Proceedings of the

Collaborative Research and Education for Asset Management 5.0

International Conference

April 29, 2026

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Lucas Equeter
Editor

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Foreword to the CREAM 5.0 International Conference

Equeter, L.

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> Il faudrait d'abord que les spécialistes, ingénieurs et autres, aient suffisamment à cœur non seulement de construire des objets, mais de ne pas détruire des hommes. Non pas de les rendre dociles, ni même de les rendre heureux, mais simplement de ne contraindre aucun d'eux à s'avilir.
> *What would be needed, first of all, is for specialists – engineers and others – to care enough not only to produce items, but not to destroy human beings. Not to make them docile, nor even to make them happy, but simply never to compel any one of them to debase themselves.*
>
> *Expérience de la vie d'usine* (1941)
> Simone Weil

Reading Weil's words, one may wonder whether Industry 5.0 is truly the new concept it is promoted to be. Yet the complexity of today's industry — and, beyond it, the overwhelming complexity of the issues our world faces — makes the implementation of Industry 5.0 a challenge worth our attention. The definition of Industry 5.0 itself, articulated around human-centricity, resilience, and sustainability, retains a certain vagueness even once stripped of its policy prose, and this vagueness is part of what motivates our conference.

The contributions gathered in this volume provide a clearer view through three prisms: a geographical one, linking the Japanese Cabinet's vision of Society 5.0 to the European formulation of Industry 5.0; a sectoral one, bringing together voices from industry and from academia, including reflexive contributions on how 5.0 is taught; and a conceptual one, examining each of the three pillars of the definition in turn.

From these perspectives emerges a working definition of Asset Management 5.0: a provider of key performance indicators for the components of Industry 5.0, a way for engineers to give quantitative form to these objectives and to track their evolution over time. As such, Asset Management 5.0 constitutes a new chapter in asset management. It redefines value beyond performance in its usual acceptation, by including indicators that reflect a broader picture: the human-centricity of our processes, their sustainability, and their resilience. This objective can only be reached through dialogue between the three points of view above.

This is what brought the CREAM 5.0 consortium together. Under the T.I.M.E. Association, we wished to showcase the global interest in Asset Management 5.0 — not only as an industrial matter, but, in our capacity as academics, as an educational priority. With four founding partners on three continents, the consortium brings together genuine multicultural perspectives on human-centricity, sustainability, and resilience.

In these proceedings, the reader will find three sessions presenting recent advances on broad topics: Education, Training and Sustainable Work Organization; Sustainable Manufacturing, Materials and Process Optimization; and Asset Management, Digital Twins and Decision Support. These sessions address, in turn, the importance of preparing the industrial workforce for the 5.0 perspective, the concrete ways in which 5.0 concerns may reshape tangible industrial processes, and the broader industrial strategies that follow.

Complementing the sessions, two keynote addresses anchor the conference: Prof. NAKAGAWA Masao (Doshisha University), on "Latest situation of Society 5.0 in Japan and discussion on convergence knowledge," bringing the Japanese perspective directly into the conversation; and Prof. Ruth CARRASCO GALLEGO (Universidad Politécnica de Madrid), on "Shaping Minds, Designing Resilient Futures: Engineering for the 5.0 Era," articulating a vision of engineering education for the coming decades.

In the near-sighted world we inhabit, my personal hope is to build momentum. But momentum without strategy is quick to become wasted energy. This, to me, is the essence of Industry 5.0: a strategy that contributes to a world that remains habitable and hospitable, where no one is compelled to debase themselves. Across disciplines and across borders, in and out of this conference, I wish for the fruitful dialogues that may lead us toward a sustainable future — and, I hope, toward a second edition of this conference.

Lucas Equeter
Mons, April 2026

From Fatigue Models to Factory Floors: An Experimental Design for Human-Centered Production Scheduling in Industry 5.0

Beghain, P., Equeter, L.*, and Dehombreux, P.

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The Industry 5.0 paradigm, as promoted by the European Union, places human-centricity, sustainability, and resilience at the core of industrial development. In this context, worker well-being is no longer a secondary concern but an integral component of a broader equilibrium between economic productivity and profitability, environmental constraints, and social sustainability. Among the factors affecting this balance, fatigue — encompassing its physical and cognitive dimensions — plays a central role. Fatigued workers are more prone to errors, slower cycle times, and increased injury risk, all of which degrade both the human and economic aspects of production. Yet, despite a growing body of literature on fatigue modeling and physiological fatigue measurement, a significant gap remains: no experimental work has been conducted to demonstrate, in a real production environment, that integrating real-time worker fatigue estimation into production organizations can simultaneously enhance worker well-being and industrial performance. Addressing this gap requires models capable of jointly capturing learning and fatigue dynamics — where experience accumulation and skill development interact with cognitive load, physical strain, and recovery cycles — so that performance can be described as a time-dependent, human-centered process rather than a static parameter. When informed by real-time data, such models enable simultaneous multi-dimensional optimization of economic performance, technical quality, and human sustainability.

Existing research provides valuable building blocks. The learning-forgetting-recovery framework proposed by Jaber et al. (2013) established the theoretical relationship between fatigue, recovery, and worker learning curves, highlighting the fundamental optimization trade-off between physical recovery and cognitive forgetting during rest periods. Asadayoobi et al. (2021) further refined this by incorporating fatigue effects into learning curve models. More recently, Asadayoobi et al. (2023) explored optimizing stochastic task allocation and scheduling plans for mission workers subject to learning-forgetting, fatigue-recovery, and stress-recovery effects, and Hu et al. (2025) studied AI-based flexible job-shop scheduling that accounts for worker fatigue, while Park et al. (2023) demonstrated the feasibility of real-time fatigue assessment using smartwatch-derived heart rate data. However, most current contributions remain either theoretical, simulation-based, or limited to fatigue measurement without closing the loop between fatigue estimation, scheduling decisions, and measurable production outcomes.

This work presents a comprehensive experimental protocol designed to bridge this gap. The proposed framework is fully quantitative and aims to test the hypothesis that incorporating online estimates of worker fatigue into production scheduling yields measurable improvements in the aforementioned multi-dimensional metrics. The protocol is designed for deployment in a production-line environment with machine operators, though it is intended to be generalizable to other industrial settings.

The experimental design rests on three pillars. First, real-time fatigue estimation based on wearable devices and non-invasive sensors — specifically smartwatches capturing heart rate reserve (%HRR) and heart rate variability data, and cameras capturing percentage of eye closure (PERCLOS). This builds on and extends the work of Park et al. (2023), who relied solely on heart rate, by incorporating heart rate variability as an additional physiological indicator of fatigue state. Second, validated self-report questionnaires administered at defined intervals to cross-validate the physiological fatigue estimates against workers' subjective experience. Third, production performance measurements — including but not limited to throughput, defect rates, and cycle times — collected in parallel to establish the link between fatigue-aware scheduling and operational outcomes.

Crucially, this data drives a closed-loop scheduling system. The experimental logic triggers specific interventions based on detected fatigue states, including the insertion of dynamic breaks tailored to strike a balance between necessary fatigue recovery and the avoidance of the forgetting effect, operator reassignments and rotations, and real-time adjustments to production batch sizes. A preliminary numerical simulation phase, acting as a Proof of Concept (PoC), is also planned upstream of the field experiment. To compensate for the initial lack of field data, this simulation is calibrated using standard, literature-validated parameters for fatigue accumulation and learning rates. This simulation will serve to establish candidate scheduling strategies informed by online fatigue estimates, thereby narrowing the experimental conditions to be tested on the shop floor.

Given the European context in which this research is conducted, the experimental protocol has been developed in strict compliance with the applicable ethical and legal framework. This includes adherence to the General Data Protection Regulation (GDPR) for all physiological and personal data collected, informed consent protocols ensuring workers' voluntary and fully informed participation, data anonymization procedures, and measures to mitigate the risk of perceived surveillance in the workplace, actively addressing the privacy and social acceptability barriers emphasized in the European Industry 5.0 roadmaps. Ethics committee approval will be sought prior to any data collection.

The contribution of this work is threefold. First, it proposes a structured experimental protocol specifically designed to test the integration of real-time fatigue monitoring into production scheduling in an industrial setting. Second, it addresses the full chain from measurement to decision-making to performance evaluation. Third, it embeds ethical and legal considerations as integral components of the experimental design rather than afterthoughts, consistent with the human-centered values of Industry 5.0.

If validated, the proposed approach could inform new work scheduling standards in production industries, shifting from fixed-schedule paradigms to adaptive, fatigue-aware organization of work. This represents a concrete pathway toward the Industry 5.0 vision: improving industrial competitiveness not at the expense of workers, but through their well-being. Future research will focus on implementing the protocol in a partner production facility and analyzing the resulting data.

Training the Task Force for the Industry 5.0 Transition: Insights from the Erasmus+ CoDEMO Project

Douard, N.[*,1], Dubruc, N.[*,2], Elias, E.[3], Phan, R.[4], and Boucher, X.[4]

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The emergence of Industry 5.0, introduced by the European Union in 2021, marks a significant evolution in how industrial development and innovation are conceptualized. Moving beyond the predominantly technology-driven paradigm of Industry 4.0, Industry 5.0 promotes a more human-centric, sustainable, and resilient model of industrial development (Breque, M. et al., 2021).

Such a systemic transformation cannot rely on technological deployment alone. It requires the development of new competencies among both future graduates and current professionals. This is one of the objectives of the Erasmus+ CoDEMO project (2024–2026), coordinated by Mines Saint-Étienne (MSE) and funded by the European Commission. To embrace the multidimensional nature of Industry 5.0, the CoDEMO consortium brings together a multidisciplinary and multisectoral partnership across six European countries.

