



QUALITY MANAGEMENT SYSTEMS IN FURNITURE
MANUFACTURING: A REVIEW IN THE CONTEXT
OF THE CIRCULAR BIOECONOMY

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ARTICLE INFO	ABSTRACT
Article History: <i>Received: 12 January 2026</i> <i>Revised: 3 April 2026</i> <i>Accepted: 29 April 2026</i> <i>Published: 15 September 2026</i> Keywords: <i>Wood-processing industries, wood waste valorisation, environmental sustainability, production processes, defect detection</i>	The aim of this study was to examine how the integration of structured process controls, resource- efficient planning, and circular bioeconomic practices can optimise timber use in furniture production, minimise waste, and enhance long-term environmental sustainability. The study applied case-study analysis, a comparative evaluation of enterprise management approaches, and an assessment of technological advancements to develop strategies for improving material efficiency and operational resilience. Drawing on peer-reviewed literature, the research examined the application of Total Quality Management (TQM) and International Organisation for Standardisation (ISO) 9001 standards to reduce wood waste in cutting, milling, and packaging processes. The implementation of the Plan–Do–Check–Act (PDCA) model, quality councils, inspection checklists, and internal audits demonstrated measurable results; for example, a Polish furniture company achieved a 21.6% reduction in reprocessing time within one year. Circular economy practices such as converting leftover wood into briquettes, Medium-density Fibreboard (MDF), or particleboard, lowered raw material costs by between 15% and 20% in the United States (US). By comparison, China managed to increase the volume of reused forest biomass resources to 98% in 2024. India also demonstrated an increase in the use of forest waste by up to 70%, particularly in the Punjab and Karnataka regions. In Albania, furniture manufacturers, which implemented ISO 9001 standards, saw average material waste reduced from 24.5% to 15.25%. These findings can help furniture manufacturers, policymakers, and sustainability managers implement quality-driven, circular, and technology-enabled solutions to improve resource efficiency, reduce costs, and support environmental sustainability objectives.

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Introduction

The Quality Management System (QMS) within furniture companies, is a critical determinant of production efficiency, which influences the industry’s ability to use forest resources rationally in line with the principles of the circular bioeconomy. Despite the substantial forest-resource base available in many developed European countries, the sustainable use of timber remains a significant challenge, exacerbated by limitations in monitoring systems and the continuing need to improve resource efficiency.

Consequently, the development and implementation of a modernised management framework capable of combining quality standards, environmental responsibility, and economic viability is essential for enhancing the competitiveness of furniture manufacturers.

Quality management practices within the European furniture industry remain fragmented and unevenly implemented. Although the industry adheres to basic production standards, the integration of circular bioeconomy principles

remains in its nascent stages. The absence of a unified methodology for assessing the efficiency of wood use, weak coordination between enterprises and institutions, and the restricted adoption of best practices has led to excessive raw material losses and missed environmental and economic opportunities. These shortcomings undermine sectoral competitiveness and hinder the development of sustainable strategies for the forestry and furniture industries.

The integration of circular bioeconomy principles in Albania to further its sustainable development agenda was examined by Hysaj (2025). The study determined that effective resource management was closely linked to a country's progress towards European sustainable development goals. The findings highlighted the need for systemic changes in production processes, with quality management serving as a principal mechanism for reducing waste and increasing the competitiveness of enterprises. Similarly, Kola and Çerpja (2024) explored the potential and opportunities of the circular economy in Albania and identified significant opportunities for its application within the furniture sector arguing that the furniture industry could become one of the leading adopters of circular economy principles via the use of recycled wood and the optimisation of production cycles, and the introduction of innovative quality control systems. Their findings suggested that effective quality management facilitates the transition from a linear to a circular economic model while reducing environmental impacts.

Despite the potential benefits of implementing the circular economy mechanism, several potential challenges remain, Prendi *et al.* (2024) analysed the risks associated with adopting circular economy practices, particularly among small and medium-sized enterprises (SMEs). The study identified several issues: The lack of financial resources, insufficient staff qualifications, and weak institutional support, which complicate the adaptation of innovative approaches to quality management.

The contribution of quality management systems in enhancing the international competitiveness of companies was addressed by Murmura *et al.* (2024). The study demonstrated that the implementation of certified standards such as ISO 9001 (International Organisation for Standardisation, 2015a), provides a foundation for optimising that strengthens organisational credibility in international markets. Furthermore, the authors found that quality systems contribute not only to improving production but also to the rational use of resources, by defects and unproductive costs. Likewise, Teta (2023) investigated the application of Total Quality Management (TQM) among Albanian enterprises. Although TQM implementation remains at an early stage in Albania, the study identified significant potential for improving product quality, optimising processes, and integrating the principles of the circular economy.

Hoda and Angjeli (2024) examined the development of green and circular economic pathways in Albania. Their study highlighted the integration of these approaches as a strategic requirement for achieving national sustainable development objectives and aligning with European standards. The authors concluded that the success of this transition depends largely on the ability of enterprises to implement comprehensive quality management systems capable of balancing economic performance with environmental protection. Furthermore, the study emphasised the need for an enabling regulatory and institutional framework that encourages the adoption of innovative approaches, particularly within the furniture industry, which possesses substantial potential for resource conservation.

The development of circular business models within the manufacturing sector was explored by Hasa (2022). The study demonstrated that the utilisation of recycled materials and the recovery of production waste are effective strategies for reducing environmental impacts while enhancing economic performance. The findings indicated that quality management

systems facilitate the integration of such models into business operations by standardising processes related to the collection, sorting, and reuse of materials. Within the furniture industry, these practices create opportunities for establishing sustainable value chains focused on minimising wood waste and strengthening long-term competitiveness.

