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Implementations of Digital Transformation and Digital Twins: Exploring the Factory of the Future

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Abstract: In the era of rapid technological advancement and evolving industrial landscapes, embracing the concept of the factory of the future (FoF) is crucial for companies seeking to optimize efficiency, enhance productivity, and stay sustainable. This case study explores the concept of the FoF and its role in driving the energy transition and digital transformation within the automotive sector. By embracing advancements in technology and innovation, these factories aim to establish a smart, sustainable, inclusive, and resilient growth framework. The shift towards hybrid and electric vehicles necessitates significant adjustments in vehicle components and production processes. To achieve this, the adoption of lighter materials becomes imperative, and new technologies such as additive manufacturing (AM) and artificial intelligence (AI) are being adopted, facilitating enhanced efficiency and innovation within the factory environment. An important aspect of this paradigm involves the development and utilization of a modular, affordable, safe human–robot interaction and highly performant intelligent robot. The introduction of this intelligent robot aims to foster a higher degree of automation and efficiency through collaborative human–robot environments on the factory floor and production lines, specifically tailored to the automotive sector. By combining the strengths of human and robotic capabilities, the future factory aims to revolutionize manufacturing processes, ultimately driving the automotive industry towards a more sustainable and technologically advanced future. This study explores the implementation of automation and the initial strides toward transitioning from Industry 4.0 to 5.0, focusing on three recognized, large, and automotive companies operating in the north of Portugal.

Keywords: Industry 4.0; collaborative robots; digital transformation; digital twins; factory of future; hybrid vehicles; strategic roadmap

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1. Introduction

From AI-powered robots streamlining production lines to 3D printing minimizing waste, the convergence of transformative technologies is revolutionizing industries. This clears the path for a future where factories with unprecedented efficiency, sustainable practices become the norm, and remote collaboration unlocks new possibilities. This paper explores the interconnected domains of digital transformation (DTR) and digital twins (DTWs), exploring their important roles in shaping the factory of the future (FoF). At the heart of this transformation lie the Internet of things (IoT) and the industrial Internet of things (IIoT), offering a conduit to usher in the circular economy (CE). However, the emergence of the Green IoT paradigm, focused on energy reduction and the carbon footprint, finds itself in juxtaposition with the advent of edge artificial intelligence (AI) [1]. Industry 5.0 represents the next phase in manufacturing evolution, fusing automation, digitalization, and human ingenuity to cultivate intuitive, interactive, and sustainable work environments. Moreover, advanced fabrication approaches like additive manufacturing (AM), prominently known as 3D printing, emerge as a cornerstone technology enabling customization, efficiency, and waste reduction compared to subtractive manufacturing [2]. To navigate the complexities of Industry 4.0 in small- and medium-sized enterprises (SMEs), the formulation of tailored maturity models (MMs) assumes significance [3,4].

The global upheaval caused by the COVID-19 pandemic has not only catalyzed a pattern shifts in day-to-day business operations but has also accelerated digital maturity aspirations. Manufacturing entities are expediting their DTR endeavors and raising their digital readiness levels (DRLs) in response to the pandemic's impact [5]. The imperatives of "Digitize or drown!" and "Innovate or die!" underscore the essence of DTR as a driving force. As Industry 5.0 gains traction, the convergence of technology-focused Industry 4.0 with smart logistics and smart factories amplifies research endeavors [6]. This exploration extends to diverse industries' adoption of DTR, unveiling how enterprises embrace novel technologies for their distinct business landscapes [7]. The concept of the DTW emerges as a bridge between virtual simulations and real-world operations. This seamless exchange of data between digital and physical twins (PTWs) in real time empowers operational efficiency, smart manufacturing (SM), and informed decision-making [8]. Exploring the evolution of DTWs from their origins to their projected future is crucial for understanding the benefits they offer to specific industries. This analysis aims to unify various manifestations and definitions of DTWs found across the literature, simplifying the identification of DTWs amid other related terms like "product avatar", "digital thread", "digital model", and "digital shadow" [9]. Furthermore, the symbiosis of building information modeling (BIM) and DTWs holds the potential to revolutionize digital construction across the lifecycle [10].

The evolution of robotic technology introduces new dimensions to manufacturing, addressing productivity and ergonomic concerns. Collaborative robots (cobots) stand as exemplars of Industry 4.0 progress, offering enhanced productivity, adaptability, and safety. However, efficient design remains a challenge, as ergonomic assessment tools are not tailored to these devices [11,12]. A facet of this concept involves human–robot collaboration (HRC), which aims to synergize the finest capabilities of humans and robots to jointly accomplish shared tasks. For instance, an assembly process necessitates a fusion of dexterity, intelligence, and sensing skills. Collaborative robotics emerges as a potential remedy for addressing the issue of musculoskeletal disorders (MSDs) within the industrial domain. The utilization of cobots has the potential to revolutionize manufacturing by addressing efficiency and ergonomic concerns. Exploring their applications and showcasing advancements in human–robot collaboration (HRI) in the coming years hold immense potential [13]. In contrast to traditional industrial robots, collaborative robots offer heightened productivity, flexibility, adaptability, and safety. These user-friendly machines feature intuitive interfaces, allowing even those without formal programming experience to easily adjust settings and functionally [14].

The FoF is designed to embrace circular economy principles and take advantage of sensors and AI from Industry 4.0 to optimize resource usage and minimize waste, leading to a more sustainable production environment. This paper focuses on case studies and assessment tools to extend circular principles across product lifecycles, facilitating the robust evaluation and monitoring of circular efficiency [15]. The urgency for manufacturers to embrace Industry 4.0's transformative potential is undeniable, yet the uniqueness of each business necessitates tailor-made strategic roadmaps (SRs) for a successful transition [16]. The primary facilitative element of the IoT concept lies in the amalgamation of diverse technologies and communication solutions. The next generation of intelligent systems integrates identification and tracking technologies, sensor and actuator networks (both wired and wireless), advanced communication protocols for ultra-fast data exchange, and distributed intelligence for smarter decision-making at the device level. This combination enables real-time monitoring, optimized resource management, and automated processes, and improved communication for the next-generation Internet (NGI), leading to significant improvements in efficiency and functionality [17]. Amid the IoT model, the fusion of diverse technologies shows the approach for novel solutions. Further research is crucial for defining the precise boundaries and application frameworks of Industry 4.0, despite valuable insights gleaned from European strategic roadmaps (ESRs) and the broader scientific literature [18]. The fusion of radio frequency identification (RFID), cyber-physical systems (CPS), IoT, and data mining propels Industry 4.0 towards novel forms of personalization and shared value creation [19]. In this rapidly evolving landscape, DTWs transcend the industrial area and venture into various sectors, heralding efficiencies in terms of time and cost. The convergence of DTR and DTW technologies heralds a revolution with the potential to reshape multiple facets of our lives [20]. This paper undertakes a comprehensive survey of the digital transformation and digital twins paradigms, unveiling their profound influence on the regional and international FoF. The automation of processes emerges as a key enabler, leading to increased productivity, improved production control, and a decrease in difficulty for workers, thereby enabling better process management.

The current case study encompasses various topics, such as Industry 4.0, safety and ergonomics, digital twins, and lightweight additive manufacturing, which contribute to the overarching vision of the FoF. The diverse examples presented herein are drawn from three automotive companies located in northern Portugal, ranging from internal logistics to mobile intralogistics, utilizing intelligent robot and automated vehicles. These include the hierarchical pyramid implementation of DTR and DTW, real-time analysis of physical objects, virtual replication in HRC definition, and adoption of automation and the early steps taken towards transitioning from Industry 4.0 to 5.0. The present investigation has a specific focus on three well-established automotive companies in northern Portugal. These companies have a global reputation for manufacturing car components (Section 2), seat leathers (Section 3), and technology-driven vehicles (Section 4). The focused aims for each of the sections are as follows: internal logistic utilization using mobile robots, the human-centered mechanism design for collaborative robots, and the virtual modeling of factories with simulations and tests.