From an educational perspective, Industry 5.0 calls for the development of complex competencies, including systems thinking, ethical awareness, and the ability to manage trade-offs between performance, sustainability, and human factors. Based on an extensive needs analysis, this contribution presents the design, deployment, and first feedback of a certification-based training framework targeting higher education students. The work focuses on the pedagogical integration of this certification within a French generalist engineering curriculum: the Ingénieur Civil des Mines program. We describe the learning pathways designed to foster Industry 5.0 competencies and analyze key enablers and barriers related to their implementation within an existing curriculum and a European project framework.

The Industry 5.0 approach integrates three core dimensions—human-centricity, sustainability, and resilience—while promoting collective intelligence. In CoDEMO, this approach is operationalized through a progressive certification scheme structured around three levels: beginner, explorer, and decision-maker, aligned with the diversity of roles involved in organizational transformation.

The pedagogical design builds on core courses already embedded in the engineering curriculum, which serve as a foundation before explicitly introducing Industry 5.0 principles. Competency development then occurs through experiential learning activities at each certification level (Medini, K. et al., 2020).

At the beginner level, Industry 5.0 is introduced through second-year group-based innovation projects selected by teachers according to four criteria: the potential for digital integration within the innovation and the extent to which the three core dimensions of Industry 5.0 are taken into account. Among more than 60 projects originating from diverse clients, 20 meet the criteria. Students are guided to move beyond a solution-oriented mindset and to critically examine the meaning, adoption conditions, and impacts of their innovations. Expert tutoring supports reflective practices, encouraging students to question assumptions such as feasibility versus relevance or performance versus appropriation, while addressing human, environmental, and organizational dimensions. Motivation is reinforced through a national challenge rewarding the most promising projects, followed by an international competition organized by the CoDEMO consortium. Projects are evaluated using a structured assessment grid based on the following criteria: the innovative nature of the product, grounded in user analysis and economic feasibility; the level of technical development and operational feasibility; and the integration of the four pillars of Industry 5.0. In 2025, ten projects from five countries were presented in Berlin and we are expecting the same next june 2026 in Paris.

At the explorer level, students participate in an intensive 21-hour elective module designed as an immersive learning experience. Based on a real-world healthcare case study provided by the research component of CoDEMO, the module focuses on improving patient pathways in dental practices. It combines design thinking, user-centered analysis, and iterative prototyping, alternating theoretical inputs and hands-on activities. This setting allows students to experiment with Industry 5.0 principles in an authentic context and to develop transversal competencies such as empathy, interdisciplinary collaboration, and systems thinking (Elias, E. et al., 2026).

The decision-maker level corresponds to longer and more complex learning situations, such as extended projects or professional training periods, in which students can apply Industry 5.0 principles in real organizational contexts.

Student feedback highlights the value of the approach, particularly in terms of project structuring, relevance to professional practice, and the emphasis on human-centric innovation. Participants notably stressed the importance of design thinking as a transferable method they intend to reuse in their future careers.

Finally, the paper discusses lessons learned from the program's implementation. At the European level, the project provided a strong structuring framework that enabled interdisciplinary collaboration, shared pedagogical design, and cross-country feedback within a constrained timeline. At the local level, successful integration relied on in-depth knowledge of the curriculum, alignment with credit-bearing activities, and the mobilization of a committed teaching team. Challenges remain regarding student recruitment for elective courses and the perceived value of certification tools such as open badges. Nevertheless, motivational mechanisms—innovation challenges, an international prize, and a community of practice—play a key role in sustaining engagement.

To date, more than 130 certifications have been awarded at MSE, with over 300 expected across the consortium by the end of 2026. Beyond quantitative indicators, this contribution underlines the relevance of systemic, experiential, and research-informed pedagogical approaches to support the development of Industry 5.0 competencies. By aligning curriculum design, learning activities, and evaluation, higher education institutions can play a central role in preparing graduates capable of critically engaging with—and leading—Industry 5.0 transformations.

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Centres of Vocational Excellence as Learning Organisations

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European regions face accelerating skills gaps driven by rapid technological change, outmigration of young people and limited access to modern, practice-oriented training infrastructures. Employers increasingly require a workforce capable of operating in digitally enhanced, AI-assisted and green-transition environments, while existing training systems often rely on outdated equipment, analogue pedagogies and insufficient work-based learning. Our new project therefore creates a bridge between learning organisations and egional vocational centres which responds to these challenges by developing regional skills ecosystems designed to prepare both youth and adult learners for the future of work.

The rapid, simultaneous push towards digitalization and sustainability, creates the most significant skills challenge of the 21st century. VET systems are struggling to keep pace, leading to a widening skills mismatch. There is an urgent need to integrate digital competencies into every day practice. The transition to low-carbon economies requires "greening" of jobs across all sectors. VET must rapidly incorporate green competencies (e.g., resource efficiency, sustainable material usage, circular economy principles).

To meet these new skill demands, VET delivery must fundamentally change, moving away from a traditional, input-focused model. The sector must adopt an outcome-based, student-centered approach that emphasizes active learning, problem-solving, teamwork, and critical thinking. VET systems are increasingly serving a more and more challenging and diverse student population, exacerbating existing equity issues. Effective support for vulnerable learners necessitates a shift toward an institution-wide commitment to inclusion, rather than relying on ad-hoc support practices by individual teachers. Our solution is the creation of Centres of Vocational Excellence which is the „CoVE approach".

The established framework of CoVEs offers the systematic mechanism needed to address these multi-layered challenges. CoVEs are designed to act as drivers of innovation, connecting VET providers closely with industry, research, and local/regional development. Our project proposes a crucial addition: the most effective way to build and sustain a CoVE is by adopting the principle of the Learning Organisation.

Several elements can be highlighted as innovative, moving beyond standard practices and addressing EUSDR policy priorities, like strengthening CoVEs by systematically transforming them into learning organisations. CoVEs are typically viewed as hubs for collaboration and industry alignment. Our model ensures the project's results endure, as the participating organisations gain the internal capacity to transform themselves in response to future, yet-unknown challenges.

Using AI for trainers' support, especially the experts recruited from industry who lack formal pedagogical qualifications, is of great help in rapidly creating structured, student-centered lesson plans. This innovation leverages technology to solve a critical human resource gap in VET. The project doesn't treat sustainability and digitalization as separate add-ons but as integrated requirements for modern vocational trades.

The project provides multiple qualification and requalification pathways, including short-cycle vocational modules, AI-supported task training, VR-enabled simulation practice, and green-technology skill-upgrading. Target groups include unemployed youth and elderly adults seeking digital resilience, and vocational high school students completing practice-based education. Training programmes combine instructor-led learning with hybrid formats, e-learning components and simulation-based practice, enhancing accessibility and adaptability.

By integrating modern infrastructure, innovative pedagogies and transnational knowledge exchange, the project strengthens equal access to quality education, enhances lifelong learning, and equips the region's workforce with agile, industry-relevant competences.

By collaborating transnationally, the project immediately tests the adaptability of the Learning Organisation Methodology across diverse national VET structures (which may and will include different systems). This ensures the final methodology is truly robust and transferrable across European regions and even beyond Europe, as well.

Our approach follows the STEM Education Strategic Plan which sets out EU measures for advancing STEM education and training to increase talent across the EU because joint transnational programmes and short courses will be developed leading to micro-credentials in strategic STEM sectors through the Centres of Vocational Excellence.

Another important aspect of our approach that pilot STEM education centres will be developed in cooperation with the European network of Digital Innovation Hubs across the participating EU countries with the goal of improving how STEM is delivered and experienced in primary and secondary education. These centres can be supported by Erasmus+ for creating dynamic learning ecosystems that drive innovation in STEM teaching and learning in schools in cooperation with cultural associations, creative industries, universities and research institutions.

As final result, implementation of STEM skills foundries can be achieved in strategic sectors by involving companies to mentor young student entrepreneurs, in cooperation with vocational education and training providers and with higher education institutions. As final result, digital innovation hubs acting as STEM skills foundries can provide access to laboratories, technical infrastructures and equipment, development of intellectual property, as well as facilitating access to venture capital.

This should also bring together VET and higher education providers, talented VET and higher education students and the world of finance, particularly venture capital. This contribution to the development of larger and more inclusive STEM talent pipeline also implies a comprehensive approach to STEM education and training in European Member States as demonstrated by the project "Forward looking STEM education by implementing Vocational Education and Training in cooperation with Digital Innovation Hubs" which can also be presented at the CREAM conference in Mons.

Operationalising Sustainable Asset Management for Industry 5.0: A Practical Framework to Improve Energy Efficiency and Reduce Emissions

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Industry 5.0 marks a decisive shift in how industrial organisations define progress. Beyond productivity and digitalisation, the European Industry 5.0 vision emphasises sustainability, resilience, and a human-centric approach to industrial development. For asset-intensive sectors, this evolution has direct consequences: Asset Management and Maintenance can no longer be treated as purely technical or cost-driven disciplines. They increasingly need to contribute demonstrably to energy efficiency improvement, greenhouse gas (GHG) emission reduction, and transparent ESG performance—while safeguarding reliability, safety, and economic viability.

European climate objectives (including the 2030 and 2050 targets) and sustainability reporting requirements such as CSRD are accelerating this transition. Yet many organisations struggle with a practical challenge: sustainability ambitions are often formulated at corporate level, while implementation must happen through thousands of day-to-day decisions on assets, maintenance strategies, engineering modifications, shutdown planning, energy systems, and replacement investments. The gap between "sustainability strategy" and "maintenance reality" remains a major barrier. This is precisely where a structured Sustainable Asset Management approach is needed: not as an additional reporting layer, but as a practical operating model that helps technical services translate sustainability objectives into actionable priorities, measurable improvements, and continuous learning.