Similarly, Canco (2022) examined the possibilities of improving the inventory management systems of Albanian manufacturers. The authors noted that traditional approaches to accounting for materials and finished goods did not meet modern efficiency requirements and frequently resulted in inefficient resource use. The findings emphasised that integrating advanced inventory-management practices within the quality management system can reduce production costs and rationalise the use of raw materials. This part has a direct impact on the furniture industry, where the loss of raw materials directly affects the sustainability of business models.

The study aimed to assess the impact of integrating process control, effective resource planning and circular bioeconomy approaches on improving resource efficiency and strengthening environmental sustainability in furniture production. To achieve this goal, a set of objectives was identified: (1) to assess the impact of implementing Total Quality Management (TQM), ISO 9001, and ISO 14001 environmental standards to waste reduction and productivity management; (2) to analyse contemporary digitalisation and automation methods used in furniture manufacturing processes; and (3) to examine the practical mechanisms of the circular bioeconomy and the use of recycled materials in furniture production to ensure the economic and environmental sustainability of enterprises.

Materials and Methods

The study adopted an empirical research design and covered the period from 2019 to 2025. The research was based on a comparative analysis

of wood use practices within the furniture industries in Germany, Sweden, Italy, Poland, Albania, Denmark, Finland, Norway, the Baltic States, Austria, Switzerland, India, China, Romania, Hungary, Ukraine, the United States of America (USA), France, the Netherlands, and the Czech Republic, with an emphasis on quality management, circular bioeconomy principles, and sustainable technological integration.

The selected countries were chosen because they represent a diverse selection of different furniture industry development and quality management models within the context of the circular bioeconomy. The comparative approach enabled an assessment of the relationship between the implementation of quality management systems and Plan-Do-Check-Act (PDCA) cycle (Realyvásquez-Vargas *et al.*, 2018) and improvements in resource efficiency, reductions in defect rates, and enhanced competitiveness among furniture manufacturers. Furthermore, they examined the principles and applications of several quality-management tools including Statistical Process Control (SPC) (2025), TQM (Ali, 2024), and Six Sigma (2021).

Germany, Sweden, and Italy were selected to represent mature markets with a high level of technological sophistication, which made it possible to identify long-term effects of TQM and Six Sigma systems. In Germany, the implementation of lean manufacturing and modern quality management systems was analysed via an analysis of equipment manufacture HOMAG and sawmill Hirschbach GmbH, both of which have implemented optimisation measures to improve efficiency (HOMAG Group, 2025; Hirschbach GmbH, 2025).

In Sweden, benefits of TQM implementation were assessed in relation to reduced material losses and improved efficiency in edge bonding operations. In Italy, the study examined a case involving the reduction of defects in veneered surfaces through the integration of Six Sigma methodologies within an ISO 9001-certified quality management framework.

Albania and Ukraine were included as examples of transformational economies where the implementation of quality management systems directly contributed to increased competitiveness and access to European markets. In Albania, the analysis focused on the FPM Tuttomobili (2025) furniture factory.

The study relies primarily on secondary data sources and publicly available company information. Consequently, variations in reporting practices, data availability, and methodological approaches across countries may influence the comparability of results

Content analysis of publicly available information was used to evaluate the effects of PDCA implementation on defect reduction and international market expansion (SeeNews, 2025). In addition, data published by the Organisation for Economic Co-operation and Development (OECD) (2024) were used to assess reductions in material waste among Albanian furniture manufacturers following the adoption of the Quality Management System (QMS). For Ukraine, the assessment focused on the implementation of bioenergy production lines within the furniture manufacturing sector (United Nations Industrial Development Organisation, 2023).

The study also considered cases from Denmark, Finland, France, Norway, and the Baltic States. The countries were selected for their high environmental standards and emphasis on the sustainable use of resources, which addressed the role of integrated ISO systems in reducing waste and emissions. Internal and external auditing practices in furniture manufacturing were analysed using examples from Denmark and Finland (Energy Efficiency Case Study, 2019). A hypothetical scenario was modelled in which furniture factories in Denmark and Finland, certified according to ISO 9001 (International Organisation for Standardisation, 2015a), conduct internal audits quarterly and external audits on an annual basis to reduce non-compliance. Reductions in formaldehyde emissions and improvements to

waste sorting in Norway were assessed using examples from Vestre (Deep Decarbonization, 2022), Formfin Møbler AS (2025), and Helland Møbler (2025).

In the Baltic States, the study investigated the influence of integrated quality management systems on reducing wood combustion losses and water consumption during surface-treatment processes through the cases of BDESK (2025), Kitman Thulema (Green Thinking at Kitman Thulema, 2024), Be-Ge Baltic (2024), and Baltic Sea Region Strategy Forum (2019). The French case focused on the adoption of eco-labelling and quality management systems to increase the market share of circular products (Espace-Loggia, 2023). In addition, the broader policy context was considered through reference to the European Commission's Circular Economy Action Plan (A New Circular Economy Action Plan, 2020).

Austria, Switzerland, Romania, and Hungary have demonstrated the benefits of digitalisation and automation in woodworking, combined with investments in staff training. At the same time, Austria and Switzerland described the introduction of Enterprise Resource Planning (ERP) systems and digital process monitoring. In Romania, the impact of the introduction of an optical system and Computer Numerical Control (CNC) on reducing energy consumption and increasing the use of recycled wood was identified in the example of EGGER (2025). The relationship between increased productivity and waste reduction through AI control was studied on the example of Hungary.