2. Configuration of Digital Transformation

Digital transformation is the process of using technology to fundamentally change how businesses operate, deliver value to customers, adapt to the evolving digital landscape, and improve efficiency and innovation. On the other hand, a digital twin is a virtual replica or representation of a physical object, system, or process [21]. It is created using digital data and simulations to mimic the real-world counterpart. Digital twins help monitor, analyze, and optimize physical assets and processes, enabling better decision-making and performance improvements in various industries like manufacturing. Within this digital transformation, digital twins play a key role, and they are closely related concepts. Digital transformation is the broader process of using technology to change how organizations operate and deliver value. Digital twins replicate the digital counterparts of physical assets or processes, created as a part of digital transformation efforts. In essence, digital twins are a powerful tool within the digital transformation toolbox, enabling businesses to make more informed decisions, enhance efficiency, and drive innovation by exploiting the insights and simulations they provide.

2.1. Logistic Challenges

The traceability system (TS) presents a promising avenue for potential improvement, employing digital technologies to enhance the monitoring of the production process and internal logistics. It ensures the authenticity and immutability of data, supported by a digital control and monitoring platform. It is essential to note that the company is not responsible for the external transportation of final products to customers, and this falls outside the scope of the supply chain. As illustrated in Figure 1, the focus of traceability lies in individually limited internal logistics for the automobile parts/assembly producer company. Nevertheless, traceability can be extended to cover the entire journey, up to the point of product delivery to the customer. Heavy and bulky components like steel rails, wind turbine blades, and large motors significantly impede the technical challenge of traceability. Tracking the origin, history, and location of these massive parts becomes complex, potentially leading to increased costs, safety hazards, and maintenance difficulties. This challenge also presents an opportunity for innovation in the field. This case study suggests the implementation of collaborative human–robot technologies, which require the following components:

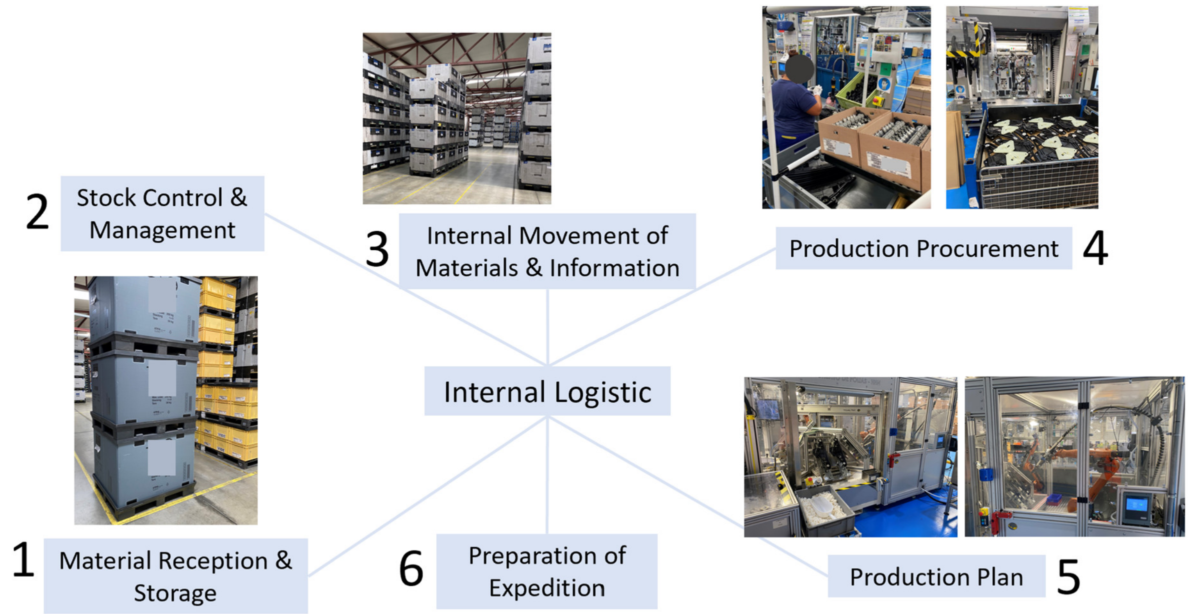

Figure 1. Internal logistic demonstration.

–Utilization of logistics trains equipped with AGV to facilitate the supply of workstations with components and transport lifters to the warehouse.

It is notable that IMR and AGV are both types of mobile robots, but they differ in their functionality and operation. IMRs are more versatile, adaptable, and intelligent, with advanced sensors, cameras, and mapping. They can perform a wider range of tasks in various environments with a higher degree of autonomy and safety features. IMRs can be programmed or trained to perform a variety of tasks, including inspection, logistics, and collaborative work with humans. On the other hand, AGVs are more specialized, fixed-route robots, following a line or path on the ground for navigation, or magnetic strips, wires, or QR codes designed for material transport in factories and warehouses. Moreover, IMRs are often equipped with advanced safety systems to avoid collisions with humans, whereas AGVs are designed to operate in segregated areas and may not have safety features. The development of an autonomous mobile robots with a perception-based navigation system is currently underway, and, coupled with the challenge of designing complex architecture and movement, there is a need for designers to construct it to operate effectively and compactly across various mediums [22,23].

–Enhanced inventory control of both the warehouse and in-process components through the cross-validation of data from the manufacturing execution system (MES), lifters assembled at each station, and transported items in the warehouse. Currently, operators are manually recording production by barcode after the completion of small batches. The integration of the MES with the maintenance system to ensure seamless data exchange and co-ordination is necessary.

–Development of a digital platform that displays real-time information about the internal movement of vehicles, component production, in-process stock levels, machine stoppages due to material shortages, and stoppages caused by breakdowns and malfunctions.

–Implementation of personal protective equipment (PPE) control, including the use of an object detection or RFID algorithm to issue alerts in non-serious cases and control machine operation in mandatory cases. The detection algorithm will generate alerts in non-serious cases when a worker is not wearing the required PPE but will not prevent the worker from continuing work. However, machine actuation control for mandatory cases will be employed when the use of PPE is essential to prevent serious accidents, ensuring that the system prevents a machine from starting if a worker is not wearing the appropriate PPE.

The roadmap for integrating digitalization into the factory of the future and additive manufacturing in Industry 5.0 involves the seamless convergence of advanced fabrication technologies [24]. This journey emphasizes the benefit of automation to transform manufacturing processes. Additionally, additive manufacturing (3D metal/plastic printing) will play a key role in I 4.0 and I 5.0 by enabling on-demand, customized production, reducing waste, decreasing weight, and enhancing product design flexibility [25]. The goal is to create highly efficient and sustainable manufacturing systems that are interconnected and capable of producing complex, personalized products with minimal environmental impact.

2.2. Intralogistics Approach

1. Industry 5.0 exemplifies itself in an innovative internal logistics system for factories. The system utilizes lightweight, retractable, and portable racks integrated with an autonomous mobile robot (AMR) for efficient material movement. This setup highlights allied automation through the collaboration of the AMR and the racks. The use of potentially porous aluminum structures, combined with digitalization, further embodies Industry 5.0's principles. In-house research and development are feasible for smaller-scale simulation. It creates an agile, interconnected, and data-driven internal logistics system that can adapt to the evolving needs of the factory, ultimately leading to increased efficiency and productivity. Mobile intralogistics progress is defined by below terms and shown in Figure 2.