This presentation introduces the MORE4Sustainability Sustainable Asset Management Framework as a structured and implementation-oriented reference model for Maintenance and Asset Management organisations. The framework defines Sustainable Asset Management as managing industrial assets in a way that minimises environmental impact, maximises energy efficiency, and reduces GHG emissions, while maintaining operational performance and lifecycle value. It deliberately focuses on levers that technical services can influence directly at industrial sites, particularly the reduction of Scope 1 and Scope 2 emissions through asset-related decisions and operational improvements.

A key strength of the framework is that it organises Sustainable Asset Management into four interrelated quadrants with a logical implementation sequence:

Asset Portfolio Optimisation: integrating sustainability criteria into portfolio decisions, identifying non-sustainable installations, and prioritising replacement, retrofit, or redesign choices based on lifecycle and sustainability considerations.

Asset Health Optimisation: improving asset condition, lifespan, and performance through strategies such as predictive maintenance, asset care, and high-precision maintenance, thereby reducing waste, rework, and unnecessary resource consumption.

Energy Consumption Optimisation: systematically reducing energy waste and improving energy efficiency in electrical and thermal systems, supported by measurement, analysis, and targeted improvement actions.

GHG Emission Optimisation: reducing residual emissions through practical measures such as electrification pathways, renewable energy integration, thermal recovery and reuse, and prevention of fugitive emissions.

The sequencing is intentionally pragmatic: sustainability efforts deliver the strongest and most reliable results when the asset base is first aligned with sustainability objectives, then stabilised through improved asset health, followed by energy optimisation, and finally by targeted emission reduction measures. This avoids common pitfalls such as investing in isolated "green" measures while underlying asset condition issues or structural inefficiencies continue to drive energy waste and emissions.

To make the framework actionable, the presentation also explains the accompanying implementation roadmap, which provides a step-by-step logic for deployment in real organisations. The roadmap covers: defining strategy and targets (including translating corporate sustainability goals to the Asset Management domain), performing a structured self-scan and selecting actions, building the business case and obtaining approval, establishing tactical enablers and foundations, executing and monitoring the action plan, and finally institutionalising an annual evaluation and improvement cycle. Throughout these steps, the framework encourages disciplined linking of sustainability objectives to operational KPIs, investment decisions, and governance routines—so that sustainability becomes a default decision criterion rather than an ad-hoc initiative.

The session is positioned as a practitioner-oriented contribution: it does not propose sustainability as a separate "departmental topic," nor as an abstract ideal. Instead, it frames Sustainable Asset Management as an evolution of existing Asset Management principles—extending lifecycle thinking to explicitly include energy and emission performance, and providing structure to connect maintenance excellence with ESG outcomes. The presentation will highlight how a shared language and common framework support cross-functional alignment between technical services, production, energy management, engineering, procurement, and sustainability reporting functions.

Participants will leave with a clear understanding of (1) why Sustainable Asset Management is becoming essential in an Industry 5.0 context, (2) how the MORE4Sustainability Framework structures the technical levers for energy efficiency and emission reduction, and (3) how the roadmap enables organisations to move from intention to execution, supported by measurable indicators and continuous improvement.

Joint Cost and Environmental Assessment of Tool Replacement Strategies Under Imperfect Wear Monitoring in Milling

Colantonio, L.*,1, Moroncini, G.[1], Sénéchal, O.[2], Dehombreux, P.[1], Ducobu, F.[1], and Equeter, L.[1]

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The management of cutting tools directly affects machining costs, environmental impact, and product quality. In industry, tools are typically replaced after a fixed operating time. Although simple and conservative, this practice often discards functional tools, increases machine downtime, raises production costs, and amplifies environmental impacts, since each tool has a non negligible manufacturing footprint.

A more efficient approach is to equip machine tools with sensors that monitor tool condition and enable replacement only when the tool approaches the end of its life. This tool condition monitoring strategy can reduce machining costs by 2–30 % [1,2]. Monitoring may rely on cutting force signals or tool image acquisition systems [3], and models such as Cox PH [4] or Bayesian approaches [5] can estimate wear. Recent studies show that artificial intelligence based models outperform traditional ones, reaching wear estimation errors below 15 % [6,7].

Evaluating the economic and environmental performance of a replacement policy requires information on both aspects. While optimized tool replacement has been studied for steel machining [8], different strategies have not been compared. This work therefore provides a combined economic and environmental assessment of several tool replacement strategies for Ti6Al4V milling to support data driven industrial decisions.

To carry out this assessment, a simulation model is developed. This model consists of three key components: cutting tools, a CNC machine, and Ti6Al4V workpieces. The cutting tools are modelled with variable lifespans drawn from a Weibull distribution, and their degradation trajectories are reconstructed using a hyperbolic sine function, as in [9]. The machine is represented as a medium sized CNC unit consuming a constant amount of energy during machining. The workpiece is assumed to be a high added value component that is machined according to the specifications defined by the selected cutting tools. The quality of the produced workpiece depends on the condition of the cutting tool during its machining. A workpiece is classified as "scrap" if the tool wear exceeds 300 micrometres at the end of machining; otherwise, it is considered "good". Each of these components is characterized by its cost and CO_2 equivalent emissions, as reported in the literature.

Three tool replacement strategies are evaluated:

Scenario 1. Fixed period replacement, reflecting common industrial practice.

Scenario 2. Replacement based on imperfect wear monitoring, allowed only between workpieces.
Scenario 3. Replacement based on imperfect wear monitoring, also allowed during machining.

Each scenario is optimized: replacement time in Scenario 1, and wear thresholds in Scenarios 2 and 3. The results show that Scenario 1 is the least efficient. Scenario 1 has an average production cost of 16.20 EUR per part, whereas Scenarios 2 and 3 achieve average costs of 15.64 EUR and 14.80 EUR, respectively. Using tool-condition-based replacement therefore has a positive impact on the economic cost of machining operations.

Similar conclusions can be drawn for the environmental impacts. This reduction is mainly due to the fact that, to produce the same total number of parts (scrap and good), the tool-condition-based strategies generate fewer scrap parts. This decrease in scrap reduces the raw-material cost as well as the tool cost when results are normalized per produced part.

In general conclusions, the economic performance of maintenance strategies is closely tied to how cutting tools are managed. The method most commonly used in industry, replacing the tool after a fixed machining time (Scenario 1), proves less efficient than strategies based on imperfect monitoring of tool wear. When the tool can be replaced between the machining of two parts (Scenario 2), condition monitoring reduces the economic impact by $3.5\,\%$ and the environmental impact by $1.5\,\%$. These improvements increase to $8.7\,\%$ and $8.1\,\%$, respectively, when tool replacement is allowed during the machining of a part (Scenario 3).

These results clearly highlight the benefits of integrating tool-condition monitoring. However, since the model represents a simplified version of a real production system, several additional factors must be considered in practice, such as the cost and integration of monitoring equipment, the potential for false alarms, the resulting downtime, and other implementation-specific challenges that were not captured in the simulation.

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Human Factors Assessment for Manufacturing Process Selection. A Rapid Evaluation Methodology Based on the BICEPS Taxonomy. Application to the Design of a Biocomposite Production Line in Cameroon including 5.0 concepts.

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In the framework of the ValoFiBan project, which focuses on the sustainable manufacturing of bio-sourced composite products from banana pseudo-stems in Cameroon, designing production lines requires a paradigm shift towards Industry 5.0 principles: human-centricity, sustainability, and resilience.

Traditional design methods often prioritize technical and economic performance, considering human factors only as secondary or late-stage corrections. This proposal outlines a rapid human factors evaluation methodology intended for the early design phase, providing designers with a structured aid to compare manufacturing processes—such as thermoforming, injection, or compounding—without the need for complex computer simulations.

As highlighted by Arkouli et al. [2], integrating HF early in the operations design phase is essential to mitigate discomfort and safety risks that lead to musculoskeletal disorders (MSDs) and production delays. While traditional methods often rely on digital human modeling (DHM) and virtual simulations, they can be resource-intensive and difficult to apply when equipment choices are still being defined. This methodology draws inspiration from the ISO/TR 12295:2014 "Quick Assessment" approach, which identifies activities that are "certainly acceptable" or "certainly critical" early in the concept phase to avoid costly late-stage redesigns.

The central pillar of this methodology is a robust taxonomy derived from the BICEPS framework (well- BeIng, Cognitive, Environmental, Physical ergonomics and Safety). The evaluation ensures a 360-degree view of the operator's interaction with the system across five critical dimensions:

1. Physical ergonomics (P): evaluates task factors such as working posture, gestures, physical forces and pressures, duration, repetition in relation with the workstation factors such as accessibility, adjustability, manoeuvrability. 2. Cognitive ergonomics (C): evaluates task complexity, interface clarity, and mental workload to prevent human errors and ensure intuitive action sequences. 3. Environmental ergonomics (E): addresses thermal comfort, noise and vibration, lighting, and air quality which can be very sensitive for composite manufacturing. 4. Well-being (B): measures job autonomy, workload realism, social interactions, and recognition to ensure psychological resilience. 5. Safety (S): identifies mechanical, electrical, electromagnetic;, thermal, and toxic hazards according to standards. A special attention is paid here for natural fiber-specific risks such as the inhalation of banana fiber dust, skin allergies, and exposure to biological agents like mold release agents. The evaluation process utilizes a standardized 1-to-5 scoring scale, ranging from "Inacceptable" (risk level too high) to "Excellent" (aligned with best practices). When concerning scores are detected, the procedure recommends a more detailed assessment using one of the appropriate standards (EN 12295, RULA, OWAS, ...).