Finally, the inclusion of the United States, China, and India ensures a comprehensive analysis, reflecting the extent of circular economy practices in the largest furniture and board producers. In Poland, the impact of PDCA implementation on reducing raw material processing time and reducing reject rates was examined in detail. The data was normalised to improve comparability across countries; however, differences in regulatory frameworks, technological maturity, and production

structures may influence the observed results. Therefore, cross-country comparisons should be interpreted with caution, as outcomes may vary depending on local conditions.

Results

Quality management in the furniture manufacturing industry extends beyond simple product inspections and encompasses a systematic approach to continuous improvement and, the strategic alignment of organisational objectives with environmental and economic sustainability. Contemporary quality management frameworks emphasise not only compliance with consumer expectations but also the optimisation of production processes to minimise waste generation and environmental impact (Fedotova *et al.*, 2021; Skorupińska *et al.*, 2024). Standards such as TQM and ISO 9001 (International Organisation for Standardisation, 2015a) provide structured frameworks that integrate quality into every quality of the value chain.

TQM promotes a culture of continuous improvement by encouraging employees at all organisational levels in quality-related processes, increasing transparency and preventing defects rather than merely detecting them. Similarly, ISO 9001 as a globally recognised standard formalises quality management principles through documented procedures, customer-focused policies, performance metrics and ongoing internal audits. Both systems align with the growing focus on sustainable resource management, particularly in industries that rely on natural resources, such as furniture manufacturing.

Within the furniture sector, these systems gain even more significance as wood is a heterogeneous material whose characteristics vary according to species, moisture content, grain direction and defects such as knots or cracks (Horbachova *et al.*, 2024; 2025). Consequently, quality assurance in woodworking must begin at the raw material procurement stage and continue through sawing, drying, cutting, machining, assembly, surface treatment, and packaging.

Methodologies such as Statistical Process Control (SPC), Six Sigma, and TQM provide mechanisms for measuring, analysing, and reducing process variability (Six Sigma, 2021; Ali, 2024; Statistical Process Control, 2025). SPC, for example, employs control charts to identify process deviations in real time, enabling timely corrective action. This capability is particularly valuable during Computer Numerical Control (CNC) machining and veneer application, where minor inconsistencies may result in substantial material losses. Similarly, Kaizen emphasises incremental, continuous improvements driven by frontline employees, whereas Six Sigma seeks near-perfect performance by targeting a defect rate of 3.4 defects per million opportunities (The Kaizen Philosophy, 2025).

In wood processing this can translate into the micro-optimisation of parameters such as feed speed, blade sharpness, and moisture balance to ensure maximum profitability and minimum rework. Empirical data indicates that quality management systems can contribute to improved wood utilisation, particularly when consistently implemented and supported by appropriate organisational practices. The average proportion of wood waste in ISO 9001-certified enterprises was 13.5%, compared to 22% in non-certified enterprises (Ratnasingam & Ioras, 2014).

Germany provides a notable example of the application of quality-management principles within the wood-processing sector. Manufacturers of woodworking equipment, including HOMAG, alongside primary wood processors such as Hirschbach GmbH, have adopted lean manufacturing approaches and advanced quality-management systems to improve operational efficiency (HOMAG Group, 2025; Hirschbach GmbH, 2025). Similarly, major wood-product manufacturers, including Pollmeier and Binderholz, have reported productivity-enhancement initiatives consistent with lean manufacturing principles (Ensun.io., 2025).

In Sweden, a country known for advanced forestry and sustainable manufacturing, in 2020

TQM-based companies using CNC-integrated quality monitoring achieved a 27% decrease in sanding-related material loss and improved edge gluing efficiency by 31% (Besserer *et al.*, 2021). This effect can be explained by the integration of CNC-based monitoring systems, which enable real-time control of sanding parameters and reduce variability caused by manual operations. As a result, process deviations are detected earlier, leading to lower material waste and more consistent adhesive application.

In the meantime, in Italy, which ranks among the world's top five furniture exporters, companies following Six Sigma within ISO 9001 frameworks reduced defect rates in veneered surfaces from 8.9% to 2.6% over 14 months. This improvement may be attributed to the application of Six Sigma tools, which systematically identify root causes of defects and eliminate process variability. By standardising veneer application and controlling critical parameters, companies reduced rework and material loss. The average cost saving across 56 surveyed Italian firms was approximately EUR 510,000 per year, due to reduced rework and optimised use of hardwood veneers such as walnut and oak (Korba *et al.*, 2025). In the analysed cases, the application of QMS systems is associated with improvements in resource efficiency, particularly in contexts where employee involvement is high, although the strength of this relationship may vary depending on implementation conditions.

The culture of continuous improvement in furniture manufacturing is fundamentally supported by the PDCA cycle, a core methodology embedded within quality management systems like ISO 9001 and TQM. PDCA provides a structured, incrementally building approach for organisations to plan improvements, implement changes on a small scale, monitor outcomes and standardise successful practices (Realyvásquez-Vargas *et al.*, 2018). The cyclical process helps companies systematically reduce variability and defects while promoting adaptive learning (Salek, 2023). Practically applying PDCA has led to substantial gains in wood utilisation efficiency (Figure 1).