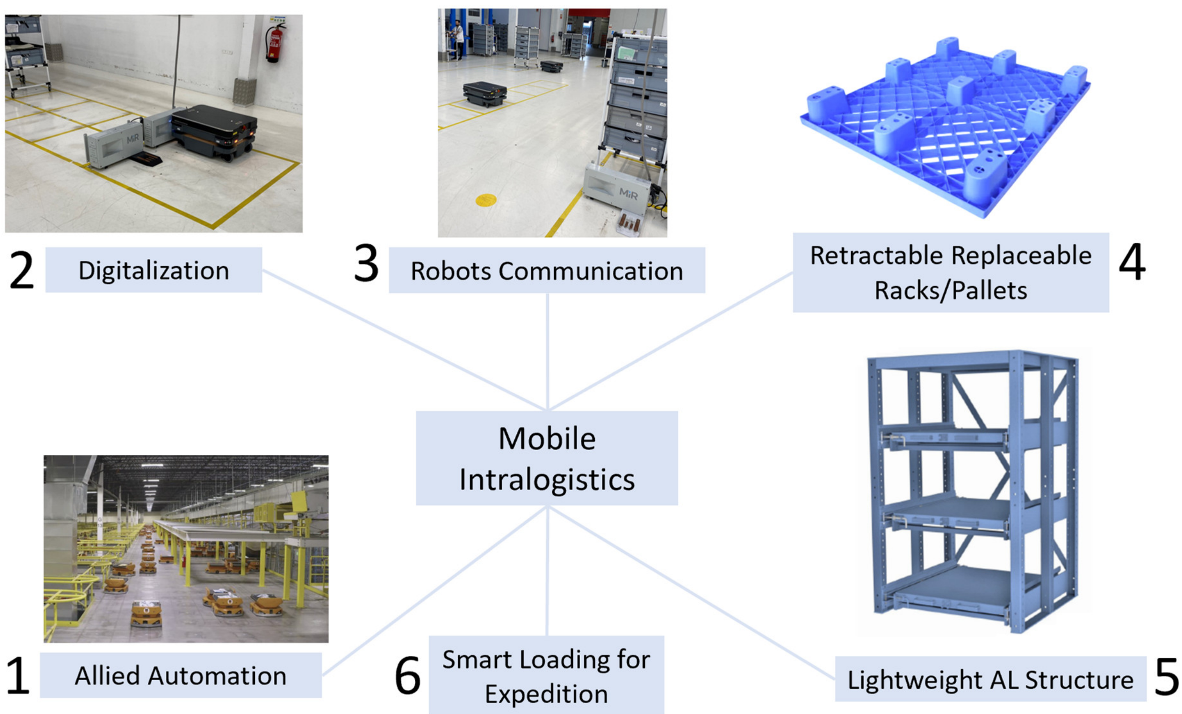

Figure 2. Mobile intralogistics.

Allied automation—This solution prepares allied automation principles to optimize the internal logistics process. By combining a mobile AMR robot with smart racks, the system ensures a seamless and coordinated flow of materials and products within the factory.

Aluminum structures: The lightweight racks and pallets are constructed from advanced aluminum structures (potentially porous), which are not only durable but also exceptionally lightweight. This design minimizes the overall weight of the system, allowing for the greater efficiency and mobility of the AGV/IMR robot.

Digitalization—It is at the core of this setup. Each rack is equipped with sensors and RFID tags for real-time tracking (RTT) and inventory management. The mobile robot/cobot is equipped with sensors and cameras for navigation and safety. All the data from these sensors are integrated into a digital platform, providing real-time visibility into the logistics process. This enables better decision-making, route optimization, communication, and predictive maintenance.

Industry 5.0—This solution aligns with the tenets of Industry 5.0 by creating a highly flexible and interconnected logistics system. AGV/IMR robots, guided by AI and machine-learning (ML) algorithms, can adapt to changing production demands. The porous aluminum racks are modular and can be reconfigured easily to accommodate different products, promoting customization and rapid retooling.

2. The use of metal additive manufacturing (MAM) and wire arc additive manufacturing (WAAM) in lightweight jig and fixture design (JFD) represents a transformative shift in traditional manufacturing practices. This innovative approach allows for the creation of highly customized and complex jigs and fixtures with significant advantages:

Design freedom for complex geometries—MAM offers unparalleled design freedom in situ. Engineers can create intricate, lightweight, and optimized structures that were previously impossible or too costly to produce using conventional methods [26]. The technology enables the production of complex geometries that precisely match the workpiece, ensuring a more secure and accurate fit. This is especially valuable for intricate or irregularly shaped components.

Reduce lead times and increase cost efficiency—Additive manufacturing drastically reduces lead times. Design modifications and iterations can be quickly implemented, making it ideal for rapid prototyping and adapting to design changes. While the initial investment in metal 3D printing equipment can be high, it often results in cost savings in the long run. This is particularly true for low-volume, high-complexity applications where the tooling and setup costs of traditional methods can be substantial. Customized jigs and fixtures result in better alignment and reduced setup times, ultimately improving manufacturing efficiency and accuracy.

3. The process of designing cutting-edge solutions for robot arms or grippers specialized in handling hard or soft materials is targeted. The primary goal is to enable the gentle and damage-free small-space picking and placing of various materials. It can use a combination of compact articulated joints (CAJ) and advanced computer vision. It should employ precise end-effectors with sensors to detect and adapt to object orientation, enabling it to navigate within confined areas while ensuring damage-free manipulation mechanisms for different stiffnesses and hardness ranges of materials. The fabrication of these parts is firmly rooted in the field of digitalization and relies on additive manufacturing techniques. The below outcomes have been followed for implementation in this stage:

- Using compact, collapsible, and easily transportable shelving units integrated with an AMR or AGV for efficient mobile intralogistics operations, facilitating the transportation of stocks and productions.
- Utilizing MAM to create lightweight jigs and fixtures offers advantages in rapid prototyping, on-site fabrication, cost and time savings, and adaptability to evolving design requirements and changes.
- Design of specialized robot arms or grippers tailored for the gentle handling of both hard and soft materials, enabling damage-free pick-and-place operations with the use of compact articulated joints suitable for confined spaces.

2.3. Mobile and Cloud Computing

The hierarchical pyramid of main parameters for DTR from bottom to top is leveled and illustrated in Figure 3. This pyramid illustrates how digital transformation is the overarching concept, with technology infrastructure and data collection as its foundation. DTW, HRC, and mobile intralogistics represent specific areas of focus within the transformation, and all these components collectively contribute to optimization and decision-making at the highest level.