This scoring is integrated into a global formula to calculate the BICEPS Index (FGH). By applying this taxonomy early, designers can objectify the choice of a manufacturing process, including technological, socio-economical, and environmental factors which are evaluated in complementary studies. For example, it allows for determining if a specific thermoforming setup reduces musculoskeletal risks better than a compounding line in the local context. This proactive approach facilitates a "Design for Ergonomics" strategy, reducing the need for costly late-stage modifications and ensuring that the ValoFiBan production line is both technically efficient and socially sustainable.

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Availability Based Design (ABD) : A Resilient and Time Efficient Approach to Product Design – Improving Designer's Response to Modern Constraints

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Designing new products remains, at large, a complex, highly multifactorial and iterative problem. It often makes a designer's life a real puzzle: achieving at least one design option that is "technically viable", "technically reliable", and cost-effective is a tricky task. In our modern, versatile, and uncertain economies, ensuring that this single design option will be available at the specified "time to market" is a real challenge. Conventional Design Process (CDP), based on the German Standards VDI2221 to 2223, VDI2225-1998 and the works of PAHL & BEITZ, lacks to consider the delivery question: these last tasks are let to other specialty teams ("over the wall approach") with the risk that the designer should start back a part or the whole design process due to unavailability of the design itself or parts of it at the requested "time to market". Such a design issue becomes even more complex when a designer has to deal with multiple designs to compare or an optimization to perform.

To adequately address these novel design issues, a detailed review of the Conventional Design Process (CDP) was conducted: the main iterative loops, bottlenecks, and time-consuming steps were identified. Building on this deep-dive analysis, a new product design approach, named Availability-Based Design (ABD), articulated around 8 main design steps, was proposed: ABD reorganizes CDP in a way that the delivery constraints of design components are integrated at the earliest steps of the design process itself. Furthermore, instead of CDP, ABD enables the designer to easily generate multiple available designs that may be ordered on given Key Design Indicators (KDI). ABD not only avoids unplanned delivery risks along the value chain but also provides additional space for the designer.

For a second time, timeline models were built for CDP and for ABD based on identified time-consuming steps. A theoretical comparison was conducted to demonstrate the benefit of ABD. A simple case study of a ball screw drive actuator (BSD) was used to compare the two processes in practice. Time durations for each time-consuming step, carefully measured from similar industrial case studies, were allocated to both timeline models, and a comparison of their performance was conducted, confirming ABD benefits. Additionally, a probabilistic layer of the availability of the design's components was added to both models. The goal here was to understand the impact of the availability ratio of the design's components on the design times of both design processes, CDP and ABD. 3 design modes, identified in industrial practice (Manual design, Semi-automated design using low-tech tools, and automated design linked to ERP systems), were considered across a full range of availability ratios, varying from $0\,\%$ (Shortage) to $100\,\%$ (Full availability). Again, the results revealed that ABD improved CDP's design times by more than a factor of 3!

To further show the robustness of ABD, different sensitivity analysis were performed on different drivers: in practice, design times are especially influenced by the number of components a design is composed of but also the number of technical checks (TC, local level of the component) and the number of Key design Indicators (KDI, global level of the whole design) needed to rationally confirm any successful design. Models were tested within a range of full availability of components (Availability ratio Delta = 100 %) to full shortages of components (Availability ratio Delta = 10 %) for simple designs (7 components) to complex ones (100 components) but also for designs requiring only a few technical verifications (7 TC and 3 KDI) to ones needing large number of technical verifications (50 TC and 15 KDI). Variations in the availability ratio per component were also simulated (e.g., a shortage on all components, a shortage on 1 component with all other components available, and a normal distribution of the shortage across the design components). Results of these robustness analyses showed that running the ABD process is always quicker than CDP, except in manual design mode in cases close to full availability (the ideal situation of the VDI2221 to 2223, which is nowadays never the case). In semi-automated design and automated design, ABD systematically exhibits far stronger performances than CDP. These results are also confirmed under full availability in automated design mode, where ABD provides multiple design options more quickly than CDP. These multiple design options allow for discussion between the designer and the project manager, e.g., to optimize the design selection. If not, as ABD brings back useful time, the designer can use it to improve the overall efficiency of the design process, to focus on specific improvements, to deeper understand the present and/or future needs of the customer, to perform a double check of critical pain points, to follow some technological watch that could further be useful to the user, to make a fine tuning of the proposed solution, to increase the quality of the technical documentation, . . . , or even, to improve the communication quality with the customer. Instead of the bottleneck situation generated by the conventional design process CDP, ABD brings back more air to decide what is efficient to make.

The present article aims to demonstrate the benefits of ABD for modern designers in today's highly versatile, competitive, and time-stressed environments.

Optimization of Processing Routes and Sustainability of Banana-Fibre-Based Biocomposites

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Introduction

Banana pseudostems represent a significant lignocellulosic biomass in tropical countries, yet they remain largely underutilized, often treated as agricultural waste (Azriena et al., 2025; Zhang et al., 2021). Their high fibre and cellulose content makes them a promising feedstock for bio-based composites, offering a partial substitution to fossil-based materials (Cabrera et al., 2023). Developing sustainable industrial processes for transforming this biomass requires the early consideration of environmental performance. Life Cycle Assessment (LCA) provides a robust framework to quantify and mitigate impacts across the production chain, linking material properties with associated mass and energy flows (ISO, 2006a; ISO, 2006b; Rodríguez et al., 2020; Gorrepotu et al., 2025).

Objectives

The main objective of this study is to develop an integrated ecodesign approach for bio-based composites reinforced with banana pseudostem fibres. Specifically, it aims to :

- Define the composite formulation through a structured brainstorming process followed by a multicriteria analysis to select the most relevant fibre–matrix combination (PLA/HDPE)
- Model the complete transformation chain from cradle to gate.
- Quantify material and energy use and associated emissions.
- Identify processing steps with the highest environmental impact.
- Guide technological choices towards lower energy and environnemental impact.

Methodology

The approach relies on process modelling using functional block diagrams, decomposing the chain into unit operations: fibre extraction, carding, drying, extrusion-compounding, and shaping via injection moulding or thermoforming (Rodríguez et al., 2020). Detailed mass and energy balances are established for each step, accounting for yields, material losses, electrical and thermal energy consumption, and mechanical energy requirements. The inventory data then feed an LCA conducted according to ISO 14040 and ISO 14044, enabling comparison of alternative fibre preparation and composite processing scenarios (ISO, 2006a; ISO, 2006b).

Results

Thermal operations, notably fibre drying and polymer melting during extrusion, emerge as the primary contributors to energy use and CO_2 emissions. Shaping processes, including injection moulding and thermoforming, also contribute significantly. These results emphasize the importance of optimizing processing parameters: lowering thermal inputs, improving yields, and reducing material losses. Integrating LCA into the design process allows the identification of environmentally favorable scenarios and supports the development of bio-composites with reduced ecological impacts. Overall, this approach strengthens the sustainability of banana pseudostem valorization, turning agricultural residues into a strategic resource for low-carbon, bio-based materials.

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Comparison of the environmental impact of the replacement of an automatic transaxle by a new one or a remanufactured one

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Introduction

Sustainability is a major challenge and necessity for industry. Composed by three dimensions, which are economy, society and environment, it is a main component of Industry 5.0, which stands as a sustainable, resilient and human-centric approach of the industry. The transition towards Industry 5.0 requires the implementation of tools able to evaluate these three pillars, for all the missions performed within a company. Due to its key role in asset management, equipment maintenance is a key entry point for integrating sustainability in company's considerations. Indeed, when a part composing a machine fails, the management of this failed part remains a critical aspect. Several options can be considered, as the repair of the failed part, its replacement by a new part or a used one, etc. These options strongly refer to circular economy [1], whose main purpose is to extend the use duration of natural resources as much as possible before discarding them, and avoid it when possible. Ten words starting with the letter 'R' usually summarize the possible actions that can be performed on a machine to reduce its impact on the environment [1]. Among them, remanufacturing has a growing importance. In fact, its principle is to gather the functional parts of a discarded machine to reuse a portion of or all of them in an identical new machine with the same level of quality and performance as a new one composed by only new components. In Belgium, the plant of Aisin Europe located in Baudour is specialized in the remanufacturing of automatic transaxles.

The purpose of this work is to evaluate and compare the environmental impact of two failed automatic transaxles produced by Aisin, one being replaced by a new transaxle, and the other being replaced by a remanufactured one, by performing a life cycle assessment [2,3], in order to check the relevance of their activity on the environmental pillar of sustainability.

Methodology

Life cycle assessment methodology is composed of four stages, which are: (i) the goal and scope definition, (ii) the inventory analysis, (iii) the impact assessment and the (iv) interpretation [2,3].

The studied product system is the automatic transmission of a car that travels 200 000 km (which is the functional unit) in Europe during its whole life cycle, with a failure occurring on the transaxle after 100 000 km. For confidentiality reasons, the specific model of the transaxle is not disclosed in this work. The two available options compared in this work are to replace the failed transaxle by a new one or a remanufactured one, in order to travel the remaining 100 000 km. Four main steps therefore compose the life cycle of the studied product system. The first one is the manufacturing of the new transaxle in Japan. This step groups all the life cycle steps referring to the mining of the ores, extraction and production of the manufacturing materials, assembly of the parts and transport of the transaxle from Japan to Europe. The second step refers to the use phase of the transaxle on a distance of 100 000 km. It is considered that the car is a hybrid model, consuming 4.4 L/100 km of oil and that the mechanical efficiency ratio is equal to 0.95. The third step is the one of interest, as it refers to the replacement of the transaxle by a new one or a remanufactured one. In the case of the replacement by a new transaxle with only new parts, this step is considered as the same as the first one. In the case of the replacement by a remanufactured transaxle, the proportion of new parts and reused parts is defined thanks to the data provided by the company, which specify the probability of replacement depending on the considered part. All the data related to the mass of the parts have been supplied by the company, as well as the plans of the transaxles. The fourth step is identical to the second one. As a remanufactured transaxle has the same level of performance as a new one, it is considered that there is no difference in their mechanical efficiency ratio.