The example of furniture manufacturing in Poland demonstrates a 21.6% reduction in processing time for raw materials within one year after establishing PDCA-based quality control points at each stage of production. In 2020 The implementation of PDCA was associated with a reduction in reprocessing time from 736 hours per month to 580 hours per month and scrap rate by 25.7%. In contrast, 2019 showed less than 1.5% improvement in reprocessing time and stable scrap rates, highlighting the impact of PDCA implementation. A practical example of integrating circular bioeconomy principles through QMS can also be observed in Polish furniture manufacturing, where PDCA cycles are applied not only to production efficiency

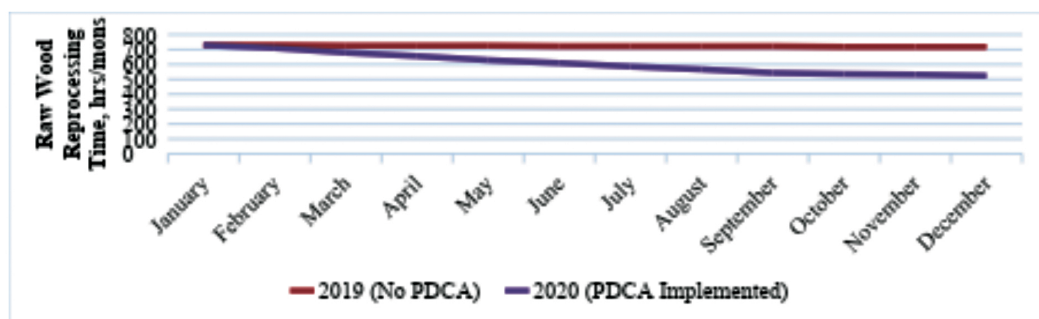


Figure 1: Monthly impact of PDCA cycle implementation in Polish furniture manufacturing in 2020 and comparison with 2019

Source: Compiled by the authors based on Salek (2023)

but also to wood waste management. Within the “Plan” and “Check” stages, companies systematically identify sources of wood residues such as offcuts and sawdust, while in the “Do” and “Act” phases these materials are redirected into secondary production streams, including particleboard and briquettes. This structured approach enables continuous optimisation of recycling processes, reducing material losses and supporting the transition to closed-loop resource use. The observed improvements result from the structured feedback loops inherent in the PDCA cycle, where continuous monitoring and corrective actions reduce process inefficiencies and prevent the accumulation of defects.

The implementation of the PDCA cycle enhances employee engagement through continuous feedback loops, providing rapid detection and correction of process defects (Nova Poshta Business School, 2025). Companies that have fully integrated PDCA into their operational processes report improvements in efficiency and a reduction in defect rates. For example, in the practical application of PDCA systems, the FPM Tuttomobili furniture factory in Albania demonstrates the high level of organisation required for continuous improvement. The company has a production facility of approximately 40,000 m² and employs around 150 people (SeeNews, 2025). The company exports its products to more than 26 countries, which indicates strong quality control and standardisation procedures, key elements of the “Check” and “Act” phases of the PDCA framework. The structure of planning, execution, verification, and feedback-based actions (which are components of the system) maintains the stability of furniture quality, reduces the number of defects and ensures competitiveness in the international market (FPM Tuttomobili, 2025). Furthermore, quality councils and cross-functional teams use PDCA to test process improvements on a small scale before full implementation, minimising the risk of costly errors. This iterative approach ensures that quality management is dynamic rather than static, promoting both operational excellence and sustainable use of wood resources.

Additionally, In Albania, a country with a growing furniture sector and increasing integration into European value chains, the adoption of QMS practices is picking up speed. Furniture SMEs which implemented ISO 9001 standards, as usual with European Union (EU) technical support, decreased average material waste from 24.5% to 15.25% within one year (Organisation for Economic Co-operation and Development, 2024). This reduction can be attributed to the standardisation of production processes and the introduction of systematic quality control procedures, which minimise inconsistencies and reduce the likelihood of material losses during manufacturing. These gains are significant for Albania, where high-quality timber is limited and imported wood is costly. Through quality systems companies are not only improving product consistency, but as well gaining access to European markets that demand both technical compliance and environmental responsibility. Furthermore, internal and external audits serve as the backbone of quality enforcement (Oncioiu *et al.*, 2020; Albania Wood Furniture Market, 2024).

In highly regulated environments such as Denmark and Finland, where quality and environmental standards are closely enforced, the integration of ISO 9001 (International Organization for Standardisation, 2015a) and ISO 14001 (International Organisation for Standardisation, 2015b) has demonstrated operational benefits. Drawing on Organisation for Economic Co-operation and Development (2019) sector benchmarks and International Organisation for Standardisation (2015a, 2015b), United Nations Industrial Development Organisation (2023) case studies, a modelled scenario suggests that ISO 9001-certified furniture factories typically conduct internal audits on a quarterly basis and external audits annually, with results indicating that more than 90% of non-conformities are detected and corrected internally before external intervention is required. For instance, in a modelled case reflecting the scale of Denmark’s large office furniture manufacturers, internal audits facilitated the identification and correction of

56 minor process deviations, corresponding to approximately EUR 230,000 in avoided losses per year (Energy Efficiency Case Study, 2019). Moreover, when ISO 14001 integrated with ISO 9001, these benefits extended further, yielding additional improvements in environmental performance and resource efficiency (Hut-Mossel *et al.*, 2021).

In Norway furniture companies Vestre (Deep Decarbonization, 2022), Formfin Møbler AS (2025), Helland Møbler (2025) in 2024 certified under both standards reduced formaldehyde emissions from engineered wood panels by 38% and improved waste sorting efficiency by 44%, enabling higher rates of recycling and reuse. In a comparative study across the Baltic States, companies with integrated quality-environmental management systems – BDESK (2025), Kitman Thulema (Green Thinking at Kitman Thulema, 2024), Be-Ge Baltic (2024), reduced their wood incineration volumes by 22% and water usage in surface finishing by 31% (Baltic Sea Region Strategy Forum, 2019). In France, where furniture producers must comply with strict eco-labelling regulations, in 2022 firms that integrated QMS and environmental management reported a 17% increase in circular product lines, including modular and disassembled furniture (Espace-Loggia, 2023).