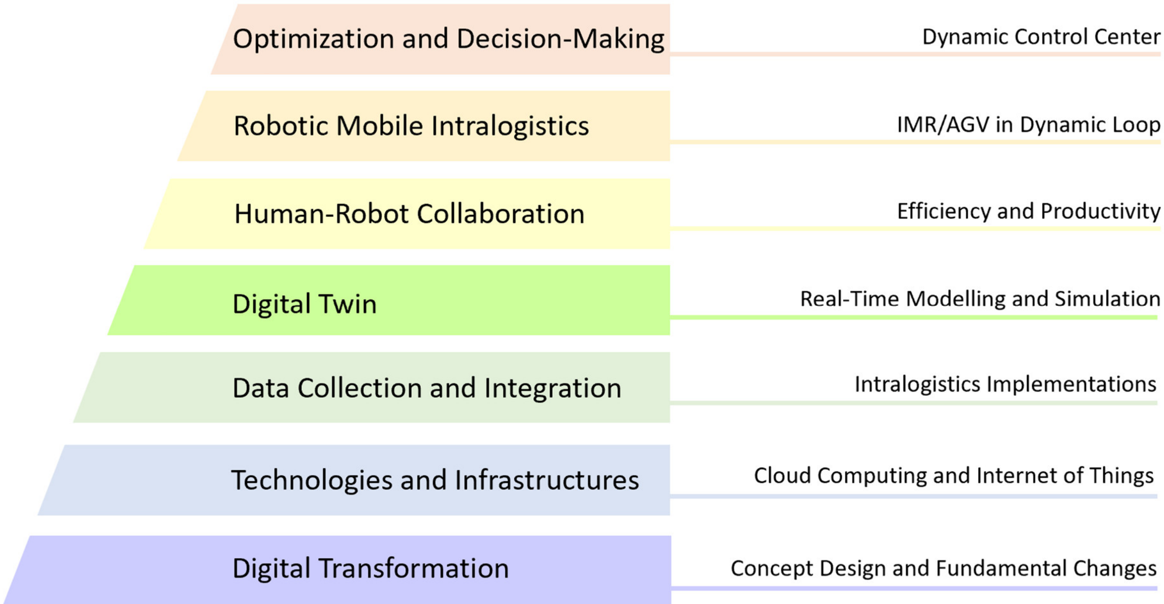

Figure 3. Hierarchy of digital transformation (DTR) based on digital twins (DTWs).

Level 1—At the base of the pyramid, the overarching concept of digital transformation encompasses the entire process.

Level 2—Infrastructures and technologies, such as IoT sensors, communication networks, and cloud computing, form the foundation for digital transformation.

Level 3—Gathering data from various sources, including robots and intralogistics processes, is a crucial step in the digital transformation journey.

Level 4—Digital twins are a key component, enabling real-time modeling and simulation of physical systems [27].

Level 5—Human–robot collaboration is an integral part of the transformation, focusing on how humans and robots work together efficiently [28].

Level 6—Mobile robots play a specific role in intralogistics, representing the application of technology to transport goods within a facility.

Level 7—At the top of the pyramid, optimization and decision-making take center stage, along with data capitalization, digital twins, and collaborative efforts to make informed choices that improve efficiency, productivity, and overall operations.

3. Configuration of Digital Twins

3.1. Physical and Virtual Systems

Key challenges to implementation include the adoption of new technologies such as additive manufacturing (AM), novel materials like metal–plastic composites, the integration of artificial intelligence (AI), the use of IMR/AGV, efficient warehouse space management, and, notably, the transition from human operators to robots with effective human–robot interaction.

Human–robot collaboration (HRC) partnerships are an approach for adaptable workgroups combining human and robot capabilities. These partnerships are leading the way in creating efficient and flexible teams that leverage both human and robot strengths. Robots are enhancing operations by rectifying human errors in factory settings, resulting in increased production speed and uninterrupted precision. The configuration of DTWs in HRC work is depicted in Figure 4, and the terms are explained here as bullet points.

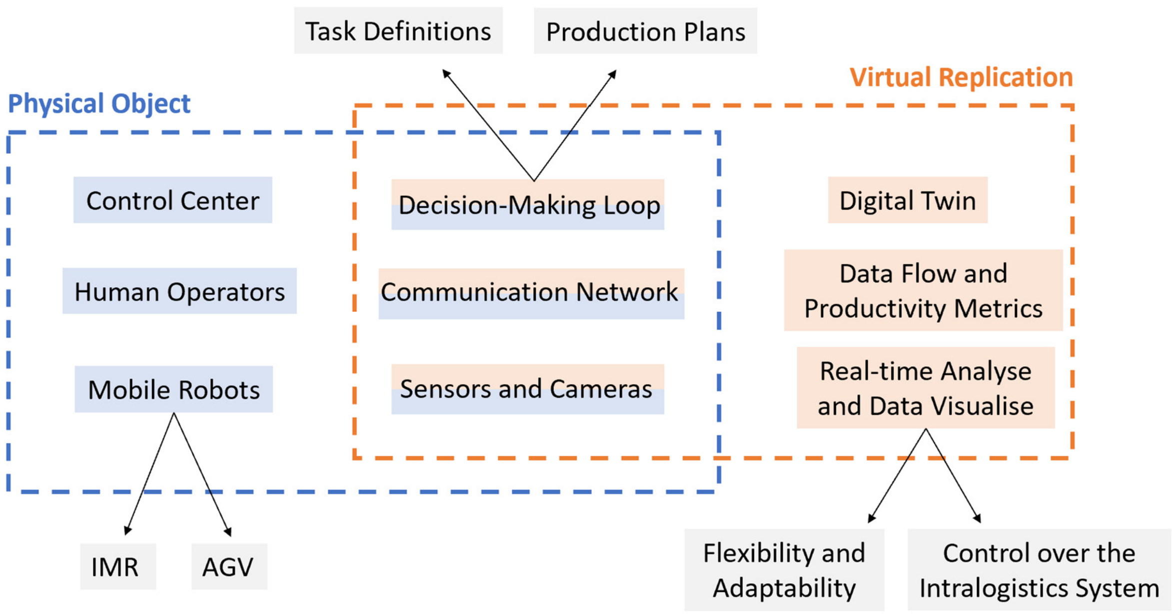

Figure 4. Digital twins (DTWs) in human–robot collaboration (HRC).

Human operator—The human worker actively participates in the intralogistics process, overseeing and interacting with robots and cobots to ensure smooth operations and increase productivity [29].

IMR/AGV robots—IMR is an autonomous mobile unit specialized in intralogistics tasks, capable of navigating and handling materials efficiently, while AGV, another mobile automation solution, is designed for material transport and contributes to streamlined intralogistics operations.

Digital twin—The digital twin is a virtual replica of both IMR and AGV robots, allowing for the real-time monitoring, analysis, and simulations of their actions and surroundings.

Sensors—Sensors on the robots collect data from the physical world, including information on the location, obstacles, and environmental conditions.

Communication network—The network facilitates data exchange between robots and their digital twins, enabling seamless real-time communication.

Data flow and productivity metrics—Data flow from physical robots to the digital twin, providing critical insights for decision-making and control. Moreover, performance metrics and data visualization tools help gauge improvements in efficiency and productivity due to the DTW influence.

Control center—The control center is the interface where operators or AI systems interact with the digital twin, monitoring and managing robot activities [30].

Real-time analytics—This tool processes data from the digital twin, offering actionable insights and performance feedback. The digital twin enables adaptive responses to change conditions, ensuring the intralogistics system remains flexible and efficient.

Decision-making loop—Decisions are made based on digital twin data, influencing the actions and behaviors of the IMR/AGV robots in a dynamic loop. In fact, the decision-making loop acts as the dynamic control center that bridges the gap between production plans and the execution of tasks by robots and humans.

Digital transformation (DTR) can be implemented across various vehicle component manufacturers. For instance, this study focuses on examining a leather company that specializes in crafting car seats and interior designs. The diverse materials used in car seats, such as foams, fabrics, and leathers, pose technical challenges in handling and transport to avoid damages. Implementing the leather defect inspection (LDI) helps reduce waste, especially with expensive leathers. To address these challenges, utilizing data collection technologies like MES, RFID, and computer vision is advised to identify and rectify tracking errors for items and personnel. Utilizing warehouse management systems, including RFID for RTT, aids in efficient material and product storage and shipping. Employing a blend of technologies ensures data accuracy. Collaborative tech implementation, along with intralogistics trains (IMR and AGV), aids in reducing the carbon footprint by facilitating the supply of raw materials, movement between workstations, and transportation to the warehouse. Note that the carbon footprint is the total amount of greenhouse gas, specifically carbon dioxide, emitted directly or indirectly by human activities, impacts in global warming and climate change, and its reduction stands as a key objective within Industry 5.0.