Thanks to these assumptions and considerations, a complete inventory of the materials composing the transaxle is obtained. This stage concludes that the most used materials in terms of mass were steel alloys (47.0 %), aluminium alloys (28.10 %), cast iron alloys (12.76 %) and stainless steel alloys (5.31 %), which corresponds to 93.2 % of the total mass of the transaxle. The unit processes related to these materials are defined by using the ecoinvent database. For the impact assessment, the computation method ReCiPe 2016 is used [4] and all the category indicators are kept in the analysis.

Results and discussion

The results show that for all the environmental category indicators, replacing a transaxle by a remanufactured one allows to reduce the impact by 20 %-30 %. By considering that the steps 1, 2 and 4 are the same for the two cases, it is shown that the impact of the remanufacturing process is approximately 4 to 5 times lower than the one of the manufacturing of a new transaxle. In both cases, the highest impact is due to the manufacturing processes, followed by the mining and extraction of the manufacturing materials.

Conclusion and perspectives

Thanks to the application of the LCA methodology, this work shows that replacing a defective transaxle by a remanufactured one has environmentally from 20 % to 30 % less impact than replacing it by a new one, for all the impact categories considered in the ReCiPe 2016. This result confirms the interest of investigating the implementation of circular economy in current industrial processes and products life cycle.

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Valorization of banana residues in Cameroon: plant fiber extraction from pseudo-stems and contributions to a sustainable, circular, and inclusive value chain

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The production of bananas and plantains generates large volumes of waste each year(1), particularly pseudo-stems, more than 95 % of which are discarded or incinerated on plantations. This practice leads to methane emissions, resource losses, and pollution, even as global demand for sustainable natural fibers continues to grow steadily. Banana fibers are recognized for their mechanical performance and their potential in textiles, composites, geotextiles, and paper manufacturing (2,3). However, despite the potential for local employment and a reduced carbon footprint, their use remains limited in some producing countries. To date, few studies have examined the technical, economic, and organizational feasibility of a local value chain for pseudo-stems. Valorizing banana residues represents a strategic opportunity for low-carbon material transitions in sub-Saharan Africa, where decentralized biomass resources remain largely untapped. The purpose of this study is to assess the potential for valorizing banana residues in Cameroon through the extraction of sustainable natural fibers. More specifically, it aims to identify the most suitable extraction technique, analyze the economic viability of a local value chain, and examine the potential impact of this sector on the development of local communities.

The methodology employed combines experimental analyses, field observations, and a technical-economic assessment. Pseudo-stems were collected from several production areas and then characterized to assess their composition(4), moisture content, and variability. Fiber extraction steps including pretreatment, manual and mechanical defibration, washing and drying were evaluated under controlled conditions to assess their technical robustness. The resulting fibers were analyzed for yield, mechanical properties, and quality. In parallel, socioeconomic data were collected from local stakeholders to model an integrated value chain. The technical-economic analysis assessed the feasibility and profitability of various scenarios, taking into account equipment requirements, collection logistics, and potential market opportunities.

The results show that banana pseudo-stems are an abundant and technically viable resource. The tested processes yielded fibers with a yield of approximately 4 % and high mechanical properties, with tensile strengths ranging from 350 to 500 MPa and moduli of 9 to 18 GPa, confirming their performance as reinforcing fibers. Similarly, they contain approximately 68-80 % cellulose, 9-21 % hemicellulose, and approximately 12 % lignin, with a moisture content between 8 and 12.3 %. The fibers exhibit low density (0.9-1.2 g/cm^3) and thermal stability up to 275 °C, confirming their suitability for a variety of industrial applications. These values are consistent with the literature(5), with the observed variations potentially attributable to growing conditions, climatic factors, and species differences(6) which could have a direct impact on chemical composition(7). The results also show that manual or mechanical extraction using simple equipment is feasible at the local level and compatible with a phased rollout of the value chain. Beyond technical performance, the establishment of decentralized extraction units is expected to create significant local employment opportunities, strengthening rural livelihoods and supporting community-based circular economy models. The technical-economic analysis reveals that a semi-industrial supply chain could become profitable, particularly if linked to existing markets such as biocomposites, sustainable textiles, biodegradable geotextiles, or paper products(8,9). With an initial investment of approximately USD 150,000, selling the fibers for between USD 5 and USD 6 per kilogram would generate profit, making the industry economically attractive. This work contributes to resource efficiency and circular value-chain development by demonstrating the socio-technical feasibility of decentralized fiber extraction systems. Finally, the use of other by-products for biogas or bioethanol production offers an interesting opportunity to optimize the value chain and enhance the overall sustainability of the system.

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Circular Logistics for Reusable Retail Assets

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We introduce the Crowdsourced Pickup-and-Delivery Routing Problem with Stochastic Asset Inspection and Maintenance Triage (CPDRP-SIMT), a novel optimisation model for circular urban logistics. The system relies on a company fleet and a pool of skill-heterogeneous crowdworkers jointly operating a two-echelon network to collect, inspect, and redeploy reusable retail display assets across urban points of sale. Asset conditions are revealed through on-site inspection by crowdworkers, whose classification accuracy depends on their individual skills and level of effort. This makes the uncertainty over second-stage recourse costs endogenous to first-stage crowdworker assignment decisions.

We formalise the problem as a two-stage stochastic mixed-integer programme with decision-dependent uncertainty and propose a solution approach based on L-shaped decomposition combined with a sample average approximation (SAA) gap certification. More broadly, this work contributes to the emerging frontier at the intersection of circular economy logistics and crowd-based operations, by explicitly integrating asset recovery and reuse decisions with the behavioural and skill heterogeneity of crowdworkers within a unified optimisation framework.

Society 5.0 – oriented manufacturing system for plastic-alternative 100% bamboo self-adhesive products: visualization and adaptive control of vibration characteristics during bamboo culm cutting for fine bamboo fiber

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In the context of Society 5.0, future manufacturing systems must concurrently achieve environmental sustainability, efficient resource circulation, and integration of human-centered technology. A pivotal challenge in this paradigm shift is replacing petroleum-derived plastics with renewable natural materials. Bamboo emerges as a promising candidate owing to its rapid growth, high specific strength, and the ability to be molded without synthetic adhesives through the self-bonding of lignocellulosic components. This study aims to develop a sustainable manufacturing process for products composed entirely of bamboo by enhancing the consistency of fine bamboo fibers produced during machining. These fibers serve as raw materials for molded bamboo components; however, their shape and quality are significantly affected by the forced vibrations that occur during the extraction process.

Bamboo culms inherently exhibit variability in geometry, stiffness, and moisture distribution. Their hollow cylindrical shape renders them particularly susceptible to forced vibrations during end milling. Such vibrations induce fluctuations in the fiber width and thickness, leading to inconsistent packing, nonuniform heating during hot-press molding, and final products with heterogeneous mechanical properties. To address these challenges, this study develops two complementary methods aimed at suppressing forced vibrations and stabilizing fiber morphology: (1) a visualization-based approach for the offline design of optimal cutting conditions, and (2) a real-time adaptive spindle-speed control system utilizing cutting sound as feedback. Together, these strategies constitute a human–machine interaction framework that enhances operator understanding and machine autonomy.

The initial approach aimed to elucidate the vibration characteristics inherent to the machining process. Modal testing was employed to ascertain the dominant natural frequencies and bending modes of bamboo culms. During spiral end milling, the vibration acceleration on the outer layer of the bamboo culm was measured and subsequently transformed into color maps, which visualized the vibration intensity as a function of the spindle speed and cutting position. These maps identified distinct resonance regions corresponding to the first and second bending modes and illustrated the shift in resonance zones as the tool traversed the spiral path. By maintaining constant feed per tooth and identifying spindle speed trajectories that circumvent the resonance zones, optimal variable-speed cutting paths were developed. Cutting experiments verified that these variable-speed trajectories significantly reduced the peak vibration displacement compared with conventional constant-speed cutting. The extracted fibers exhibited enhanced geometric stability, demonstrating that visualization-based condition design improves the machining quality of natural materials.

The performance of the feedback system based on cutting sound was assessed using three indices: the residual error between the target and actual spindle speed, delay time in responding to changes in the natural frequency, and speed dispersion resulting from the hunting behavior. The findings indicated that updating the spindle speed 24–32 times per revolution of the bamboo cylinder provided an effective balance among rapid response, stable convergence, and prevention of excessive fluctuations. Under these optimized feedback conditions, the ratio between the natural frequency and the intermittent cutting frequency remained near half-integer values, which are known to minimize forced vibration. Cutting tests demonstrated that the maximum vibration displacement was reduced to less than one-fourth of that observed under strong forced vibrational conditions. The analysis of fiber shape revealed substantial reductions in width variation, and molded bamboo plates produced from these fibers exhibited improved uniformity in terms of both surface coloration and mechanical performance. These outcomes confirm that cutting-sound-based feedback control effectively adapts to the time-varying dynamic characteristics of bamboo. Within the cutting conditions examined in this study, regenerative chatter was not experimentally observed; all vibration responses were attributable to forced vibration components at the tooth passing frequency and its harmonics. This is considered to be due to the use of a straight-flute end mill, which produces fully intermittent cutting and thereby generates periodic excitation forces at the tooth passing frequency. During the non-cutting intervals, the comparatively high damping of bamboo ($\zeta_1 = 0.017$, $\zeta_2 = 0.021$) dissipates residual vibration, suppressing the growth of regenerative chatter. The potential occurrence of regenerative chatter under different cutting conditions remains a subject for future investigation.