The concept of circular bioeconomy in the forestry sector represents a transformative model where biological resources like wood are managed, utilised and regenerated in a way that maximises efficiency and sustainability (Mikhno *et al.*, 2023; Shahini *et al.*, 2025). Unlike the traditional linear economy (where raw materials are extracted, used, and discarded) the circular bioeconomy emphasises material reuse, energy recovery, and ecosystem preservation, aligning strongly with zero-waste and climate neutrality goals. In furniture manufacturing, this means reconsideration of how wood residues such as sawdust, wood chips and offcuts are managed—not as waste, but as valuable inputs for secondary production like briquettes, particleboard (PB), and plywood. This model is anchored in systems

thinking and resource efficiency principles (Burlakovs *et al.*, 2020; Paletto *et al.*, 2022).

The European Commission's Circular Economy Action Plan (2020) defines bioeconomy as a key enabler of climate targets, promoting bio-based material loops that reduce the need for virgin biomass. In forestry, this includes closed-loop wood processing, sustainable harnessing quotas and advanced waste-to-value conversion. In ISO 14001 environmental management systems circularity is also a performance metric, guiding companies to integrate material lifecycle management into strategic planning. Additionally, Life Cycle Assessment (LCA) tools used to evaluate the environmental benefits of converting wood waste into value-added products, showing significant CO₂ savings compared to landfilling or incineration (Hasegawa *et al.*, 2022; Umair & Guliyeva, 2025).

In practice, the circular bioeconomy has demonstrated positive outcomes worldwide. In Germany nearly 87% of wood waste generated by the wood product sector is either recycled or reprocessed, leading to a 38% decrease in landfill wood volume between 2012 and 2022 (Federal Ministry for Economic Affairs and Climate Action, 2025). In the USA, where the furniture industry produces over 9 million tonnes of wood residues annually, companies like Herman Miller and Steelcase integrate circular practices by converting offcuts into engineered wood panels of compressed fuel. This shift not only reduces waste but cuts raw material costs by 15% to 20% annually. In India, where demand for middle-class wood furniture is growing, plywood and Medium Density Fibreboard (MDF) producers are reusing up to 70% of sawmill waste, especially in Punjab and Karnataka, where biomass wood chip briquettes are used in the textile and food industries (PCIAW, 2023). In China, the world's largest producer of plywood and board, national policies encourage the reuse of forest biomass. For example, more than 95 million cubic metres of forest residues were reused in 2023, leading

to a 41% increase in exports of secondary wood products (Wang *et al.*, 2023; Kerimkhulle *et al.*, 2025). From an economic point of view, the reuse of wood residues significantly increases economic efficiency and effectiveness (Figure 2).

The data presented in Figure 2 demonstrates that the use of forest waste for the production of wood products in the USA, India, and China is showing steady growth. In particular, China, as the world's largest producer of plywood and boards has significantly increased the volume of reuse of forest biomass resources, as evidenced by a sharp increase to 98% in 2024. India is also showing significant growth in the use of forest waste, especially in the Punjab and Karnataka regions, where up to 70% of sawmill waste is reused. However, compared to China, the growth rate in India is more moderate. The USA, while showing a steady increase in the use of forest waste, has a relatively lower growth rate compared to India and China, at around 40% by the end of 2024. This may be due to lower biomass recovery rates compared to other countries.

In Sweden, where circularity is embedded in national forest strategy, 95% of sawdust is reused for pellet production or particleboard. The country's circular wood sector contributes over EUR 4.7 billion to the Gross Domestic Product (GDP) annually, according to Eurostat (2023). The environmental impacts are equally profound. By converting sawdust into panels or fuels, companies reduce methane emissions

from landfill and improve carbon emissions containment effectiveness and efficiency (Hussain *et al.*, 2022; Ren *et al.*, 2025). A 2021 FAO study found that reusing wood residues instead of discarding them reduces net GHG emissions by up to 1.2 tonnes of CO₂ per tonne of residue. Applying this to large-scale manufacturers could result in hundreds of thousands of tonnes of avoided emissions yearly. Furthermore, resource-efficient management aligns with SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action), that enables forest-based enterprises to meet both regulatory and CSR benchmarks (Borrello *et al.*, 2023; Khodakivska *et al.*, 2023). Furniture manufacturers can integrate circular principles by adopting waste tracking systems, investing in residue-compacting machines, and forming regional bio-cooperatives to share secondary material streams.

In Finland and the Netherlands, small and medium-sized enterprises are actively implementing digital twins, a live virtual copy of a real physical object, machine, or system. It updates in real time using data from sensors on the actual physical object, which lets experts test ideas and fix problems on the computer safely before trying them in the real world, and Artificial Intelligence (AI) algorithms to optimise production. In Finland, the use of these technologies can reduce water consumption by up to 90% and cut energy consumption by more than half (European research supports Finnish,

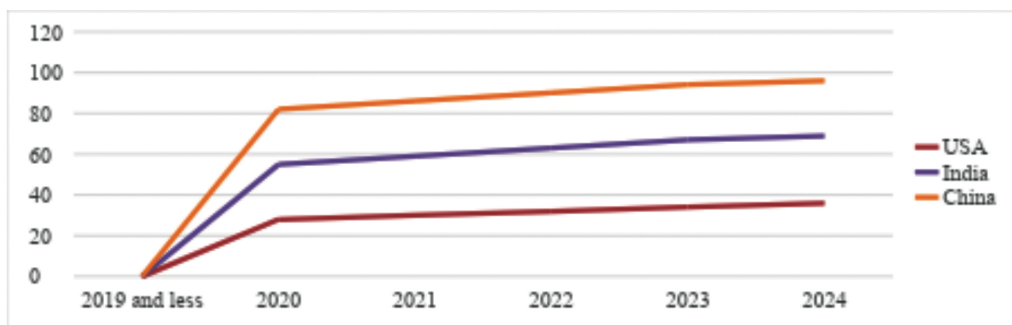


Figure 2: Regional variation in wood residue reuse rates in the USA, India, and China (2019 to 2024)

