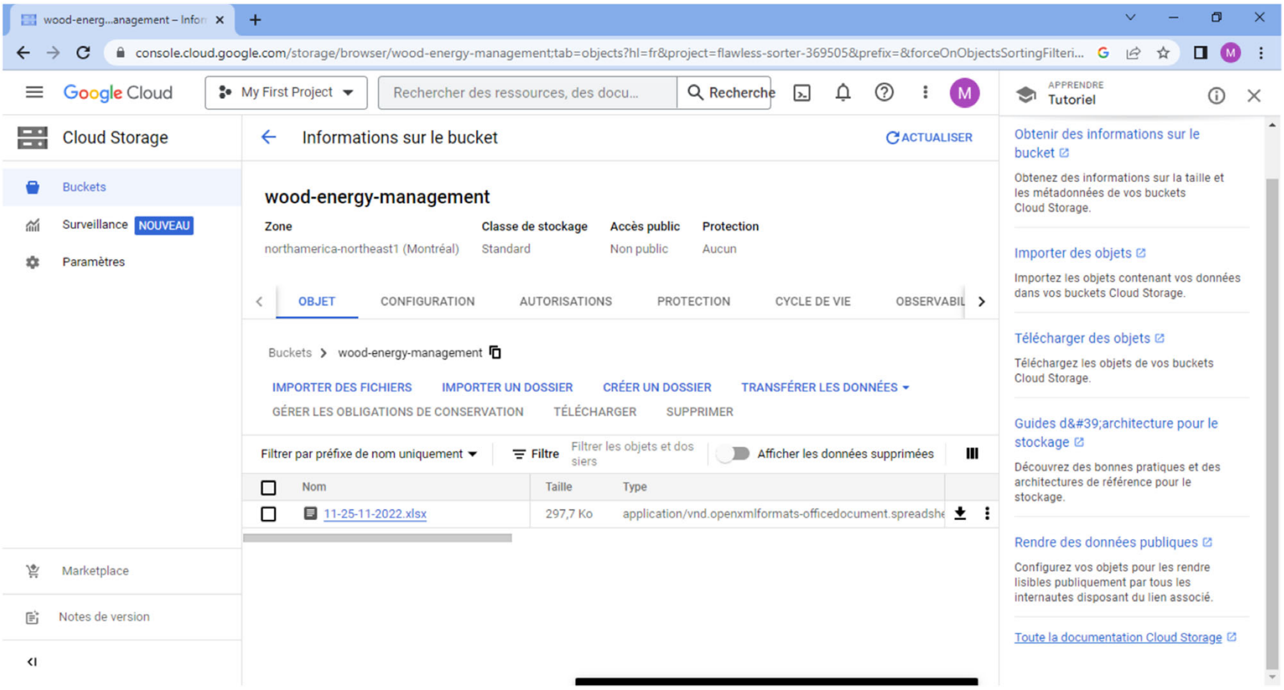

Figure 17. Google Cloud interface for remote data access and file storage.

