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# Bridging the Gap to Industry 5.0: Comparative Analysis of Technologies in Industry 4.0 and 5.0 and the Evolutionary Path of the Smart Production Lab

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**Abstract:** Since 2011, the term 'Industry 4.0' (I4.0) has gained significance in industry. After a decade of digital transformation, the European Commission is now advancing towards Industry 5.0 (I5.0). The focus is on using technology to support people, enhance ecological sustainability, and make industry more resilient. This paper examines the transition from I4.0 to I5.0, with a particular focus on the learning factory Smart Production Lab as a model for future-oriented manufacturing companies. The study involves a systematic literature review to identify key technologies and concepts of I4.0 and analyse their evolution in the context of I5.0. A comparative analysis forms the basis for a matrix that facilitates a clear comparison and guides future developments of the Lab. This research identifies the technologies underpinning the goals of I5.0 and their implications for practical applications in manufacturing. It also provides actionable recommendations for companies.

**Keywords:** Digitalization; Industry 4.0; Industry 5.0; Transformation

## 1 INTRODUCTION

The fourth industrial revolution, designated as Industry 4.0 (I4.0), has brought about significant changes in the global manufacturing landscape. This revolution is characterised by the adoption of automation, digitalisation, and interconnectivity in the manufacturing sector. It leverages advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), cloud computing and cyber-physical systems (CPS). I4.0 aims to improve overall productivity and process efficiency to promote sustainable economic development [1]. The implementation of I4.0 technologies has the potential to result in significant improvements and cost reductions across a range of industrial sectors [2]. The integration of I4.0 technologies has led to the development of smart factories and interconnected manufacturing systems. These factories facilitate enhanced productivity, reduced costs, and improved product quality [3, 4]. Consequently, the integration of I4.0 technologies into manufacturing processes has the potential to transform industries and stimulate accelerated growth [5].

However, as the digital transformation journey progresses, a new perspective emerges with the advent of Industry 5.0 (I5.0). Pushed by the European Commission, I5.0 seeks to transcend beyond the technological advancements of its predecessor by integrating human creativity, ethical considerations, and environmental aims into the core of industrial operations. I5.0 places emphasis on sustainability, corporate resilience, and societal well-being. It posits a collaborative coexistence between humans and machines, with the objective of achieving a balanced synergy that fosters innovation while prioritising environmental responsibility and social inclusivity [6].

This paper examines the transition from I4.0 to I5.0, with a focus on the learning factory Smart Production Lab of UAS JOANNEUM in Kapfenberg as a model for forward-thinking manufacturing companies. The key technologies defining I4.0 are analysed and their role for I5.0 is assessed through a literature review and a comparative analysis. This study aims to compare two industrial developments and identify their similarities and differences, and thus answer the research question:

*Which I4.0 technologies support the transformation process towards I5.0?*

The outcome is transmitted to the Smart Production Lab as a practice use case. This represents the initial stage in determining the current state of the lab, thereby enabling the definition of subsequent steps towards the transition to I5.0.

## 2 DRIVING FORCES BEHIND THE EVOLUTION TO I5.0

The transition from I4.0 to I5.0 represents not merely an evolutionary step in production but a paradigm shift towards a more human-centric, sustainable, and resilient industrial future. This change is of great relevance to the industrial ecosystem, as it involves crucial challenges and opportunities [7].

Firstly, the necessity for ecological sustainability has never been more apparent. With climate change and environmental degradation posing significant threats to global stability and prosperity, I5.0's emphasis on sustainable production practices offers a potential solution to mitigate these impacts. By integrating green technologies and circular economy principles, I5.0 aims to reduce waste, lower carbon footprints and ensure that economic growth does not come at the environment's expense [8].

Secondly, the social implications of industrial automation and digitalisation under I4.0 have raised concerns about workforce displacement and the devaluation of human skills. I5.0 addresses these challenges by reorienting the human perspective and needs within the production process. It advocates for a collaborative model where human creativity and machines' efficiency are harmonised, ensuring that technological advancements augment rather than replace human labour. This approach not only warrants the continued employment of workers but also enhances their job satisfaction and safety, thereby fostering a more inclusive and equitable industrial workforce [9, 10].