3.2. RFID-Based Smart Factory

MES is a software solution that helps manage and control the production process on the factory area and shop floor of a manufacturing facility. It provides real-time information about manufacturing operations, enabling better decision-making, increased efficiency, and improved overall performance. Therefore, cloud MES processing based on RFID configuration utilizes RFID technology for tracking and managing manufacturing processes [31]. The layers from factory to user are depicted in Figure 5. RFID tags on items communicate with the system through radio waves, allowing for real-time data collection and analysis in a cloud-based environment, promoting efficiency and visibility in the manufacturing process. For MES systems that operate based on the cloud, instead of being hosted on local servers within a factory, the MES software and data are stored and processed on remote servers accessible through the Internet. This allows for more flexibility, scalability, and, often, cost savings. Moreover, RFID technology uses radio waves to identify and track objects. In a manufacturing context, RFID tags are attached to products, components, or equipment. These tags contain data that can be wirelessly read by RFID readers and, consequently, process MES software.

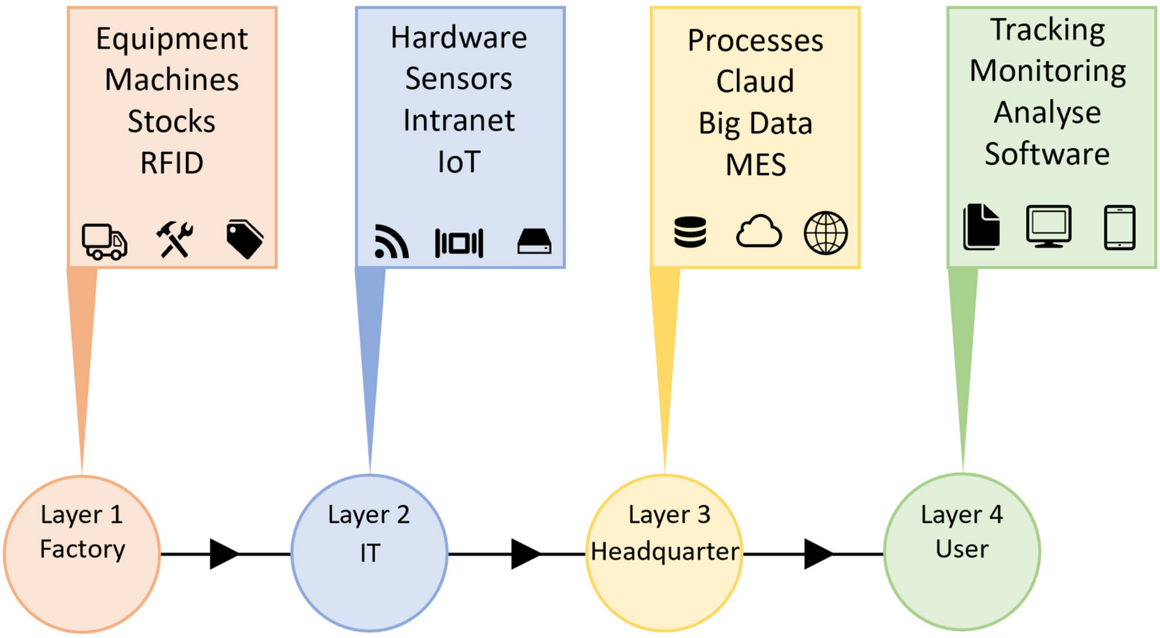

Figure 5. Radio frequency identification (RFID) configuration for manufacturing execution system (MES) processing.

Integrating digital twin technology and Industry 5.0 effectiveness in a company that uses leather for car seat production can significantly enhance efficiency, reduce waste, and improve overall operations. By integrating digital twin technology, RFID-based processes, automated machine vision, and other Industry 5.0 principles, your company can enhance its competitiveness, reduce waste, and improve the overall quality of leather car seat production. Here are some steps and considerations to involve digital twins and digital transformation through Industry 5.0 in car seat manufacturing companies.

DTW implementation—It starts with the creation of a DTW (developing a digital replication) of the manufacturing process, including the entire supply chain, from leather sourcing to the final product. Later, RTT and monitoring encompass implementing sensors and IoT devices to collect real-time data from the manufacturing floor. These data can include temperature, humidity, machine status, cutting design, and other relevant parameters.

RFID-based manufacturing process—Embedding RFID tags on each pack or piece of leather and integrating RFID readers into the manufacturing process help in tracking and monitoring the movement of leather throughout the production line. Integrate RFID data with a Cloud MES to centralize and analyze information. This can provide insights into the production process, reduce errors, and enhance traceability.

Automated machine vision for LDI—Utilize machine vision systems equipped with cameras to inspect leather for defects during the manufacturing process and connect this vision system to the digital twin for real-time defect analysis (based on size and location of defects). This allows for immediate corrective action and reduces the likelihood of defects reaching the final product.

HRC—While the pick-and-place process for leathers is currently carried out by humans, we need to consider introducing robots to this task to reduce the risk of damage during transport and enhance precision. It requires robots to ensure that they work in collaboration with human workers, especially in tasks that require dexterity and attention to detail.

Data analyses and maintenance—Analyze the data collected from sensors and IoT devices to identify patterns, optimize processes, and improve overall efficiency, and, then, implement predictive maintenance based on the data collected to reduce downtime and enhance the lifespan of machinery. Moreover, providing the necessary training to employees for the newly implemented technologies ensures a smooth transition and maximizes the benefits of digital transformation.

Sustainability considerations—Using data from the digital twin and machine vision systems to optimize the cutting process, minimizing waste and maximizing the use of materials, consider the environmental impact of your manufacturing processes and explore ways to reduce the carbon footprint, such as recycling leather scraps [32]. It is worth noting that digital transformation is an ongoing, iterative process. Continuously gather feedback, monitor performance, and adjust to improve efficiency and effectiveness.

For a detailed application and specific example, a case study of the mentioned configuration is employed to address the challenge of manual labor in picking and packing leather, replacing it with robots. The activities and deliverables goals for the leather company in north of Portugal include process identification and material priority in the production lines of the fabrics and handling (pick-and-place) of single and multiple layers. It is a regional automotive company with a global network of partnerships and distribution for car manufacturers worldwide. The *Lectra* machine handles the material cutting, optimization of usage, and positioning of papers and stacks; however, the detachment of cut parts and stacks and the pick-and-place process are performed by human operators. To automate these tasks, the implementation requires artificial vision for detecting part positions, a robotic arm operating independently of the operator, and the ability to recognize and handle single-layer leathers from multilayered ones [33]. The gripper idea of pick-and-place is illustrated in Figure 6, and the defect detection of precious leathers in Figure 7.