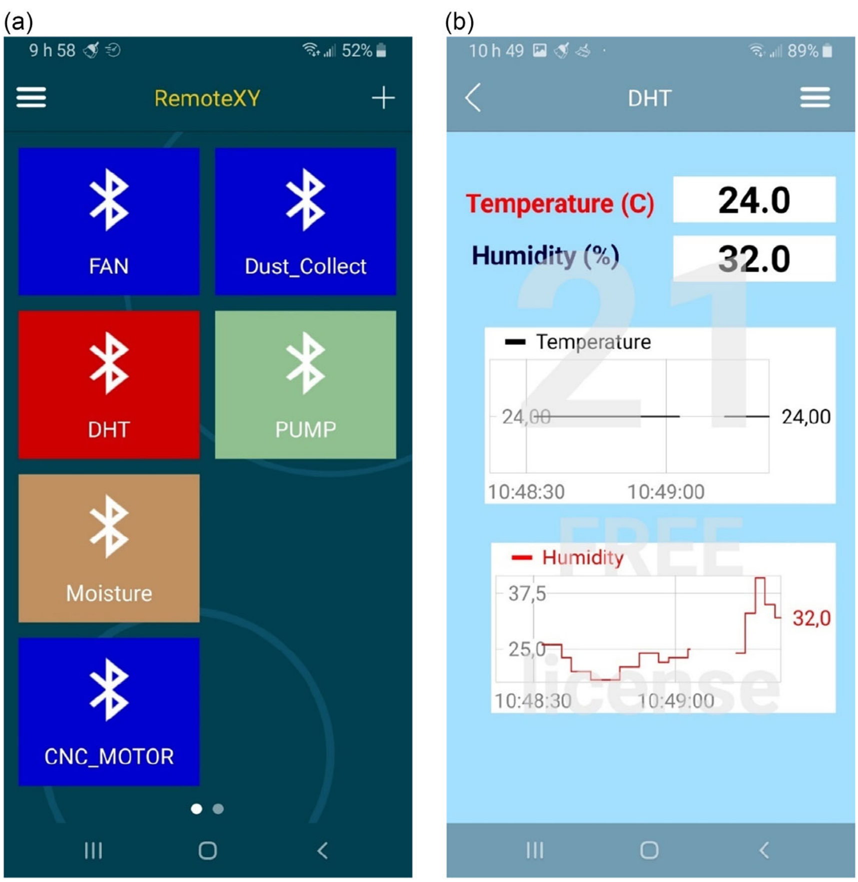

Figure 18. Mobile user interface. a) Device connection screen. b) Data visualization screen.

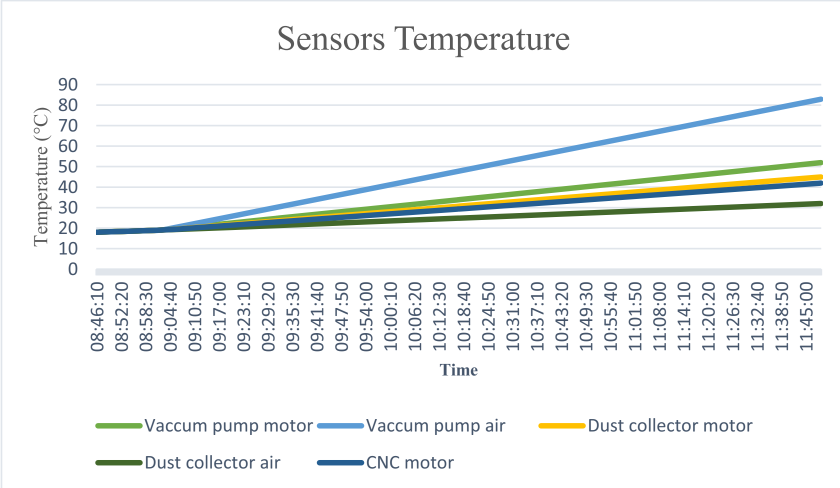

Figure 19. Time-series plot of temperature fluctuations across key equipment (CNC spindle, dust collector, vacuum pump) during workshop operations.

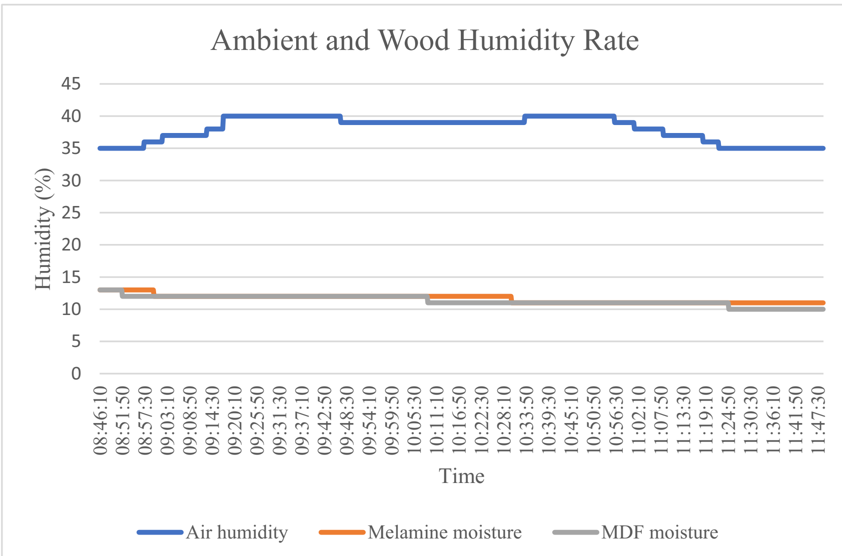

Figure 20. Evolution of air humidity and panel moisture content over time.

payback periods; and 3) evaluate potential incentives or subsidies to support adoption by SMEs.