Furthermore, the resilience of production systems has been challenged by recent global disruptions, such as the COVID-19 pandemic. The focus of I5.0 on adaptable and flexible manufacturing, supported by advanced digital technologies and human ingenuity, prepares companies to better withstand future shocks. It promotes a more agile response to changing market demands and unforeseen challenges, ensuring continuity and stability in volatile times [10]. Finally, the transition to I5.0 has the potential to significantly impact the economy. By optimising production efficiency, reducing resource consumption, and creating high-value jobs, I5.0 can drive sustainable economic growth. It enables companies to compete in a rapidly evolving global market, where innovation, sustainability, and social responsibility are increasingly becoming competitive differentiators [11].

In conclusion, it can be stated that the transition to I5.0 is particularly pertinent in the context of the current ecological, social, and economic challenges. It represents a forward-thinking vision that aligns industrial advancement with the broader goals of sustainable development, societal well-being, and economic resilience, marking a pivotal step towards a more sustainable and inclusive future.

## 3 BRIDGING THE GAP: HOW I4.0 SERVES AS THE STEPPING STONE TO I5.0

I4.0 established the technological and conceptual foundation upon which I5.0 was subsequently built and will be further evolved. The automation and digitalisation initiated by I4.0 heralded a new era in manufacturing, where CPS, IoT, and advanced data analytics play pivotal roles. These technologies have enabled production processes to become more efficient, flexible, and intelligent [12].

I5.0 represents a value-driven approach that extends the foundation established by I4.0. It integrates human intuition, ecological orientation and corporate adaptability into the production process, aiming for a balance between technological efficiency and corporate responsibility. While I4.0 created the conditions for comprehensive connectivity and automation, I5.0 focuses on re-integrating humans into the production chain, achieving personalized, flexible, and above all, sustainable production outcomes [13].

As previously noted, the primary objective of I4.0 was to enhance economic efficiency. In contrast, I5.0 places greater emphasis on ecological sustainability, as evidenced by the growing prominence of circular economy practices and resource-efficient manufacturing methods [14].

Moreover, data-driven decision-making, a pivotal aspect of I4.0, is further advanced in I5.0 through the utilisation of advanced AI and machine learning (ML). This refinement enables the implementation of personalised and optimised production processes, as well as product development and customer interaction. I5.0 aims to achieve efficient and user-friendly production solutions by integrating human expertise with intelligent and precise devices [15]. The advancement of advanced technologies, including edge computing, digital twins, interactive robots, IoT, blockchain, and 6G, can facilitate the achievement of the I5.0 objectives [16]. In addition, the integration of data-driven design processes in new product and service development can enable the creation of new or improved products and services, the establishment of long-term customer relationships, and the resolution of societal challenges [17].

In summary, I5.0 employs advanced technologies and data-driven approaches to optimise and personalise various aspects of production and customer interaction, thereby creating responsible, agile and sustainable corporations. Consequently, I4.0 serves as a crucial foundation for I5.0, not only providing the technological basis but also paving the way for an industrial revolution that harmonises technology and humanity, advancing the pursuit of a sustainable and inclusive future.

Tab. 1 provides a succinct illustration of the manner in which I5.0 builds upon the technological advancements of I4.0 while setting new priorities, particularly in support of the outlined I5.0 values.

**Table 1** Key aspects in comparison [18-21]

| Feature | Industry 4.0 | Industry 5.0 |
|---|---|---|
| Objective | Efficiency and automation | Human-machine collaboration, resilient corporations and sustainability |
| Focus | Digitalization and connectivity | Personalization, agility and ecological sustainability |
| Technologies | IoT, CPS, big data, cloud computing | (In addition to I4.0 technologies) advanced AI, human-robot collaboration, assisting technologies |
| Workforce | Replacement through automation | Augmentation and enhancement of human capabilities |
| Decision Making | Data-driven | Data and human-centric |
| Sustainability | Efficiency-focused | Resource efficiency and circular economy |

Such a comparison serves as a useful tool to clarify the evolutionary progression from I4.0 to I5.0, highlighting key changes in technology use and objectives of each phase.

The following chapter presents the methodological framework for the initial steps when changing from an I4.0 to an I5.0 perspective in companies. The example of the learning factory Smart Production Lab of UAS JOANNEUM is used to illustrate this framework.