This study introduces a comprehensive human–machine interaction framework specifically designed for the machining of renewable inhomogeneous materials by integrating intuitive visualization with real-time adaptive control. Vibration-acceleration color maps facilitate human decision-making by providing an intuitive understanding of unstable cutting zones, thereby enabling the informed selection of robust nominal conditions through operator-driven adjustment of spindle-speed range and update frequency based on visual inspection of the color map. Concurrently, the cutting-sound feedback system autonomously adjusts the machining parameters in response to real-time vibration changes, compensating for material variability and ensuring continuous process stability. This dual approach effectively bridges the gap between human insight and automated control, allowing planned and adaptive strategies to operate in synergy.

In summary, this study established a robust framework for the precision machining of bamboo and other natural materials characterized by significant variability. The integrated methods enhanced the dimensional consistency of fine bamboo fibers, improved the reliability of subsequent molding processes, and facilitated the production of high-quality $100\,\%$ bamboo products. By incorporating sustainability, sensing, digital control, and human-centered design, the proposed methodologies align with the objectives of Society 5.0 and illustrate a pathway for the integration of renewable natural materials into advanced manufacturing. These findings offer valuable insights for the development of next-generation sustainable production technologies capable of transforming variable natural resources into stable and high-value engineered products.

Point cloud geodesic distance algorithm for part inspection

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A key aspect of manufacturing is ensuring that a part complies with the criteria specified by the customer. This is verified through inspection processes that can be lengthy and tedious. This is particularly the case for flexible parts (such as sheet metal used in aircraft fuselages or car bodies) as their shape depends on the load applied (gravity, support, etc.). The most common method of inspection is to force the part into the desired shape to take measurements [1]. Unfortunately, this requires specific calibrated equipment and multiple handling operations.

However, it is possible to measure the part in its free state using geodesic distances. This is feasible because the intrinsic geometry can be considered as preserved, given that the part is thin and its deformation is elastic (same idea in [1]). Our work therefore consists of finding an algorithm that allows these geodesics to be measured with sufficient accuracy for our application. Furthermore, as the parts are primarily represented numerically by a point cloud obtained via a 3D scanner, this algorithm is designed to calculate directly on the point cloud, thus avoiding meshing operations that can lead to errors. The inspection process for these flexible parts can now be fixtureless, and can therefore be automated. This significantly reduces the workload for operators and inspection time, and allows the process to be adaptive, as it does not depend on the geometry of the part.

An initial version of this geodesic distance measurement algorithm is a version of the fast marching method [2] applied to point clouds. The method used to calculate distances on the point cloud involves using triangles built on the fly from neighbourhood lists obtained with the kNN algorithm. Unfortunately, it does not meet the accuracy criteria required in metrology: its low convergence rate makes it very imprecise for our low point density objective. We therefore propose a second version that considers the curvature of the front when calculating the distance of a point. This second algorithm shows good convergence with accuracy similar to other algorithms operating on meshes (notably MMP [3], which is known to be accurate on polyhedral surfaces). Our algorithm has other advantages over these algorithms, such as shorter calculation times and the ability to take measurements from different geometric or topological features (such as an edge or a hole), making inspection easier in relation to the geometrical product specifications (ISO GPS standard).

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Human-Centric Asset Management 5.0 for Reverse Osmosis in Beverage Production: A Digital Twin Coupled with VR/AR for Energy, Maintenance and Skills

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In beverage production, the reverse osmosis (RO) unit is rarely "just" a water treatment box: when permeate flow drifts, when differential pressure climbs, or when a CIP is delayed, it immediately shows up in energy use, production continuity, and the stress level of the team on shift. Yet many digital initiatives still stop at performance dashboards and alarms, while Industry 5.0 asks us to look at the human side of the asset as well : how decisions are made under pressure, how maintenance know-how is transferred, and how resilient the work organization remains when people rotate, languages differ, and experience levels vary.

We present an Asset Management 5.0 approach that ties three layers together around an industrial RO skid. The first layer is a cyber-physical digital twin connected to plant data (SCADA/historian) and maintenance traces (CMMS). Rather than aiming for a "perfect" model, the twin mixes a physics-informed RO core (pressure/flow, recovery, rejection) with practical health indicators and data-driven detection tuned to everyday issues: fouling onset visible through normalized permeate-flow decay, instrument drift identified by inconsistent sensor patterns, and pump efficiency loss inferred from power vs. operating point. The twin continuously computes interpretable KPIs that maintenance and operations can actually discuss in the same sentence: specific energy consumption (kWh/m^3), water losses, chemical usage for CIP, asset health indices, and risk-based priorities. It also generates constrained "what-if" scenarios: what happens to energy and membrane stress if we raise recovery by X % while keeping permeate quality within limits.

The second and third layers make this decision support usable on the shop floor: VR for training and AR for assistance, synchronized with the twin state. In VR, we let operators and technicians rehearse realistic sequences (start-up/shutdown, alarm response, CIP, membrane replacement) and, importantly, the awkward parts that drive errors: the valve that is easy to miss in a rush, the lockout/tagout steps around the high-pressure pump, the check that prevents a wrong line isolation. AR then brings the same logic into the real intervention: checklists adapt to the current operating mode, live fouling indicators are displayed in context, and a remote-expert channel helps when the issue is unusual. From a "societal aspects of labour" angle, the goal is explicit: reduce cognitive overload and intervention stress (especially on night shifts), standardize best practices without flattening expertise, and make upskilling smoother for junior/senior and multicultural teams through icon-based guidance and multilingual micro-prompts.

We evaluate the approach in a beverage production site using three families of measures: process/energy performance (baseline vs. twin-assisted setpoints and CIP timing), maintenance performance (diagnosis time, MTTR, first-time-fix rate, and quality of work-order knowledge capture), and human factors (NASA-TLX workload, usability, and ergonomic risk scores such as RULA/REBA). For the pilot deployment, our quantified targets are pragmatic: 5–10 % lower RO specific energy consumption, 20–30 % MTTR reduction for recurrent RO faults, and +10 points in first-time-fix rate through AR-guided interventions and better pre-job preparation in VR.

To support education/training and technology transfer, we package the work as a reusable module with concrete deliverables: a small VR scenario library (procedures + rare events), AR checklists and remote-expert templates aligned with CMMS workflows, and a KPI dashboard with an anonymized dataset so learners can analyze the energy–quality–maintenance–ergonomics trade-offs and propose improvement actions. This makes the RO twin not only a plant tool, but also a teaching object for Asset Management 5.0 within interdisciplinary engineering curricula.

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From Siloed Technical Governance to Multidisciplinary Asset-Centred Maintenance Leadership

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Introduction

Technical managers are increasingly expected to ensure compliance, operational stability, continuous improvement, and sustainability at the same time. In many organizations, this responsibility is moderated through multiple management systems covering environment, occupational health and safety (OHS), quality, and maintenance. While these systems are intended to support management, they often create additional complexity (Frank-Daub & Larsen 2023; Ispas & Mironeasa (2022).

Challenges Faced by Technical Managers and why diagnostic models are needed.

In collaboration with a range of companies, students investigated how management systems are implemented and enacted in everyday operational practice. The empirical basis for the research comprised more than 400 course-based student projects and to ensure methodological consistency theoretical frameworks and methodology were predefined by faculty.

The research show that across industrial sectors, managers' report remarkably similar challenges when working with the interface with management systems like they are maintained as parallel structures; responsibilities are fragmented across departments; KPIs are not aligned; management systems are administrative burdens more than a tool for continuous improvements and work is crowded out by urgent demands, audits, and firefighting (Frank-Daub & Larsen 2023; Maletič, D et.al. 2020; Gunnigle, J.P et. al. 2021).

Managers must constantly balance production demands against preventive maintenance, safety measures, and environmental controls and because the management systems are loosely integrated. These trade-offs are often addressed ad hoc rather than through systematic risk-based decision-making.

The ideal-type model and the model for multidisciplinary technology management together provide a structured methodology that supports both diagnosis and development, grounded in daily technical management practice.

Diagnosing Practice Using the Ideal-Type Model

The Ideal-type model was developed by Rocha, M., & Hohnen, P. and published in 2010. In our research and teachings, we have used the model and integrated its use to all domains and developed a ideal-type matrix for managers to use to analyse an organizations maturity level in their use of management systems. Rather than representing a linear maturity model. The model describes characteristic configurations based on two dimensions: the degree of integration with the overall organization (vertical axis) and the degree of systematic and preventive problem-solving (horizontal axis).

As illustrated in Figure 1, organizations may operate management systems in an ad hoc and loose associated manner, or in a systematic and fully integrated way. Importantly, different domains may occupy various positions in the model at the same time. This insight, emphasized in the book, allows technical managers to prioritise improvement efforts where misalignment is most critical (Frank-Daub & Larsen 2023).