Cortino et al[30] presented an interesting roadmap that facilitates tailored, low-cost Industry 4.0 adoption, aligned with the operational realities of SMEs by using three Industry 4.0 technologies (Cloud Computing, IoT, and VR). They targeted microenterprises and small enterprises with an average profit margin of around 7.4%. The average budget for innovations was 10% of the profit. They found that SMEs are willing to reinvest between 6 000 CAD and 120 000 CAD in Industry 4.0 implementation. The estimated cost of the tools used for the three technologies is 25 000 CAD, covering the complete range of microenterprises.

The promising thing is that the prices of Industry 4.0 devices and software are falling steadily and becoming more accessible to SMEs.

6.4. Life Cycle Assessment (LCA)

The environmental issues in this study are not treated in depth, particularly LCA, which tracks environmental impacts from the extraction of raw materials (wood, adhesives, finishes) through to manufacturing, distribution, use and end of life, for two reasons: 1) The lack of studies and information on Industry 4.0, energy and sustainability in the furniture industry and 2) the needs of the traditional furniture industry. However, referring to previous work,[29,31] LCA in the Industry 4.0-enabled energy optimization reveals that the most significant environmental impacts in the furniture industry often occur before the product leaves the factory.

Targeting raw materials, adhesives, and manufacturing energy offers the most significant potential for reducing the industry's

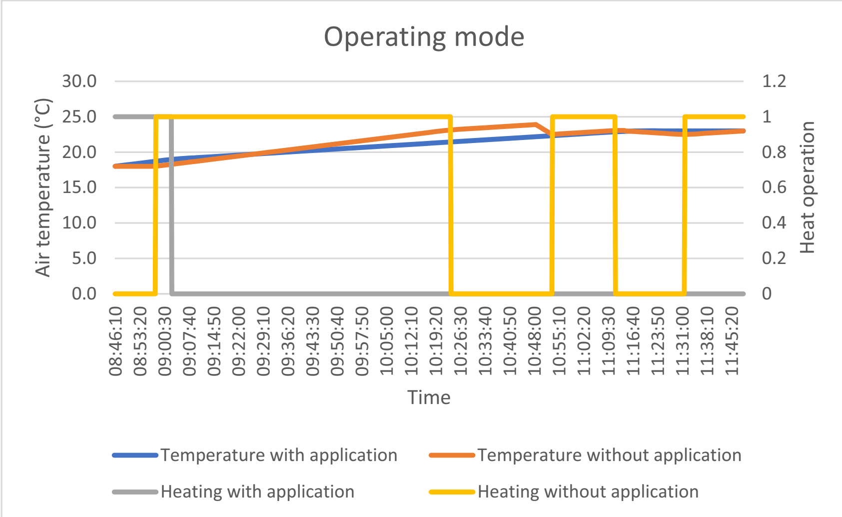

Figure 21. Comparison of ambient temperature and heater usage between assisted and unassisted operation.

Table 3. Comparison of consumption with and without using the application.

Mode	Total operating time	Consumption [Btu]	Consumption [kWh]	Consumption Propane [L]	Heating costs [CAD]
With application	16 m 30 s	68 750	20.15	2.75	2.34
Without application	02 h 01 m 20 s	505 555.56	148.2	20.22	17.19
Difference	−01 h 44 m 50 s	−436 805.56	−128.05	−17.47	−14.85

environmental footprint. By integrating digital technologies to optimize energy efficiency, reduce waste, and improve traceability.

6.5. Broader Implications

This study validates the technical feasibility and potential scalability of the Industry 4.0-enabled energy optimization concept in the wood manufacturing industry. While additional refinements, more extended deployment periods, and broader pilot tests are warranted, the results underscore its relevance for: 1) Large-scale factories looking to optimize energy-intensive processes and 2) osther wood transformation sectors (e.g., wood cutting, wood panel manufacturing) seeking to integrate Industry 4.0 technologies for energy management and sustainability.

Future research should also explore sector-specific adaptations and barriers to ensure broader adoption and contribute to the decarbonization of industrial processes.

7. Conclusions

This study proposes and validates a structured approach for integrating Industry 4.0 technologies to enhance energy efficiency in the wood furniture manufacturing sector, a crucial component of the tertiary transformation of the wood industry. By deploying intelligent sensors, actuators, and an AI-driven Energy Management 4.0 system, the framework supports real-time environmental monitoring, dynamic control of heating and ventilation, and adherence to both thermal comfort and material preservation standards.