## 4 METHODOLOGY: FRAMEWORK FOR TRANSITION ANALYSIS FROM I4.0 TO I5.0

The objective is to provide support to companies undergoing a change process to I5.0. This involves the evolution of the Smart Production Lab in Kapfenberg, Austria, from an I4.0 to an I5.0 facility, with the aim of establishing it as a good practice example. This research is part of the EU Horizon: bridges 5.0 project, which is funded by the European Union. In order to adopt a scientifically valid approach, a multi-layered procedure was developed. This commenced with the definition of the existing state of the Smart Production Lab, with a particular focus on the current technologies and their application scope. This was identified as a key aspect and starting point for the outlined transition. Based on this, recommendations for action were developed for the transformation from I4.0 to I5.0. These recommendations were based on the use of state-of-the-art methods for sustainably successful transformation processes.

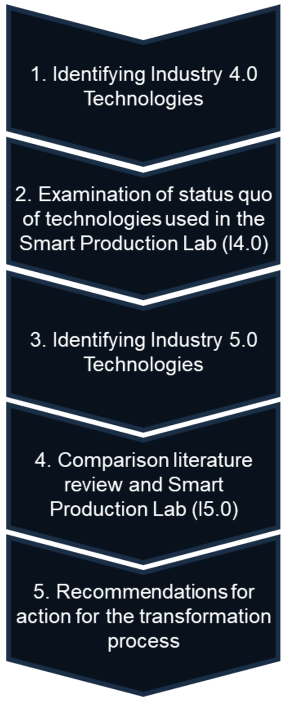


**Figure 1** Schematic procedure for the comparative analysis

Fig. 1 outlines the methodology adopted for this analysis. The first four steps are detailed in this chapter, while the fifth step, which offers recommendations for action, is discussed in a subsequent chapter. To establish a standardised and comprehensive foundation for understanding the technologies relevant to the respective industrial revolutions, a literature review was conducted.

Initially, the literature search targeted sources discussing I4.0 technologies, reflecting its introduction at the Hannover Messe in Germany in 2011 and its relevance to the digital transformation of the manufacturing industry [22].

The analysis concentrated on sources that explicitly addressed the transition and related technologies to I 4.0 and I5.0 separately. A comprehensive literature review employed two types of resources: the scientifically robust perspective from journals and conference proceedings, as well as reports from manufacturers and providers of I4.0 technologies, integrating both academic and practical viewpoints. It was executed in accordance with the methodologies of Ramdhani et al., 2014, and Okoli et al., 2014 [23, 24]. A comprehensive literature search was conducted in scientific databases, including Science Direct, Scopus, and Google Scholar, between October 2023 and January 2024. The search terms related to I4.0, I5.0, and their technologies were combined into search strings incorporating both industrial revolutions and their technologies. This foundational knowledge will serve as a basis for the comparative analysis, allowing for the assessment of the status of the Smart Production Lab and the formulation of action recommendations to align the Smart Production Lab with I5.0 standards.

## 4.1 Technologies in I4.0: A Systematic Identification

Following a comprehensive review of the identified sources using the outlined methodological approach, a comprehensive list was created which included the source, authors, a brief description and the I4.0 technologies identified by the authors for each entry. These technologies were then individually listed in an MS Excel spreadsheet. This step facilitated the highlighting of multiple mentions and ensured a clear assignment of technologies. An attempt was already made in this step to cluster the results according to their hierarchy and to classify meta- and sub-technologies. One example of this would be the classification of virtual reality (VR) as a subgroup of extended reality (XR). This illustrates the technological development paths within I4.0.

This methodological approach revealed that different authors have used varied nomenclatures for the same technology or technology group. All relevant technologies from [25-34] for I4.0 were summarized in Fig. 2.