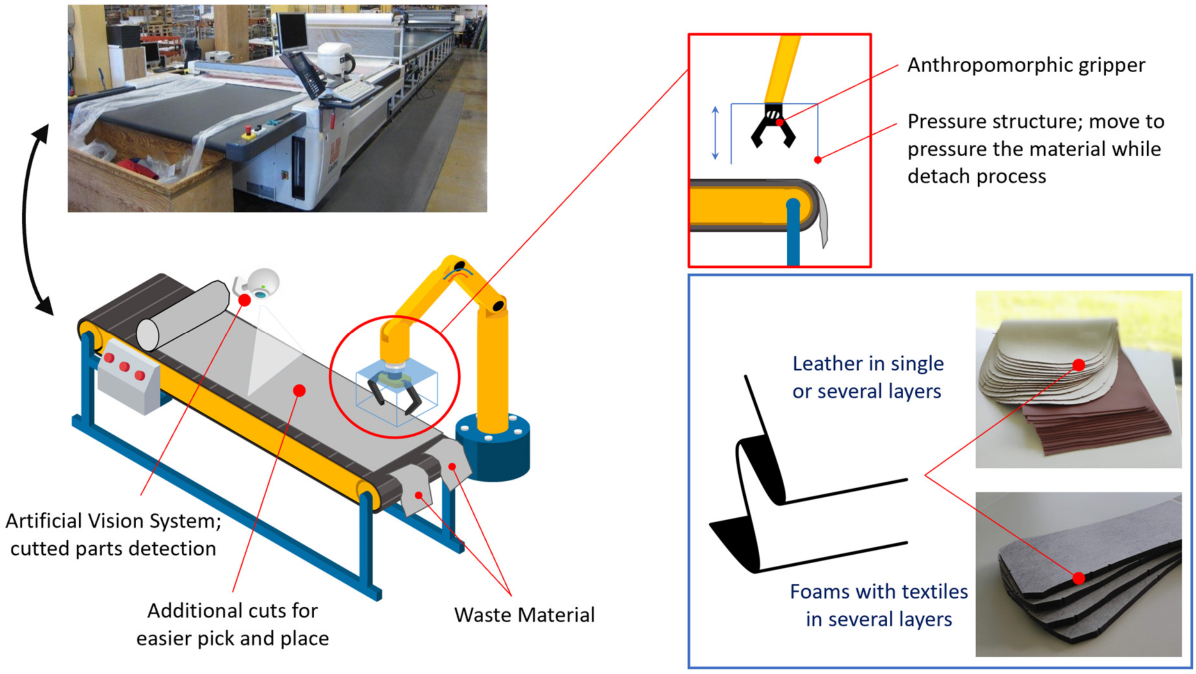

Figure 6. Detach using press and grasp, applied for human-oriented design of collaborative robots in leather-cutting process.

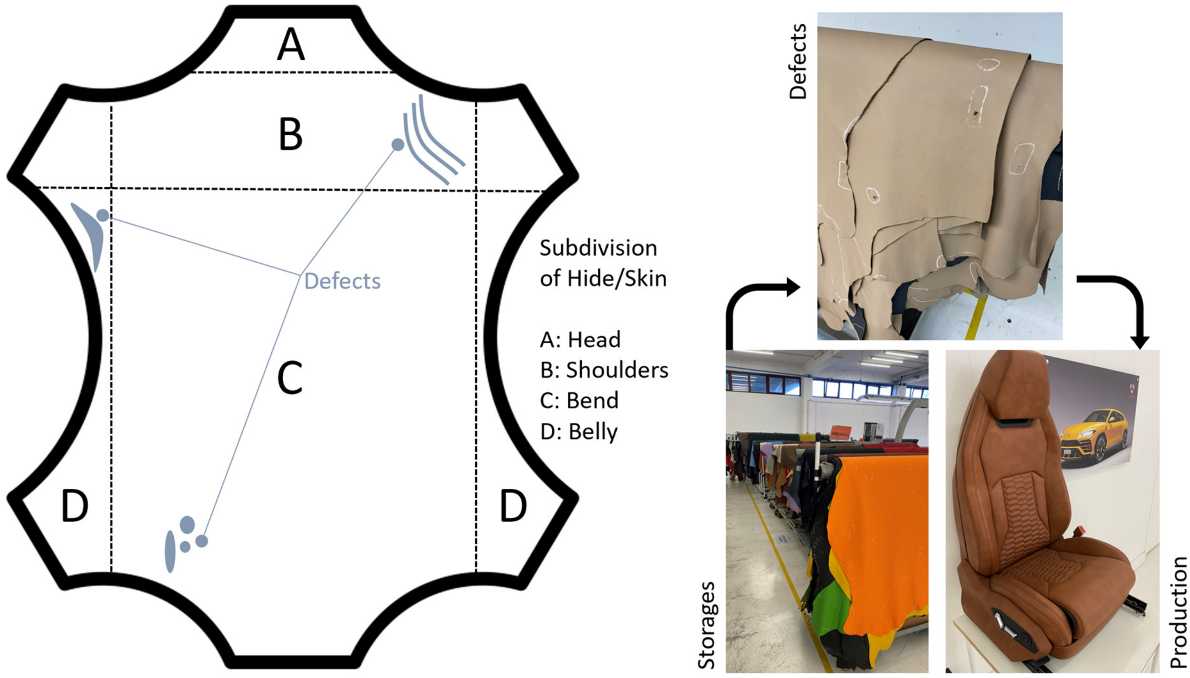

Figure 7. Leather defect detection and classification importance. Visual inspection methods by humans in the beginning can be replaced by HRC and RFID during the process. These effects occur due to different reasons, e.g., raw hides and animal wounds, damage during transport, moisture, folds, wrinkles, and dirt.

The concept of a green factory will function as a research, demonstration, and learning platform, benefiting manufacturing companies, especially those involved in advanced manufacturing such as AM [34]. This can be achieved through the fusion of advanced technologies with traditional ones, as indicated in [35], or it can relate to sustainability in the food and agriculture industries [36]. Green technology aims to achieve smarter, healthier, and more sustainable digitalization, aligning with the promotion of DTR and DTWs. Therefore, it is crucial that we integrate environmentally friendly steps to reduce ecological impact and waste.

4. Technology-Driven in Light Vehicles Industries

4.1. Manufacturing Execution Methodology

The integration of systems, applications, and products (SAP) and MES in industrial management processes is crucial for achieving an efficient manufacturing operation in the third company, focusing on light vehicles, mobility, and supply chain management. Both SAP and MES play distinct but complementary roles in the manufacturing ecosystem [37]. SAP is responsible for managing records related to materials, bills of materials (BOMs), and orders; in contrast, MES oversees the documentation of records like work in progress. There are two developments that can improve the management of the system here. First, SAP extended warehouse management (EWM) with an extended range of functions is a solution for organizing the supply chain, and, second, serving simultaneously enterprise resource planning (ERP) and MES systems for synchronized and efficient manufacturing operations [38]. This development is shown in Figure 8. The key aspects of integrating SAP EWM and MES ERP systems are data flow and communication, master data synchronization, order and production planning, quality and inventory management, real-time monitoring, reporting and maintenance, and user training and support and changes.