Source: Compiled by the authors based on Wood: Fristads contributes to biomass-based power plant supporting textile manufacturing in India (2023); Y. Wang *et al.* (2023); Material-Specific data (2024)

2024). In the Netherlands, digital twins have been found to reduce CO₂ emissions by 10%, contributing to increased production efficiency and operating cost savings (Digital Twins, 2024).

The sustainable transformation of the woodworking industry rests on two primary pillars: The integration of advanced manufacturing technologies and the development of a skilled, adaptive workforce (Boccaccio *et al.*, 2019; Kubiczek *et al.*, 2025). Theoretically, sustainable development in the wood processing sector is guided by the principles of circular bioeconomy, where resource efficiency, waste minimisation and renewable energy use are prioritised. Within this framework the transition to intelligent manufacturing (characterised by CNC systems, AI-powered optical inspection, and digital process monitoring) represents a shift from traditional linear models to closed-loop systems. These systems embody the values of regenerative production by maximising the utility of every input, decreasing environmental impacts, and supporting long-term ecosystem sustainability (Rahman *et al.*, 2025). In addition, continuous professional refining of staff ensures that human capital evolves in tandem with technological advancement, enhancing not just machine efficiency, but also the interpretive and diagnostic capacity of production teams (Gherghea *et al.*, 2020).

Practically, the theoretical model has taken root across multiple Eastern European states. In Romania, particularly at EGGER's Rădăuți factory, CNC, and optical systems introduced in 2022 significantly improved operational performance. From 2021 to 2024 energy consumption per cubic metre of finished board decreased by over 11%, and recycled wood usage climbed from 64% to 70%. Optical scanners helped lower visual defects, while automated packing reduced human error rates by 19%. This outcome is associated with the automation of repetitive operations, which reduces reliance on manual labour and eliminates common human-induced errors, thereby improving overall process precision and reducing waste. Simultaneously, investment in

worker training (roughly EUR 2.4 million over four years) ensured that the workforce could properly interpret machine data and conduct preventive maintenance (EGGER, 2025).

In Hungary, a major furniture exporter, deployment of CNC routers and AI inspection systems between 2019 and 2020 resulted in a 91% increase in production throughput with waste from offcuts and miscuts dropping by 28%. The introduction of CNC milling reduced production cycle time of a medium-sized factory from 15.6 days to 1.4 days, generated EUR 2,871 in extra revenue, and added 2,008 units annually to production capability, despite using the same raw material volume (Marciniak *et al.*, 2021).

In Ukraine, where many firms operate under constraints imposed by energy infrastructure challenges, sustainable innovation is not only a strategy, but a necessity. At HS B's facilities, investments in wood-compound Research and Development (R&D) and biomass-powered CNC lines reused 85% of sawmill residues in chipboard and compressed fuel production. The factory reported cutting natural gas dependency by over 50% from 2021 to 2023, since energy was increasingly generated in-house from bark, sawdust and trimmings. Ukrainian enterprises also benefitted from technical exchange with EU partners through digital twin training platforms with over 420 workers trained in CNC operation and visual inspection across the period. These combined technological and human-centred upgrades position Ukraine's woodworking sector as a contributor to circular manufacturing in the region (United Nations Industrial Development Organisation, 2023).

In the global context, the woodworking industry has seen rapid adoption of Industry 4.0 technologies. Between 2020 and 2024, CNC-controlled production in the wood sector expanded by 25% to 30%, driven largely by Central Europe and East Asia. In Poland (Królikowski *et al.*, 2021) and Czech Republic (Nagy *et al.*, 2025) machine vision tools decreased reprocessing errors by 35%, while global data shows that AI integration in CNC

operations helped achieve material saving of up to 20% and downtime reduction of 30% through predictive maintenance. In 2023 alone (over 45% of global woodworking firms used AI in some part of their operations) a figure projected to surpass 60% by 2026. Meanwhile, the average defect detection rate of optical systems improved to 95%, leading to fewer customer complaints and reduced warranty costs.

In Hungary and Romania employee training in tandem with new technologies proved to be relevant. A 2023 EU--funded vocational programme trained over 3,200 workers in CNC operation and visual analytics, leading to a 16% improvement in production quality scores and a 12% drop in rework-related energy costs (Ioniță & Popescu, 2024). Training also shifted factories from single-function machines to multifunctional CNC centres capable of routing, drilling, sanding, and edge-banding in a single workflow, improving equipment utilisation rates by over 20%. As the woodworking industry faces growing global demand, sustainable production practices offer a clear path forward. The fusion of smart technology with skilled labour not only reduces material and energy waste but also creates long-term resilience for manufacturers. This model, already adopted in countries like Romania, Hungary, and Ukraine proves that environmental and economic objectives can be pursued in harmony when sustainability is treated as both a technological and educational challenge. With continuous improvements in CNC control accuracy, AI diagnostics, and eco-efficient training, the woodworking sector can continue to scale up while staying deeply embedded in circular principles.