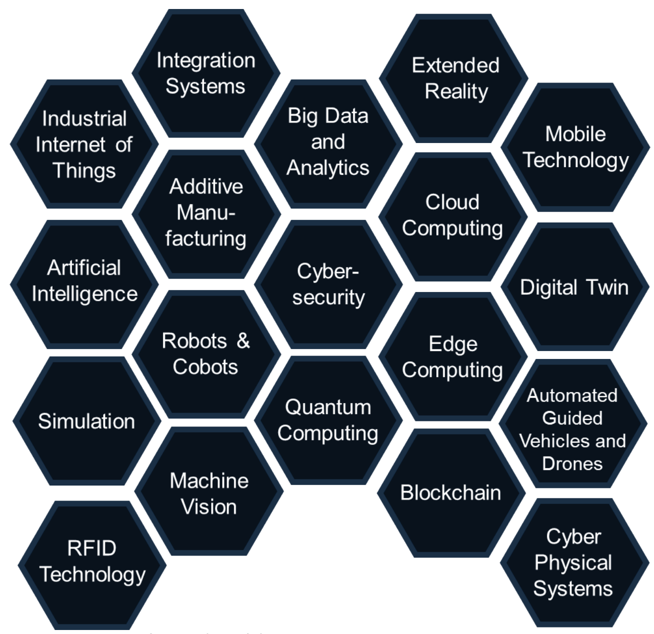


Figure 2 Identified I4.0 technologies based on literature review

Fig. 2 illustrates a honeycomb-shaped arrangement of blocks, each representing a key technology of I4.0. The name of a technology contributing to the fourth industrial revolution is given within each honeycomb cell. This visualization emphasises the diversity and complexity of technologies that synergise in the modern industrial landscape.

## 4.2 Assessing the Current State of the Smart Production Lab in the Context of I4.0

In the comparative analysis section, the current state of the Smart Production Lab is closely examined, covering its machinery, processes, educational materials, and technologies. This analysis was conducted on the basis of a comprehensive examination of the Smart Production Lab.

The potential avenues for improvement were evaluated through an examination of the existing infrastructure, process analysis, and workplace analysis. Inventory lists, process and workplace descriptions as well as qualitative interviews with responsible persons served as the data basis. The interviews were instrumental in understanding the nuanced applications of I4.0 technologies within the lab and assessing their alignment with the principles and objectives of I5.0. This methodical approach allowed for a detailed evaluation of the lab's I4.0 readiness and areas for enhancement in line with I5.0 advancements. The results are shown in Fig. 3.

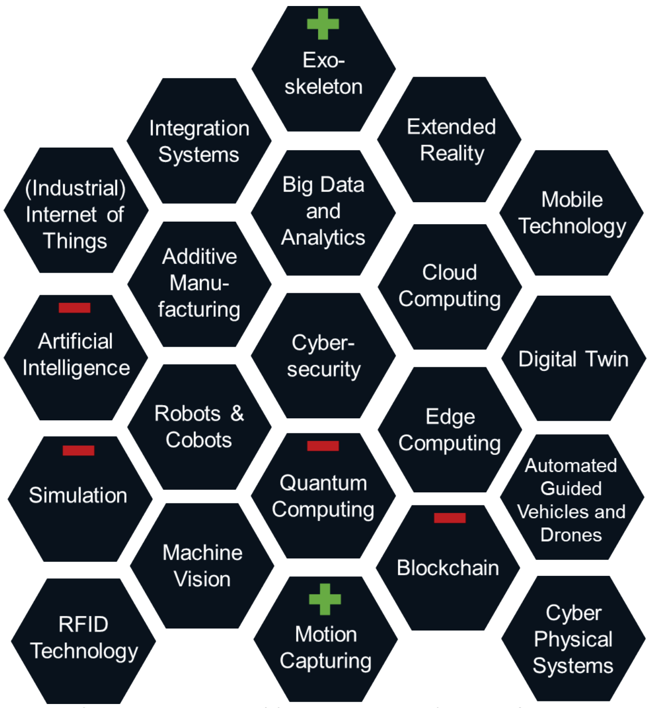


**Figure 3** Comparative analysis: I4.0 technologies identified in the Smart Production Lab

Fig. 3 represents an evolved visualization from Fig. 2, indicating the technologies currently implemented in the Smart Production Lab. The graphic has been altered so that those honeycombs where the technology was not identified in the lab have been marked with a minus sign. Those technologies that were identified in addition to the previous research have been assigned with a plus. The technology analysis indicates that the lab incorporates two additional technologies not previously identified in the I4.0 literature research: exoskeletons and motion capturing. In total, four I4.0 technologies were either not integrated into the Lab or were in development at the time of the survey and therefore not yet in the application stage.

Considering the comprehensive evaluation and visualisation of the Smart Production Lab's status with respect to I4.0 technologies, the subsequent phase requires the identification of pivotal technologies for I5.0. This step is crucial for the alignment of the lab's technological framework with the principles of I5.0, emphasising human-centricity, resilience and ecological sustainability through advanced digital and physical integration.