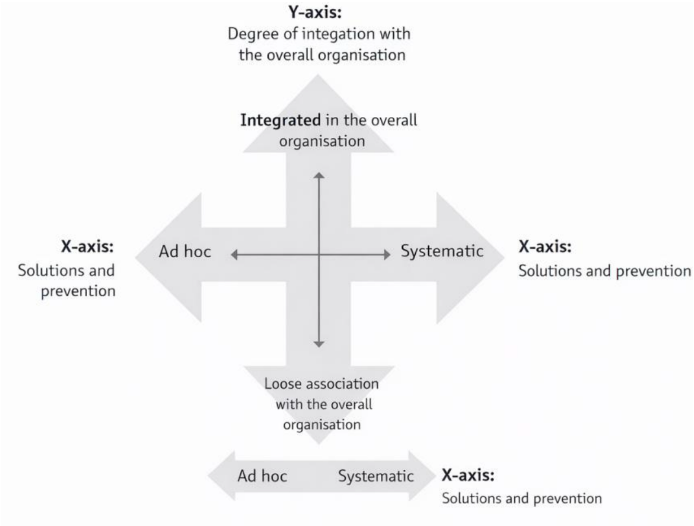

Figure 1. Ideal-Type Model for diagnosing management system maturity (inspired by Rocha & Hohnen, 2010).

Designing Improvements Using the Model for Multidisciplinary Technology Management

Once the maturity configuration has been diagnosed, the Model for Multidisciplinary Technology Management provides the framework for designing and coordinating improvements. The model was developed to highlight the interdependence between managing environment, OHS, quality, and maintenance. In order for managers to succeed with improvements in all domains, it requires the same approach and tool kit for everyday decision making and problem solving. Quality tools like 5S or CTQ tree are equally beneficiary to use to solve health and safety issues or identify critical activities for environmental improvements. Furthermore, maintenance management should always be a part of decision making, because of its effect on the other domains. It is not possible to succeed with a proactive approach to environment, health and safety and quality without having proactive maintenance strategies. As shown in Figure 2, the model integrates four technical domains on a shared organizational foundation consisting of organization, culture, and capacity for change. Across the domains, three levels of input are distinguished: official requirements (legislation and standards), organizational concepts and policies, and operational tools and analyses. This structure reflects the core argument of the book that ineffective management systems often suffer from misalignment between these levels.

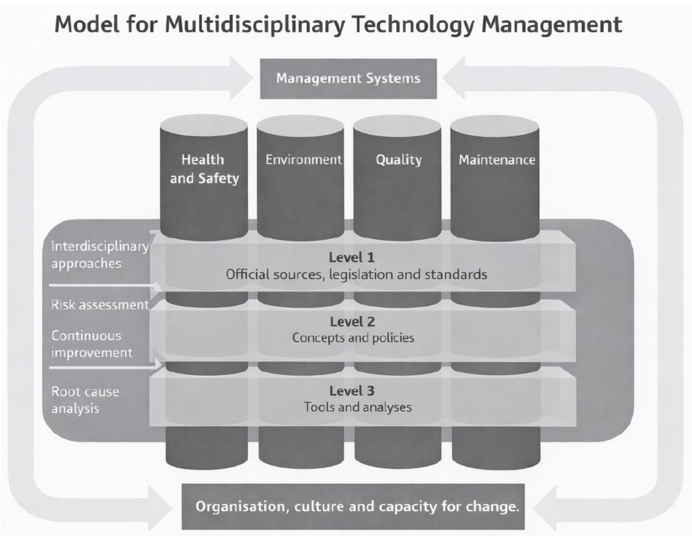

Figure 2. Model for Multidisciplinary Technology Management by Frank-Daub & Larsen, 2023

Maintenance Leadership and Asset Management

Maintenance leadership play a significant role in operationalizing the model for multidisciplinary technology management because maintenance work connects asset conditions with safety exposure, environmental impact, quality capability, and operational continuity.

In daily operations, technical managers translate system intentions into work management routines e.g. prioritization, shutdown coordination and competence development. The key argument is that with the Model for Multidisciplinary Technology Management, asset management helps managers justify preventive and renewal decisions, define redundancy and resilience requirements, and prioritize improvements based on criticality rather than isolated compliance objectives.

Conclusion

By combining diagnosis and development, the proposed approach supports technical managers in improving management systems in ways that directly enhance daily technical management.

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Industry 5.0 Virtual Hubs for Society 5.0 objectives

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Industry 5.0 places the well-being of both industrial product users and industrial workers at the center of the production process and uses new technologies to ensure well-being beyond workplaces and economic growth, while respecting the planet's production limits. The European Commission's Industry 5.0 approach offers a vision for industry that goes beyond efficiency and productivity as the sole objectives and reinforces the role and contribution of industry to society.

The European Commision therefore initiated a participatory process to define and finalize the Industry 5.0 concept and policies by establishing a consultative body, the Community of Practice 5.0 (CoP 5.0) which developed the Manifesto for Industry and Society 5.0. This manifesto, developed in collaboration with the European Commission, supports Industry 5.0 as an evolution of the current paradigm, putting research and innovation at the service of a sustainable, human-centered, and flexible European industry. This vision thus adds new dimensions to the Industry 4.0 concept, which focused on digitalization and automation.

- Sustainability: Promoting production practices that respect planetary boundaries, ensuring efficient use of resources, and reducing environmental impacts.
- People-centeredness: Placing the well-being of product users and employees at the center of the manufacturing process, ensuring safe and satisfactory living and working conditions for users.
- Resilience: Enhancing the industry's ability to cope with disruptions and crises and adapt to change, maintaining operational capacity and competitiveness.

Detailed proposals for the above pillars were under preparation by CoP 5.0 in 2025. The plenary session is planned for the 20th March 2026 in Brussels which will also make initiatives for practical implementation.

One of the planned courses of action is to create a network of HUB 5.0 ecosystems that promote and detail the principles of Industry 5.0 and translate them into local action plans. The initiative to create HUB 5.0 has already begun because the first official meeting took place on 4th April 2025 in Timişoara with international cooperation.

Consequently, a new project proposal was developed under the title HIVE5 which responded to above described challenge by establishing a European experimentation platform rooted in human-centric innovation.. The mission was defined to design, implement, and evaluate sandboxes where organisations, communities, and policy-makers co-develop solutions that demonstrate I5.0's transformative potential. These sandboxes can allow real-life testing under controlled conditions, enabling safe exploration of new organisational models, human-machine interaction, AI ethics, and community-based value creation, overcoming different challenges. Central to this was the pressing skills gap and the necessity to attract and retain top talent, foster industrial attractiveness to younger generations, and allow senior generations to keep at the forefront of technology advancements. I5.0 innovations, such as human-centric technologies and learning organisation models, are pivotal in addressing these issues.

The project ambition was therefore to pioneer as a Human-Centric Innovation Valley, where diverse European partners converge to co-create solutions, share lessons, and build a collective knowledge base. A network of industrial ecosystems could be created by developing, testing, and validating innovative methodologies that integrate human-centric technologies, participatory governance, and organizational learning methods.

The practical implementation of the project is foreseen by Virtual Hubs that develop, test and scale a human-centric experimental workspace ecosystem and they act as a flagship demonstration for I.5.0 by integrating ergonomics, emotional intelligence and circular design principles into real-life SME pilots. One of the Virtual Hubs concentrate on “Emphatic Workplaces” concept which provides a Virtual Factory environment where human-in-the-loop systems, emotional feedback integration, and hybrid AI support are piloted. This approach combines sensors, data analytics, and participatory design to create workplaces that “feel” and respond to workers’ cognitive, physical and emotional needs. It includes testing modules for smart factory integration, digital training environments, and organisational learning loops in SMEs.

Another service is the Sensory Room as the hub’s flagship experiment. It is an immersive, modular micro-environment designed to enhance human creativity, well-being and cognitive regeneration at work. It integrates multisensory stimuli—sound, light, textures, scents and tactile interaction—co-curated with artists and psychologists to foster focus, inspiration and emotional balance. The services allow users to enter for short, purposeful sessions that follow a cyclical model of creative work: concentration, sharing and release. The space adapts to both individual contemplation and small-group ideation. It also serves as a transferable model for other SMEs to replicate human-centred workspace innovation.

Their service also include coworking hubs, Outdoor Office modules, community gardens and mobile micro hubs integrated into 15 minute cities and rural contexts. These spaces are flexible, emotionally responsive and biologically aligned, supporting neurodiverse friendly, adaptable work ecosystems.

The Virtual Hubs develop and scale Lighthouse 5.0 learning system for SMEs and organisations, enabling them to acquire, share and institutionalise skills essential for I5.0. It combines lighthouse projects, incentives and a Community of Practice (CoP) to build sustainable organisational learning cultures. The hub ensures that skill development is not an isolated training activity but a systemic transformation mechanism embedded in workplaces.

This Virtual Hub model redefines work environments as inclusive, human centric ecosystems aligned with the principles of Industry 5.0 and the European Green Deal. It co designs, implements, and evaluates sustainable models of work that foster social resilience, wellbeing, and regional regeneration.

Tertiary spaces (spaces between home and office) are at the heart of this approach.

Digital Twin-Enabled Asset Management for Energy Efficiency and Resilient Industrial Systems in the Context of Industry 5.0 : A Bibliometric and Systematic Review

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Background

The transition towards Industry 5.0 emphasizes sustainable, resilient, and human-centric industrial systems. In this context, asset management plays a key role in ensuring operational efficiency, reliability, and environmental sustainability. Energy efficiency has become a critical factor for improving competitiveness and reducing carbon emissions. Digital Twin (DT) technology, emerging from Industry 4.0, enables real-time monitoring, simulation, and prediction of industrial systems, supporting intelligent and proactive maintenance and energy optimization strategies.