The methodology was refined through energy audits at three wood processing facilities and experimentally validated in the SEREX machining workshop. The system demonstrated its effectiveness in reducing energy consumption by 128.05 kWh and lowering operational costs by CAD 14.85 over 3 h from one representative day in a month-long test. These results confirm the practical viability of Industry 4.0-enabled energy optimization solutions for SMEs in the wood industry.

While the initial outcomes are promising, further research is needed to: 1) Extend the solution to other phases of wood transformation and industry sizes, such as mid-sized or large companies; and 2) tailor optimization parameters for application-specific requirements.

Future developments in AI, real-time data processing, and cybersecurity will enhance the system's resilience, scalability, and performance. Additionally, integrating modular workshop configurations and cloud-based large datasets analytics could further optimize energy use and support greater operational flexibility. 1) From a policy standpoint, enabling the widespread adoption of Industry 4.0 in SMEs will require: 2) Targeted financial incentives (e.g., tax credits, subsidies, grants); and 3) workforce training programs that address digital and automation skills gaps are crucial. Additionally, ergonomically designed interfaces are essential for successful adoption.

Stronger collaboration between academia, research centers, and industry through innovation hubs and public–private partnerships.

In conclusion, this study provides empirical evidence and a replicable framework for implementing Industry 4.0-based energy management solutions in the wood industry. The demonstrated energy and cost savings offer a scalable pathway toward sustainable, smart manufacturing with strong potential for broader industrial adoption.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Mohamed Haddouche: conceptualization (lead); data curation (lead); formal analysis (equal); investigation (equal); methodology (equal); software (lead); visualization (equal); writing—original draft (supporting). **Adrian Ilinca**: conceptualization (equal); formal analysis (equal); funding acquisition (lead); project administration (lead); supervision (lead); writing—original draft (equal); writing—review & editing (lead). **Mounir Chaouch**: conceptualization (equal); formal analysis (equal); investigation (equal); methodology (equal); resources (equal).

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

While preparing this work, the author(s) did not use generative AI technologies. The authors used AI-assisted technologies, Grammarly (www.grammarly.com) and Antidote (www.antidote.info), to improve formulation and eliminate grammatical errors. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

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artificial intelligence, energy efficiency, energy management systems, industry 4.0, Internet of Things, thermal comfort, wood industry