### 4.3 Framework for Identifying Emerging Technologies in I5.0

The following presentation summarizes relevant scientific contributions on the transformation processes between I4.0 and I5.0, with a focus on the relevant technological paradigms. The tabular presentation of these contributions is structured as follows: column 1 shows the number of sources correlating with the information contained in the respective row. Column 2 provides a concise outline of the article's content, while column 3 defines the technologies, methodologies, domains, and objectives referenced in the context of I5.0 within the articles.

**Table 2** Literature review for I5.0 transformation technologies

| Source | Description | Technologies |
|---|---|---|
| [35] | Comparison between I4.0 and I5.0. Differences and challenges addressed by I5.0 | Smart additive manufacturing, predictive maintenance, hyper customization, cyber-physical cognitive systems, collaborative robots (cobots) |
| [36] | Evolutionary vein and characteristics of I5.0. Key enablers | Ergonomics, mutual-cognitive human-robot collaboration, recommender system technology, bionics, advanced simulation, CPS, digital twin, metaverse, IoT-enabled systems, XR, IoT, holography, blockchain, decentralized computing, big data, cognitive computing, green computing, AI-based management systems, waste prevention, smart materials, disaster mitigation, renewable energy sources, sustainable agricultural production, zero-defect manufacturing, fin-tech |
| [37] | Contrasting I4.0 and I5.0: Shifting Research Priorities from Sustainability to Human-Centric Design | IIoT, ML / AI, HMI, big data, ethical technology, smart manufacturing / smart factory, CPS / digital twin |
| [38] | Transition from I4.0 to I5.0. Manufacturing | Advanced materials, intelligent manufacturing and processing, nanotechnology, sustainable manufacturing |
| [39] | Strategic roadmap how I5.0 can boost sustainable manufacturing | Cognitive cyber-physical systems, cognitive AI, human interaction and recognition technologies, XR, industrial smart wearables, intelligent (adaptive) robots, intelligent energy management system |
| [40] | Concept of I5.0 and enabling technologies | Individualized HMI, bio-inspired technologies and smart materials, digital twins and simulation, data transmission, storage, and analysis technologies, AI, technologies for energy efficiency, renewables, storage and autonomy |
| [41] | Potential applications and supporting technologies of I5.0 | Edge computing, AI, cobots, 6G and beyond, digital twins, blockchain, Internet of everything |
| [42] | Conceptualization of I5.0 from the perspective of viability | IoT, 5G, edge computing, trace and tracking systems, blockchain, early-warning system, big data analytics |

This structured approach facilitates a comprehensive understanding of the key technologies and strategic directions underpinning the evolution from I4.0 to I5.0. Following the methodology employed for I4.0 technologies, a similar categorisation and clustering were executed for the technologies related to I5.0. Notably, in contrast to the evaluation of I4.0 technologies, the authors' focus shifted from the technologies themselves to their proactive application towards optimisation and their contributions to ecological sustainability, resilience, or human-centricity. This aligns with the three pillars of I5.0.

For example, there was a notable increase in the mention of technologies designed to enhance ecological sustainability in industrial practice, including waste reduction, energy efficiency, renewable energy sources, storage solutions, and autonomy. Additionally, there was a pronounced presence of Human-Machine Interaction (HMI), which suggests a clear parallel.

To ensure comparability with I4.0 technologies, a systematic sorting of statements from each cited source was conducted. This was facilitated by creating a MS Excel spreadsheet, wherein each entry related to I5.0, such as "Predictive Maintenance" or "Ergonomics", was allocated a row. The association to sources and authors was managed via a column. This resulted in a comprehensive datasheet, with authors listed in the range B1:I1, titles of papers in B1:I11, and a brief description of the papers in B3:B11. Technologies, methodologies and solutions were categorised from cells 4 to 47. Subsequent sorting involved grouping explicitly assignable statements (e.g. all mentions of digital twin) into single rows. The subsequent phase, clustering, entailed a detailed examination of the content. The objective of clustering was to distinguish between actual technologies (such as XR, Big Data or AI) and pursued practices, goals and approaches (for instance, sustainable production, disaster mitigation or ergonomics). The outcome of this segmentation is the following Fig. 4, which combines the visualisation for I4.0 technologies with insights from the secondary literature research on I5.0 technologies.