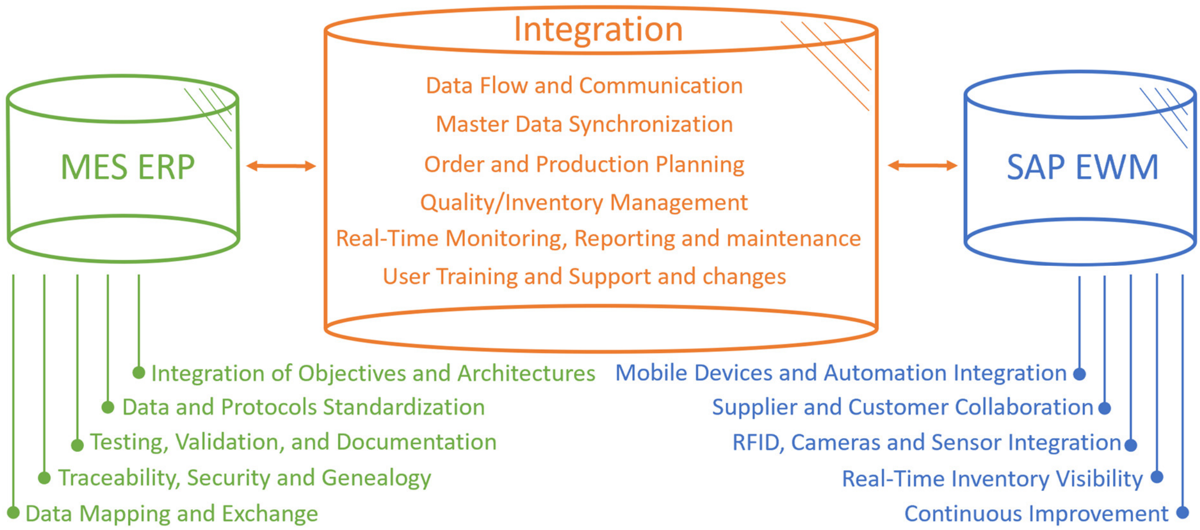

Figure 8. Integration of MES enterprise resource planning (ERP) and SAP extended warehouse management (EWM) systems.

The integration of SAP EWM and MES ERP systems is crucial for seamless and efficient operations in a manufacturing environment [39]. By addressing these key factors, organizations can enhance the integration of SAP EWM and MES ERP systems, leading to improved efficiency, accuracy, and overall performance in both warehouse management and manufacturing execution processes. Here are key factors to consider for a successful integration:

Data flow, consistency, and accuracy—Ensure that the data shared between SAP EWM and MES ERP is consistent and accurate. Inconsistencies can lead to errors, delays, miscommunications, and inefficiencies.

Standardized data formats and protocols—Define standardized data formats and communication protocols for data exchange between SAP and MES to ensure compatibility and smooth integration. Moreover, harmonize or synchronize master data, including product definitions, production schedules, and inventory data, to avoid discrepancies and ensure a single version of truth across systems.

Real-time data exchange—Aim for real-time data exchange to enable quick decision-making and responsiveness to changes in the manufacturing environment. It includes testing and validation, user training, continuous monitoring and optimization, and AGV/cobots movements. Provide training to end-users on the integrated system and implement change management strategies to facilitate a smooth transition. This is crucial for user acceptance and the effective utilization of the integrated solution. Conduct thorough testing, including unit testing, integration testing, and end-to-end testing, to identify and resolve any issues before deploying the integrated solution into a production environment, and regularly optimize the integration process based on feedback and evolving business needs.

Business process alignment—Design the integration solution to be scalable, accommodating future growth and changes in business processes. Ensure that the integration architecture is flexible enough to adapt to evolving business requirements. Regarding the scalability (ability of system to handle a growing amount of work or workload) and flexibility (ability of system to adapt easily to changes, whether they are changes in the business environment, customer requirements, or technological advancements), align business processes between SAP EWM and MES ERP to ensure that workflows are synchronized and there is a flow of information between warehouse management and manufacturing execution.

The digital transformation aims to establish a digital twin, i.e., horizontal and vertical digital processes that function as a virtual mesh adjacent to the real world that is both collaborative and responsive to change and immensely volatile needs. The main objective of a mobility industry player in northern Portugal, as illustrated in Figure 9, is to reduce supply chain bottlenecks. However, despite its advanced technological maturity, achieving this goal hinges on overcoming the challenge of integrating various technologies to ensure seamless interoperability.

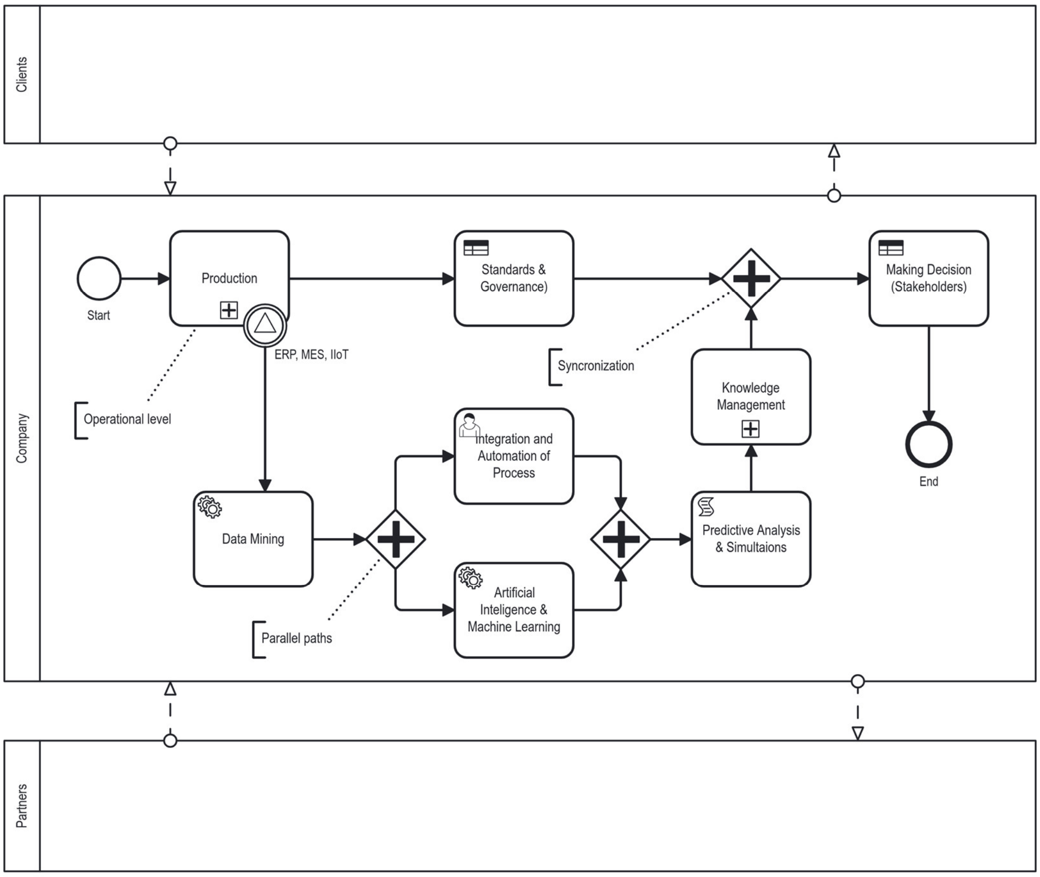

Figure 9. Schematic of future of a light vehicle industry to accelerate mobility solutions.

Therefore, process orchestration is the goal, so that various concepts harmonize to create a symphony of efficiency and productivity. At the center of the factory is production, supported by ERP systems that manage resources and workflow and MES that acts on manufacturing operations, while RPA automates repetitive tasks, freeing up employees for more strategic activities. GenAI injects artificial intelligence into production, optimizing processes and preventing failures. ISO guarantees quality through international standards, while Standards and Governance establish the rules that govern the symphony. Predictive data analysis provides valuable insights for decision-making, while knowledge management preserves and shares accumulated knowledge. With these capabilities, in addition to monitoring and control, the digital twin makes it possible to create a virtual model of the factory, allowing for simulations and tests before implementation in the real world.

The quadruple helix model (QHM) is a concept used in innovation studies and regional development to describe the interaction among four key stakeholders in the innovation process. It builds upon the triple helix model, which includes universities, industries, and governments as the main actors in innovation [40,41]. The QHM adds the fourth helix, civil society. These four helices in the QHM are as follows:

Academia, universities, and research institutions—The first helix represents the traditional knowledge creation and dissemination institutions, such as publications.