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[1] M. Haddouche, A. Ilinca, *Energies* **2022**, *15*, 2384.
[2] B. Sjøbakk, *The Strategic Landscape of Industry 4.0*, Springer International Publishing, Cham **2018**.
[3] M. Haddouche, F. Martini, M. Chaouch, A. Ilinca, *Materials* **2024**, *17*, 1177.
[4] Z. He, Y. Zhang, Z. Wang, Z. Zhao, S. Yi, *Drying Technology*, **2016**, *34*, 1141.
[5] ICER (International Confederation of Energy Regulators), A Description of Current Regulatory Practices for the Promotion of Energy Efficiency, ICER Report, **2010**, Ref. I10-CC-02-04.
[6] H. Kagermann, W. Lukas, W. Wahlster, *Industrie 4.0: Mit dem Internet der Dinge auf dem Weg zur 4. industriellen Revolution, VDI Nachrichten*, VDI nachrichten, Düsseldorf **2011**, p. 2.
[7] P. K. Muhuri, A. K. Shukla, A. Abraham, *Eng. Appl. Artif. Intell.* **2019**, *78*, 218.
[8] J. H. Ang, C. Goh, A. A. F. Saldivar, Y. Li, *Energies* **2017**, *10*, 610.
[9] R.-M. Mario, A.-C. Cristhian, *in Engineered Wood Products for Construction* (Ed: G. Meng), IntechOpen, Rijeka **2021**, p. 20.
[10] W. W. Henning Kagermann, J. Helbig, *Final report of the Industry 4.0, Working Group: Securing the future of German manufacturing industry, Recommendations for implementing the strategic initiative INDUSTRIE 4.0*, Office of the Industry-Science Research Alliance Germany, Germany **2013**, p. 18.
[11] P. Odoroaga, Smart Factory Concept. Smart Industry Process Icons in Alamy. 2016. Available online: https://www.alamy.com/stock-photo-smart-factory-conceptsmart-industry-process-icons-123093167.html (accessed on 20 February 2022). (PDF) Energy Efficiency and Industry 4.0 in Wood Industry: A Review and Comparison to Other Industries. Available from: https://www.researchgate.net/publication/359466091_Energy_Efficiency_and_Industry_40_in_Wood_Industry_A_Review_and_Comparison_to_Other_Industries (accessed: Oct 05 2025).
[12] L. D. Xu, E. L. Xu, L. Li, *Int. J. Prod. Res.* **2018**, *56*, 2941.
[13] Gouvernement du Québec, M.d.l.É.e.d.R.N, *Politique énergétique 2016-2025: Efficacité Et Innovation Énergétiques* (Ed: M.d.l.É.e.d.R naturelles), Bibliothèque et Archives nationales du Québec, Québec **2015**.
[14] C. K. Belt, *Energy-Management-for-the-Metals-Industry*, 1st Edition, (Ed: E.T. Built Environment, Physical Sciences), CRC Press, New york **2017**.
[15] D. Gordić, M. Babić, D. Jelić, D. Konćalović, V. Vukašinović, *Sci. World J.* **2014**, *4*, 596958.
[16] M. W. Jeffery Greenblatt, J. McMahon, *California's Energy Future: Buildings & Industrial Efficiency*, Lawrence Berkeley National Laboratory, California **2012**, 36.
[17] A. McKane, D. Desai, M. Matteini, W. Meffert, R. Williams, R. Risser, *Thinking Globally: How ISO 50001 - Energy Management Can Make Industrial Energy Efficiency Standard Practice*, Ernest Orlando Lawrence Berkeley National Laboratory, California **2009**.
[18] European Parliament, *Directive 2006/32/EC on Energy End-Use Efficiency and Energy Services and Repealing in Official Journal of The European Union*, (Ed.: C.o.t.E. Union), **2006**, European Parliament: Europe (15 members)., Belgium, p. L 114/67-68.
[19] A. A. Mate, Energy analysis and diagnostics in wood manufacturing industry, MS Thesis, West Virginia University, USA **2002**.
[20] M. Fischer-Kowalski, W. Huttler, *J. Ind. Ecol.* **1999**, *2*, 107.
[21] M. N. Rajić, R. M. Maksimović, P. Milosavljević, D. Pavlović, *Sustainability* **2019**, *12*, 1.
[22] B. Zhuming, X. Li Da, W. Chengen, *IEEE Trans. Indus. Inf.* **2014**, *10*, 1537.
[23] Z. Pödör, A. Gludovátz, L. Bacsárdi, I. Erdei, F. N. Janky, *Info. Commun. J.* **2017**, *9*, 24.
[24] ANSI/ASHRAE, American Society of Heating, R. a. A. C. E., Thermal Environmental Conditions for Human Occupancy, Addendum d to ANSI/ASHRAE Standard 55-2017, 2020.
[25] M. Seewaldt, J. Nagel, D. Geckler, U. Bracht, *SNE Simul. Notes Eur.* **2017**, *27*, 61.

[26] P. Onu, A. Pradhan, C. Mbohwa, *Heliyon* **2023**, *9*, e20547.
[27] L. Maretto, M. Faccio, D. Battini, I. Granata, Models for the Cost-Benefit Analysis of Digitalization and Industry 4.0: A Systematic Literature Review, Lecture Notes in Mechanical Engineering **2023**, pp. 675–682.
[28] P. Beaulac, M. Issa, A. Ilinca, J. Brousseau, *Energies* **2022**, *15*, 916.
[29] M. N. Sakib, G. Kabir, S. M. Ali, *Sci. Total Environ.* **2024**, *907*, 167611.
[30] A. Cotrino, M. A. Sebastián, C. González-Gaya, *Appl. Sci.* **2020**, *10*, 8566.
[31] S. I. Vallarta-Serrano, E. Santoyo-Castelazo, E. Santoyo, E. O. García-Mandujano, H. Vázquez-Sánchez, *Energies* **2023**, *16*, 5440.
[32] SEREX, Institutional Presentation, https://serex.ca/blogue/f/pr%C3%A9sentation-du-serex-360%C2%B0-2022, Amqui, Québec, Canada **2022**, (accessed: October 5, 2025).