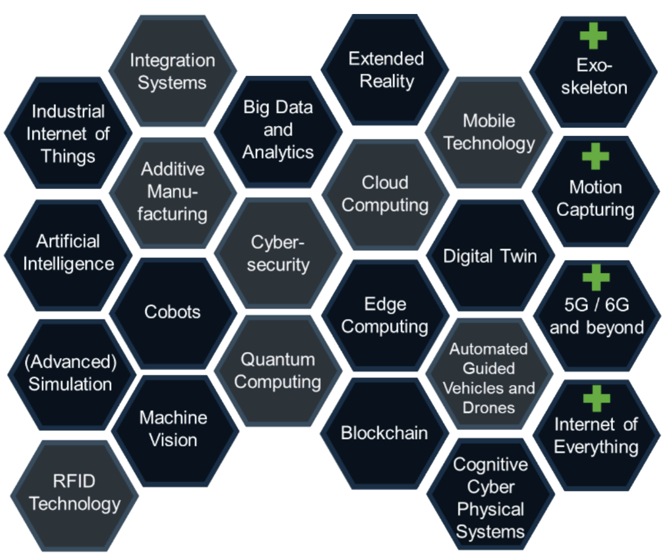


**Figure 4** Identified I5.0 technologies (enhanced with technologies within the lab)

Two technologies in particular – the Internet of everything and 5G/6G and beyond – are newly listed (marked with a plus in Fig. 4). The technologies that were not explicitly reiterated for I5.0 in the initial literature search on I4.0 technologies are shaded light grey in Figure 4. This indicates that certain technologies were either important for I4.0 but have no direct relevance for I5.0 or are already seen as a new technological standard and are therefore no longer explicitly mentioned. This may be attributed to the authors' assumption of a certain degree of technology integration or a shift in focus introduced by I5.0. As demonstrated in Table 1, the motivation to use technology transitions from efficiency and automation (I4.0) to human-machine collaboration and sustainability. Furthermore, ergonomics is identified as a pertinent aspect for I5.0, although it is not associated with a specific technology. Therefore, exoskeletons and motion capturing, which are already present in the Smart Production Lab, are highlighted to represent this aspect, acknowledging the significant role ergonomics plays in the human-centred orientation of I5.0.

## 5 FINDINGS: TECHNOLOGICAL READINESS AND TRANSITION TOWARDS INDUSTRY 5.0

Fig. 4 and the conducted comparative analysis indicate that the Smart Production Lab is technologically well-prepared as a teaching and research facility to demonstrate digitalisation. The literature review for I5.0 has also indicated that a substantial portion of I4.0 technologies can serve as a basis, with technological advancements and innovations enabling new applications and industrial use cases.

The investigation reveals that while the Smart Production Lab is equipped with I4.0 technologies, including advanced manufacturing systems and analytics-driven decision-making tools, there is an emergent transition towards embracing the principles of I5.0. This transition is characterised by an intensified focus on human-centric designs and assisting technology, which are intended to complement human workers, not displace them, and a heightened commitment to sustainable production methodologies.

Furthermore, the analysis revealed potential opportunities for the integration of bespoke production techniques and the implementation of the principles of a circular economy, outlining pathways for the laboratory's evolution towards the I5.0 archetype. By leveraging these insights, the Smart Production Lab can continue to serve as a model for forward-thinking manufacturing companies, demonstrating effective strategies for navigating between the current industrial technological landscape and the visionary objectives of I5.0.

In order to align the Smart Production Lab with the forward-thinking paradigm of I5.0, a strategic approach is imperative, one that integrates technological innovation, education, and sustainability. Forging robust partnerships with industrial entities is critical to access cutting-edge technologies such as collaborative robots and IoT solutions, thereby bolstering research and development in main areas like digital twins and advanced simulation methods. A fundamental aspect of this transition is the comprehensive training of employees and students in new technologies and methods such as additive manufacturing and XR. Concurrently, the lab must intensify its sustainability initiatives, integrating principles of the circular economy and utilising recycled materials in additive manufacturing processes to promote energy-efficient production modalities.

These initiatives are not merely navigational tools through the technological transition towards I5.0; they are also instrumental in affirming the lab's role as a beacon for training next-generation professionals and promoting sustainable manufacturing practices.