Industry and businesses—The second helix relates to the private sector, including businesses and corporations that drive economic development and innovation through commercialization.

Government and public sector—The third helix shows governmental bodies and agencies that create policies, regulations, and infrastructure to support innovation and economic growth.

Civil society—The fourth helix is citizens, non-governmental organizations (NGOs), and community groups who are engaged in the innovation process. They provide input, demand accountability, and contribute to the social context of innovation.

The QHM, specially, emphasizes the importance of collaboration and interaction among the technology institutes and industries for sustainable and innovative digitalization. Then, with the oversight and funding from government agencies, NGOs attend on creating a virtual model of the factory, complete with unit simulations.

4.2. Technology Roadmap and Industry Impact

The phases of industrialization have marked significant shifts in the way societies and economies operate. Here is a brief definition of each phase from Industry 3.0 to Industry 6.0, and it is worth mentioning that our study only emphasizes on satisfying the 4.0 and 5.0 revolution's condition and its transition. These phases of industrialization reflect the evolution of technology and its impact on manufacturing processes, and it is demonstrated in Figure 10. Each phase has brought about transformative changes, leading to increased efficiency, productivity, and innovation in the industrial sector.

Industry 3.0, digital revolution—This phase was characterized by the adoption of computerization and automation in industrial processes [42]. It began in the late 20th century and saw the integration of electronic systems for manufacturing and control. The introduction of computers and programmable logic controllers (PLCs) in this revolution increased efficiency and precision in manufacturing.

Industry 4.0, smart factory—Industry 4.0 builds on the foundation of Industry 3.0 and involves the widespread use of smart technology, sustainability functions, IoT, and CPS [43]. It aims to create smart factories and interconnected systems, integration of IoT, big data, AI, and ML into manufacturing, increased connectivity, real-time data analysis, and customization of products.

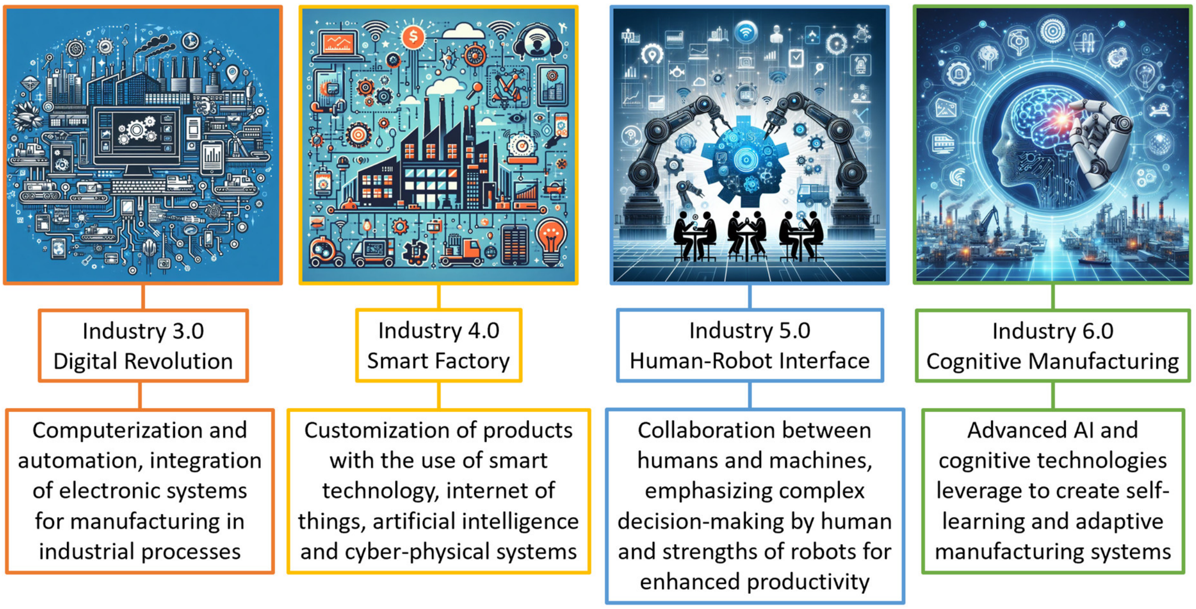

Figure 10. Evolution in industrialization: transition from Industry 4.0 to Industry 5.0.

Industry 5.0, human–robot interface—Industry 5.0 focuses on the collaboration between humans and machines, emphasizing the role of human workers alongside advanced robotic systems. This phase aims to combine the strengths of both humans and machines for enhanced productivity, creating a framework centered around the key enabling technologies driving Industry 5.0 [44]. Advanced robotics with a focus on human–robot collaboration, an emphasis on creativity, problem-solving, and complex decision-making by human workers are key features.

Industry 6.0, cognitive manufacturing—It represents the upcoming wave of industrialization characterized by cognitive manufacturing [45]. This phase utilizes advanced AI and cognitive technologies to create self-learning and adaptive manufacturing systems. Autonomous and self-optimizing systems powered by advanced AI algorithms and machines capable of learning from experience, making decisions, and adapting to dynamic production environments are expected in this revolution.

Based on this brief industrial phase description, currently, we are mostly in Industry 4.0 with an advancement in digital transformation and moving slowly to Industry 5.0 with the utilization of digital twins. Industry 5.0 is an emerging concept that builds upon Industry 4.0 but with a stronger focus on human–robot collaboration and autonomous vehicles.

The three aforementioned sections focused on companies globally renowned for manufacturing and mass-producing car components. These sections, respectively, focus on internal logistic utilization using mobile robots for doors and windows' component assembly factory (Section 2), the human-centered mechanism design for collaborative robots in the seat leather company (Section 3), and the virtual modeling of factories with the ability to conduct test simulations for a multi-technology-driven company (Section 4), with a focus on both theory and implementation. The investigation into automation within worldwide industries located in the northern Portugal region was grounded in local potentials. The graphical presentation of theories and definitions concerning this digitalization has been simplified for process explanation and is depicted in Figures 1–10 herein. In addition to this strength, the research has been limited by the inability to name or publish photos of the companies. Subsequent progress in related factories will be monitored as part of this ongoing work.

5. Conclusions

The survey into the implementation of digital transformation and digital twins in the field of the factory of the future has showcased a remarkable shift in manufacturing paradigms. The foundation of this transformative process extends from internal logistics to the integration of mobile intralogistics, applying the capabilities of IMR and AGV robots. This integration, coupled with the real-time analysis of physical objects and the virtual replication inherent in human–robotic interaction, has ushered in a new era of industrial innovation. The adoption of Industry 4.0 to 5.0 approaches has yielded tangible benefits, leading to a substantial increase in productivity, sustainability, and efficiency across production lines. The reduction in material waste, coupled with improved production control, attests to the positive impact of these advancements. Notably, the transition from traditional robotic systems to advanced technologies, such as detach-and-grasp and pick-and-place robots for a leather company and artificial vision for defect detection, underscores the commitment to enhancing precision and minimizing reliance on human operators. Moreover, the exploration of additive manufacturing, encompassing metal 3D printing and PLA/ABS polymer printing, has emerged as a pivotal subset for rapid prototyping within the manufacturing ecosystem. The versatility and speed offered by these technologies hold the promise of revolutionizing on-site prototyping processes. Finally, in the context of the future factory for the light vehicle industry, artificial intelligence plays a significant role in optimizing production processes by enabling predictive maintenance, efficient resource allocation, and development of autonomous vehicles.

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