Methods

This study adopts a systematic literature review (SLR) combined with bibliometric analysis to investigate the role of Digital Twin technology in asset management for energy efficiency and industrial resilience within the Industry 5.0 context. Publications were retrieved from Scopus and Web of Science (2015–2025). After applying predefined inclusion and exclusion criteria, a final dataset was analyzed using bibliometric mapping and thematic analysis.

Results

The findings reveal a significant increase in research on Digital Twin-enabled asset management, particularly in predictive maintenance, energy optimization, and sustainable industrial systems. Digital Twins enable real-time monitoring, fault detection, and predictive analytics, improving asset reliability and reducing downtime.

Beyond maintenance, they contribute to energy efficiency through process optimization, reduction of energy losses, and adaptive control of industrial systems. The results highlight a strong link between maintenance optimization and energy efficiency, where improved maintenance directly reduces energy consumption.

In addition, Digital Twins support human-centric applications such as decision support, training, and human–machine collaboration aligned with Industry 5.0 principles. However, interoperability, cybersecurity, and implementation costs remain key challenges.

Conclusions

Digital Twin technology is a key enabler for integrating predictive maintenance, energy efficiency, resilience, and human-centric industrial systems. The study highlights its strategic role in supporting sustainable industrial transformation within Industry 5.0.

Information Structuring for Asset Management 5.0: The Case of an Energy Maintenance-Oriented Digital Twin in the JUMENGI Project

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Introduction

The development of digital twin-based approaches in the construction sector is part of a progressive transformation of information management practices. This transformation is marked by the extension of Building Information Modeling (BIM) beyond design phases toward operation and maintenance (Eastman et al., 2011 ; Succar, 2009). In this perspective, a digital twin is generally defined as a dynamic virtual representation of a physical asset, capable of integrating heterogeneous and evolving data from multiple sources to simulate, monitor, and optimize its behavior throughout its lifecycle (Grieves & Vickers, 2017).

The JUMENGI research project aligns with this dynamic by proposing an integrated digital twin approach oriented toward building energy maintenance. The project's objective is to develop and validate an operational method based on the coordination of data from BIM models, business information systems, IoT sensors, and energy simulation models.

Research Question

In this context, the central problem can be formulated as follows: how can heterogeneous data from BIM, information systems, and sensors be structured and articulated to enable their operational use in a digital twin oriented toward building energy maintenance?

This question relates more broadly to the capacity of informational systems to support decision-making in an environment characterized by a diversity of formats, timelines, and involved stakeholders.

Methodology

The methodology adopted for the JUMENGI project relies on an experimental and iterative approach, combining case study analysis and the progressive development of an informational architecture. Two contrasting cases were selected to confront the approach with real-world situations: a residential project with BIM models and sensor data, and a commercial building characterized by fragmented documentation and initially lacking a usable BIM model.

Data analysis identified the main limitations of existing systems, notably the absence of energy parameters in BIM models, difficulty accessing structured data, and interoperability issues between systems.

To address these challenges, a dedicated energy maintenance ontology was developed, defined as a "formal and explicit conceptualization of a shared domain" (Studer et al., 1998, p. 185). Inspired by the IFC standard while adapted to project needs, this ontology structures relationships between building elements, technical equipment, maintenance events, and data sources. This ontology forms the foundation of a knowledge graph implemented in a graph-oriented database. Additionally, a digital platform was developed, featuring a REST API, a graph database, and a BIM viewer based on BIMData.io, to make this data usable in an operational context (Tang et al., 2025).

Results

The results demonstrate the feasibility of integrating heterogeneous data within a unified environment based on a knowledge graph. This integration allows for the cross-referencing of information from BIM models, sensors, and technical documents, offering a coherent view of the building and its systems.

However, the results also highlight the limits of current approaches. Existing BIM models often appear insufficient for the operational phase due to a lack of relevant maintenance information and unsuitable structuring. The developed ontology structures this data but requires continuous adjustments to adapt to real-world data constraints, particularly regarding equipment location and relationship consistency.

Furthermore, the development of a platform integrating visualization, sensor data, and alert management constitutes an initial operational demonstration of the digital twin. The integration of advanced analysis methods, notably for fault detection, opens perspectives for predictive maintenance, a field where AI-powered models show significant reductions in unplanned downtime (Semeraro et al., 2025), although their effectiveness remains dependent on data quality.

Conclusion

The JUMENGI project demonstrates that implementing an operational digital twin relies primarily on the ability to structure, contextualize, and articulate heterogeneous data. It emphasizes the importance of an integrated informational approach combining modeling, semantic structuring, and the development of technical tools tailored to operational phase uses.

The results suggest a need to rethink BIM modeling practices by integrating energy maintenance needs from the outset. Future work should focus on automating the semantic enrichment of BIM models, improving ontology robustness against real-world data, and validating predictive maintenance approaches on a larger scale.

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A Human-Centered Digital Approval Architecture for Sustainable and Resilient Smart Manufacturing

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The transition toward Industry 4.0 and Industry 5.0 requires manufacturing organizations to modernize legacy paper-based processes and integrate traceable, data-driven workflows into cyber-physical environments. Despite advances in enterprise resource planning systems, many mid-sized manufacturers continue to rely on fragmented, manual approval procedures that generate delays, data inconsistencies, and environmental waste.

This paper proposes a modular, lightweight digital approval workflow framework designed to replace paper-based shop-floor approval processes, including deviation management, manual consumption documentation, and scrap validation. The system is structured around a role-based architecture incorporating digital form submission, multi-step approval routing, real-time tracking, automated PDF archival, and audit logging. Developed using Streamlit and Python-based backend services, the framework prioritizes rapid deployment, usability, and scalability while maintaining traceability and governance compliance.

A case-based evaluation conducted in a mid-sized automotive manufacturing facility demonstrates measurable operational and sustainability impacts. Simulation results indicate a 100 % reduction in paper consumption, an 87 % decrease in document-related errors (from 15 % to 2 %), and a near-total elimination of approval delays previously averaging one day per request. Additionally, the system contributes to reduced CO_2 emissions and administrative overhead while improving transparency and accountability.

The proposed framework offers a practical pathway for small and medium-sized manufacturers seeking to accelerate digital transformation without the complexity and cost of full ERP overhauls. By combining workflow standardization, sustainability metrics, and modular architecture, the study contributes to the advancement of smart, human-centered, and environmentally responsible manufacturing systems aligned with Industry 5.0 principles.

Multi-Stakeholder Decision Making for Medical Equipment Management and Crisis Resilience

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During a crisis, decision-making becomes a critical process with several crisis related limitations. The only strategy to survive a crisis in any domain, is by preparedness and resilience planning. Crisis resilience is the ability to prevent or adapt to conditions caused by external or sometimes internal factors that disrupt the normal flow of work. This translates the preventive maintenance approach for example, where maintenance is implemented before the failure to avoid major breakdowns. In healthcare, this aspect gets even more critical considering that a major health crisis can put patients' health at risk, expose them to health complications, injuries or even death. Instant measures are not recommended in case of a crisis: equipment or staff may not be available, decision-making process and solution implementation face time limitation and potential risk outcomes outweigh its benefits.

That is why it is essential to define an equipment management plan by identifying the convenient replacement and maintenance strategy for medical equipment in health facilities, especially critical and life-sustaining devices. This strategy should ensure the availability of equipment during normal and crisis situations, balancing clinical effectiveness, financial sustainability and other operational factors that affect the decision-making process and the workflow in a hospital environment.

While traditional medical equipment management has focused on regulatory and standards compliance, manufacturer recommendation-based replacements, and cost optimization, this research adopts a multi-criteria framework consistent with industry 5.0 standards. This approach combines human-centric decision-making, multi-criteria methodology and resilience planning, particularly for critical medical equipment in healthcare facilities where failures of assets have a direct impact on patient outcomes and safety implications.

edical equipment management is not only technical or cost effective. Our approach involves criteria that recognize the human role and takes into consideration clinical staff familiarity with the equipment, the training burden on technical and medical staff, the easiness of maintenance and handling of equipment and general staff satisfaction. This contributes in an effective maintenance and replacement strategy planning: A clear and well-defined strategy responds to the staff's needs, creates clear work schedules, reduces pressure on maintenance department and clinical personnel by guaranteeing the availability of efficient equipment that does not endanger the patient and thus the staff's wellbeing.

To be able to balance cost effectiveness, availability of equipment, staff satisfaction, technological obsolescence, and other operational factors in decision-making, we suggest the use of Multi-Criteria Decision Analysis methods (MCDA) to be able to select the convenient decision alternative for equipment replacement and maintenance. MCDA is a tool set to help evaluate and prioritize multiple criteria to systematically compare different decision alternatives.

The use of MCDA techniques in healthcare related decisions and equipment management has been focusing on issues like prioritization of equipment for maintenance [1-3]; prioritizing for equipment replacement [4-6]; classifying spare parts and optimizing inventory management [7]; and selection of maintenance strategy [8].

The purpose of this research is to generate a decision support system for medical equipment management to help decision makers select the parameters for an investment and maintenance strategy for critical medical equipment: case of ICU ventilators. This includes the selection and evaluation of the critical criteria for the decision, the evaluation and ranking of decision alternatives and presenting a decision support system for the multi-criteria process.

The Analytic Hierarchy Process (AHP) is chosen for pairwise comparison of criteria: patient safety; cost of ownership; staff satisfaction; sensitivity to obsolescence and easiness of procurement and logistics, and decision alternatives ranking regarding the fleet size and the age of replacement.

The results of this methodology allowed the selection of the optimal replacement and maintenance strategy for ICU ventilators, based on the age of replacement and the total number of equipment which affects the maintenance operations and cost and the number of equipment available thus the resilience to a healthcare crisis.

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