The Smart Production Lab is situated within the context of I5.0, integrating a range of technologies that are essential to the realisation of the goals and principles of I5.0. An analysis of the technologies envisioned for I5.0 and those already deployed in the lab provides a detailed understanding of the lab's direction, the key technologies driving the transformation process, and the upgrades required. This comprehensive analysis is important to chart the path for future improvements and align with the goals of I5.0. In light of the aforementioned considerations, the research question can be answered as follows:

**Positioning in relation to I5.0**: The lab incorporates key technologies considered essential for I5.0, such as:

- Integration systems and Industrial Internet of Things (IIoT): These technologies are foundational for the interconnectivity of machines, facilities, and products, facilitating efficient, data-driven production.
- RFID technology: Critical for resource and product tracking, it enhances supply chain transparency and efficiency.
- Additive manufacturing: Enables hyper-customisation and efficient, on-demand production, aligning with the goals of I5.0 regarding flexibility and customer centricity.
- Cobots and exoskeletons: Support human-robot collaboration, to foster ergonomic work conditions and efficient production processes.
- Big Data and analytics: Indispensable for predictive maintenance and decision-making, these technologies allow for smart and forward-looking production management.
- CPS and digital twins: Key technologies for the simulation, monitoring, and optimisation of production processes in real-time.

**Key Technologies for the transformation process from I4.0 to I5.0**: The following technologies are instrumental in the transformational process toward achieving the goals of I5.0:

- Cobots and exoskeletons: Provide direct support for human-robot collaboration and ergonomic workplaces.
- Digital twins and CPS: Enable enhanced planning, simulation, and control of production processes.
- IIoT and edge computing: Critical for real-time data collection and processing, they support an agile and flexible production environment.

**Necessary** areas of improvement: To achieve full compatibility with I5.0 and to maximize its potential, the following upgrades are detected as necessary:

- XR and industrial smart wearables: Integration of these technologies could be intensified to improve work instructions and assist employees in complex tasks.
- Cognitive AI and human-interaction technologies: Advancing towards more intuitive, adaptive, and cognitive interactions between humans and machines may require increased investments in AI and ergonomic interaction technologies.
- Green technologies and sustainable production methods: While the laboratory already employs advanced technologies, there is a need to intensify the focus on sustainability and energy efficiency through the utilisation of renewable energy sources and the implementation of smart energy management systems.
- Simulation and AI for decision support: In order to ensure entrepreneurial resilience, organisations and their employees must enhance their problem-solving abilities and adaptability, as well as develop and anchor a holistic system understanding at all levels. Intelligent, AI-supported systems can support this.

The current inclusion of the aforementioned technologies positions the Smart Production Lab at the avant-garde of the I5.0 revolution, demonstrating a commitment to innovation, efficiency, and human-centric automation. In conclusion, the Smart Production Lab is well-positioned to adopt and integrate the key technologies essential for the realisation of I5.0's vision. The analysis of technologies mentioned for I5.0 and those used in the lab allows for a differentiated perspective on the lab's orientation, the key technologies for the transformation process, and the need for technological upgrading. This underlines the suitability of the lab for training and supporting companies on their way to I5.0.

## 6 CONCLUSION

The Smart Production Lab is well-positioned to facilitate the transition to I5.0, leveraging key technologies such as IIoT, cobots, digital twins, and big data analytics. However, there are areas, notably in XR, cognitive AI, and sustainability, where additional investments and developments could expedite the shift to a fully human-centred and sustainable production, in line with the values of I5.0. A key insight from this research is the shift in focus from the technologies themselves to their role as a means to an end, used strategically and efficiently to achieve set goals and initiatives. Following the initial step of identifying the status quo and envisioned future, further steps towards the transformation process are outlined for the Smart Production Lab and the Institute of Industrial Management at UAS JOANNEUM. These steps will be primarily implemented as part of the EU Horizon Project, Bridges 5.0, which will run until 2026. In order to provide a forecast of the forthcoming developments and associated research activities, the planned next steps are as follows:

1) A detailed mapping of current technologies to the three pillars of I5.0.
2) A roadmap for the education and development of competencies with respect to the three pillars of I5.0. It is of the utmost importance to more deeply integrate the values and attitudes associated with them into the transformation process and research activities.
3) Technological upgrades and integration into the Smart Production Lab as well as the definition of goals and aspects of the technologies and their contributions.

4) Demonstrating the advantages of technology integration with I5.0 considerations for companies, by making research findings accessible to interested business representatives through tours, lectures, and workshops at the Smart Production Lab.

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