Discussion

With the growing demand for efficient use of natural resources and integration of sustainability principles into production processes, the role of quality management systems is becoming increasingly significant. These systems serve not only as mechanisms for product quality control but also as instruments for optimising production processes and improving resource

efficiency, but also a comprehensive method of optimising production processes, reducing waste and improving the economic and environmental efficiency of enterprises. In this case, it is necessary to address the interaction of technological innovations, organisational approaches, and staff competence in shaping the systemic sustainability of production and circular use of materials. This approach can be used to assess quality management in a broader context as a key tool for ensuring resource efficiency, implementing the principles of the circular bioeconomy, and supporting the long-term sustainable development of industrial sectors.

From a strategic perspective, quality management systems serve as an organisational foundation for the implementation of circular bioeconomy principles in the furniture industry. Unlike isolated technological solutions, QMS provides a structured framework that integrates resource efficiency, waste minimisation, and continuous improvement into all stages of production. Through tools such as PDCA cycles, internal audits, and standardised procedures, companies can systematically monitor material flows, identify opportunities for reuse of wood residues, and ensure the consistency of recycling practices. This transforms the circular bioeconomy from a collection of isolated practices into an integrated and scalable organisational framework into a managed and scalable system embedded within enterprise operations.

In this context, quality management systems such as PDCA, internal audits, and TQM play a crucial enabling role in the implementation of circular bioeconomy practices. These tools support the systematic identification, monitoring, and reuse of wood residues, facilitating the transition from linear production models to closed-loop material cycles.

Falcone *et al.* (2020) conducted a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis of the forest bioeconomy in Italy, identifying the strengths and weaknesses of implementing the principles of sustainable

resource management, as well as opportunities and threats to the development of the industry. The study emphasised that systematic planning and integration of environmental criteria into production processes contribute to increasing the efficiency of wood use and optimising waste. These findings are consistent with, which found that the introduction of quality management systems and circular bioeconomy principles in the furniture industry significantly reduced wood losses and increased efficiency of material processing in Italy and other European countries.

Bianchi *et al.* (2024) reviewed practical examples of circular bioeconomy implementation at different scales of implementation. The study addressed the role of integrated management systems, digital technologies, and by-product recycling in reducing environmental burdens and increasing economic efficiency. The present study supports, which revealed that the use of digital tools, CNC technologies, and PDCA methodology in furniture production in different countries has optimised resources and increased the efficiency of production processes.

Circular economy initiatives in the forest bioeconomy with an emphasis on the use of non-wood biomaterials were reviewed by Miassi and Dossa (2024). The study demonstrated that the secondary use of by-products such as plant waste, reduces pressure on forest resources, and creates additional economic benefits. The study also examined aspects of the practical implementation of these principles in the furniture industry, where wood waste was converted into biofuel, MDF, and panels, providing significant material savings and reducing environmental impact.

At the same time, Schipfer *et al.* (2024) described the circular bioeconomy as a driver of systemic integration of production processes. The study proved that the integration of environmental, technological, and management approaches contribute to a comprehensive increase in resource efficiency and waste reduction. The results directly correlate with the study, where the application of quality

management systems, digital platforms, and circular economy principles in European and Eastern European furniture companies has led to increased productivity, wood savings, and the introduction of environmentally efficient practices at every stage of production.

Barañano *et al.* (2022) conducted a comprehensive assessment of the development of the forest bioeconomy in different regions of Europe, identifying key success factors, barriers, and regional specificities of the implementation of circular strategies. The study included an analysis of regional policies, existing technology platforms and wood reuse practices, which identified successful resource management models. These results correlate with the study conducted, where the introduction of quality management systems in furniture companies in various European countries contributed to a significant reduction in wood losses, increased efficiency of production processes, and implementation of environmental standards. The authors' SWOT analysis methodology supported a similar approach in their study to assess the strengths and weaknesses of implementing QMS and CNC technologies in furniture companies.

A multi-criteria approach to matching circular economy technologies with regional conditions was proposed by Güldemund and Zeller (2024), demonstrating that the adaptation of strategies to local resource, economic, and environmental characteristics increases the efficiency of implementation. The study addressed the use of quantitative and qualitative indicators for the selection of optimal technologies, including criteria of economic feasibility and environmental impact. This directly correlates with the results of the study, where the successful application of digital systems, CNC technologies and the PDCA cycle in the furniture industry depended on incorporating the specifics of national supply chains, resource availability and staff qualifications in Poland, Romania, and Ukraine. Using descriptive analysis and comparison of regional data, the study confirmed the

practicality of an adaptive approach to QMS integration in different conditions.

Bayram *et al.* (2024) conducted a systematic review of the definition and contexts of product quality in a circular economy, focusing on the relationship between quality, material efficiency, and economic sustainability. The study summarised the experience of various European and international practices, determining that the integration of quality management standards, and material flow monitoring is critical to reducing resource waste and increasing economic efficiency. Similar trends were observed with the study, where the integration of TQM, ISO 9001, and internal audits resulted in reduced defects, optimised wood and improved economic and environmental performance of furniture production in Europe and Asia.

Lange *et al.* (2021) explored the development of a sustainable and circular bioeconomy in the EU through cross-sectoral partnerships, scaling up innovation, and rapid knowledge integration to benefit climate, environment, biodiversity, and economy. The study emphasised the importance of resource sharing, staff training, and digital platforms for the systemic integration of circular bioeconomy principles. The conclusions support the use of practical quality management tools such as PDCA, Kaizen, and internal audits to achieve sustainable wood use and economic benefits. This correlates with the study, which found that a combination of technological innovation, digital platforms, and staff training in the furniture industry has contributed to systematic improvements in resource efficiency, waste reduction, and implementation of principles at national and regional levels in Albania.

Comparing the results of the study with international examples, the findings suggest that increasing the efficiency of wood resources and the sustainability of the furniture industry is more likely to be achieved through an integrated approach that covers technological, economic, and environmental aspects. From a technological point of view, the introduction of quality management systems and digital

manufacturing technologies can enhance control over production stages and may contribute to reducing waste and improving process accuracy when effectively implemented. Continuous process improvement through cycles of planning, execution, inspection, and adjustment facilitates the rapid detection of defects and reduces rework, which increases the overall productivity of enterprises. Thus, improving the efficiency and sustainability of the furniture industry requires a combination of systematic quality management, technological innovation, development of professional skills, and implementation of circular bioeconomy principles. Such an integrated approach may facilitate the simultaneous achievement of economic, operational, and environmental objectives. of economic benefits, high productivity and environmental responsibility of enterprises.

An important factor influencing the successful implementation of quality management systems and digital technologies is the role of human capital. In practice, companies complement technological upgrades with systematic staff training programmes, continuous professional development, and incentive mechanisms aimed at increasing employee engagement in quality improvement processes. At the same time, potential resistance to organisational change is addressed through gradual implementation, clear communication of expected benefits, and the involvement of employees in decision-making processes. These measures ensure that QMS tools and digital solutions are not only technically adopted but also effectively integrated into everyday operational practices, supporting the long-term sustainability of process improvements.

The findings should be interpreted with caution because the analysis relied primarily on secondary data sources and publicly available company information. Differences in reporting methodologies, production structures, and regulatory environments across countries may influence the comparability of reported outcomes.

Conclusions

The study developed a comprehensive understanding of the role of quality management systems on the efficiency of the furniture industry and the findings indicate that the integration of ISO 9001, Total Quality Management (TQM), Six Sigma, and the Plan–Do–Check–Act (PDCA) cycle contributes to improved wood-use efficiency, reduced waste generation, and enhanced production performance.

Evidence from European furniture manufacturers demonstrated measurable operational benefits associated with the implementation of quality management systems. ISO 9001-certified enterprises reported an average wood-waste rate of 13.5%, compared with 22.0% among non-certified enterprises. In Sweden, companies with CNC monitoring and TQM systems in place reduced grinding losses by 27% and increased edge banding efficiency by 31%. Italian manufacturers applying Six Sigma within ISO 9001 frameworks reduced veneered-surface defect rates from 8.9% to 2.6%, while Albanian furniture producers were able to reduce waste from 24.5% to 15.25% per year following ISO 9001 implementation.

The study further demonstrated the value of the PDCA cycle in supporting continuous improvement. In Poland, the application of PDCA has reduced processing time from 736 hours per month to 580 hours per month and reduced the reject rate by 25.7%, while before the implementation, the increase did not exceed 1.5%. The study also determined that integrating quality systems with environmental standards enhances performance: Norwegian, companies with dual ISO 9001 and ISO 14001 certifications reduced formaldehyde emissions by 38% and increased waste sorting efficiency by 44%; Similar improvements were observed in the Baltic States and France, where resource consumption declined and the number of circular product lines increased.

The study found that the circular bioeconomy is a key factor in reducing the environmental

burden. In Germany, 87% of wood waste is reused, which reduced landfill volumes by 38%; in the USA, waste reuse reduced raw material costs by 15% to 20%; in China, more than 95 million cubic metres of forest residues were reused in 2023, which led to a 41% increase in exports of secondary products; in Sweden, the reuse of 95% of sawdust generates more than EUR 4.7 billion of GDP annually.

Cross-country evidence further indicates that digitalisation and automation can substantially reduce production resource intensity. Examples from Romania, Hungary, and Ukraine demonstrated improvements in energy efficiency, recycled-material utilisation, productivity, and energy independence through the adoption of CNC technologies, optical inspection systems, artificial intelligence, and biomass-based energy solutions.

Overall, the findings suggest that the integration of quality management systems with circular bioeconomy principles contributes to lower defect rates, improved resource efficiency, and enhanced environmental performance. However, the study does not provide a comprehensive evaluation of implementation costs, profitability, or return on investment. Consequently, the findings should primarily be interpreted in terms of operational and environmental performance improvements rather than overall financial outcomes.

The principal limitation of the study is its emphasis on technological and production-related aspects of quality management, with comparatively limited consideration of organisational, cultural, and behavioural factors. Future research should investigate implementation costs, workforce-development requirements, organisational barriers, and the long-term economic impacts of integrating quality management systems and circular bioeconomy practices across different regional contexts.

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Author Contributions Statement

Armond Halebi conceptualised the central research idea and developed the theoretical framework of the study. Armond Halebi also contributed to the design of the research, supervised the overall research process, and critically reviewed and revised the manuscript. Dritan Ajdinaj carried out the empirical research, performed the data analysis, and drafted the initial version of the manuscript. Dritan Ajdinaj participated in revising the article and approved the final version for submission.

Conflict of Interest Statement

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

Ethical Conduct

This study adheres to principles of academic integrity and responsible research practice. It is based exclusively on secondary data from publicly available sources, including official statistics, policy documents, and open-access corporate reports. No primary data were collected, and no human participants, personal data, or confidential information were involved. Therefore, formal ethical approval was not required. Ethical standards were ensured through transparent data use, accurate citation, and responsible interpretation of results.

Declaration of AI-usage

AI-based software (QuillBot) was employed solely for checking grammar, improving language clarity, and refining stylistic consistency.

Data Availability Statement

The data supporting the findings of this study are derived from publicly available sources, including international statistical databases, official policy documents, and open-access corporate and industry reports referenced in the article.

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