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Innovative competencies for industry 4.0 in Portugal: Trends, gaps, and research agenda

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Abstract

This paper aims to investigate the technical and interpersonal skills required for the labor market in Industry 4.0 in Portugal, proposing a future research agenda. The study adopts a systematic literature review methodology, drawing on documents from the Scopus database and covering papers on the Fourth Industrial Revolution and professional skills in Portugal. After applying filtering criteria, 18 papers were analyzed. The findings highlight the importance of technical skills such as automation, data analysis, and artificial intelligence, as well as the growing relevance of interpersonal skills such as communication and collaboration in multidisciplinary teams. This study is relevant because it proposes a research agenda that addresses gaps in the impact of Industry 4.0 on professional skills, focusing on developing interdisciplinary skills, assessing the effects of automation, fostering sustainable innovation, and adapting curricula. For society, it contributes by emphasizing the need to prepare workers for digital transformation, thus promoting competitiveness and innovation in the labor market. To address the challenges of Industry 4.0, educational institutions, companies, and governments must collaborate in training a qualified workforce by integrating technical and interpersonal skills.

Keywords: Human Resources, Industry 4.0, Skills, Work, Worker.

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1. Introduction

The Fourth Industrial Revolution, driven by advances in the Internet and sophisticated sensors, redefines the production environment by integrating digital tools into intelligent and autonomous processes. This context aims to enhance responsiveness and enable mass customization, as Liao, et al. [1] and Moniz, et al. [2] noted. According to Dalenogare, et al. [3] the main enabling technologies of Industry 4.0 include the Internet of Things (IoT), Big Data analytics, cloud computing, additive manufacturing, autonomous robotics, cyber-physical systems, augmented reality, and digital twins, which together form the foundation for digital transformation in production systems. Recent studies, such as Prokopenko, et al. [4] underscore the strategic convergence between IoT, cyber-physical systems, and mechatronics as essential for digitalization. In recent years, advanced artificial intelligence and machine-learning methods have emerged as pivotal innovations in the Industry 4.0 landscape [5, 6].

The impact of these technologies transcends production processes, affecting workers' quality of life, including anxiety and depression [7]. According to Kuo, et al. [8]. Industry 4.0 represents a new phase in the industrial sector, characterized by automation, digital technologies, and interconnected systems that enhance competitiveness and operational efficiency. This revolution reshapes business operations and redefines the skills workers need to excel in a constantly evolving environment [9]. As noted by Leng, et al. [10] the integration of artificial intelligence, IoT, and Big Data requires professionals to develop competencies that go beyond traditional technical abilities, incorporating data-driven decision-making, system integration, and continuous learning. Guzmán Sánchez-Mejorada, et al. [11] highlight that training in computer science and related fields is critical for solving complex problems and integrating data into production. Flexibility and adaptability, identified by Guerlinguer, et al. [12] have become essential. In this sense, Belina, et al. [13] the future workforce must integrate technical expertise with socio-emotional competencies to respond to the accelerated transformations of Industry 4.0.

Digital transformation enables companies to create value and competitive advantages. Industry 4.0 allows innovative solutions in factories interacting with advanced technologies, creating highly connected environments and rapid responses to customization demands Santos, et al. [14]. Santa Rita, et al. [15] emphasize that strategic indicators, such as patents, drive innovation and competitiveness. With more automated processes, the physical workload is reduced, enabling employees to focus on strategic and intellectual tasks, playing a decisive role in operations management [16, 17]. However, this raises questions about the sustainability of future work, a theme explored by Picinin, et al. [18]. Girardi, et al. [19] highlighting that competencies related to quality of life and worker well-being are decisive to ensure long-term sustainability in industrial environments.

Specialized literature emphasizes that hard skills – specific knowledge and technical abilities – are fundamental for operational tasks [20]. However, soft skills, involving communication, leadership, and adaptability, are equally important Ulrich and Dulebohn [21]. Hamada [22] and Picinin, et al. [23] had already pointed out that balancing technical and behavioral skills fosters innovative and resilient production environments.Specialized literature emphasizes that hard skills – specific knowledge and technical abilities – are fundamental for operational tasks [20]. However, soft skills, involving communication, leadership, and adaptability, are equally important Ulrich and Dulebohn [21]. Hamada [22] and Picinin, et al. [23] had already pointed out that balancing technical and behavioral skills fosters innovative and resilient production environments. Combining these skills is vital for professionals to perform duties, adjust to changes, and collaborate effectively in multidisciplinary teams [24]. Companies increasingly recognize this balance, as observed by Silva, et al. [25] who highlight the importance of soft skills in Industry 4.0. Turcato, et al. [26] also stress that developing digital and socio-emotional competencies is essential for preparing workers for the challenges of technological convergence.

Beyond operational advantages, Industry 4.0 reduces natural resource consumption through automation [27]. Organizations adopting this philosophy enhance competitiveness and influence supply and customer chains [3, 28]. These companies foster innovative and creative environments that improve industrial performance [29]. While hard skills are essential, soft skills play a decisive role in innovation and problem-solving [21]. Companies increasingly value teamwork, communication, and leadership in changing contexts [30]. A review on technological challenges in Industry 4.0 by Kovaleski, et al. [31] underscores the need for a holistic approach to skills, encompassing technical and human aspects. Amarante, et al. [32] reinforce this by demonstrating that competencies linked to innovation and human well-being are central for sustainable adaptation to Industry 4.0.

The concept of Industry 4.0, introduced in Germany's High-Tech Strategy in 2011, aimed to increase competitiveness by integrating production with information and communication technologies [33]. Despite the absence of a single definition, the term synthesizes a paradigm of automation and digitization from design to manufacturing, operation, and maintenance [34]. Cyber-physical systems, IoT, and Internet of Services (IoS) facilitate connection and cooperation between people, machines, and logistics systems, enhancing responsiveness and coordination in supply chains [35, 36]. Previous studies by Hamada [22] and Picinin, et al. [23] had already anticipated integrating technical and behavioral capabilities to build resilient environments. In this line, Klafke, et al. [37] argue that technological intensity requires professionals to continuously update their skills and integrate innovation-oriented capabilities.

This technological convergence requires an integrated approach to human resource management. The interdependence between technologies and processes makes it essential to develop policies combining technical training, knowledge management, and socio-emotional skills [26]. Moreover, the convergence of IoT, cyber-physical systems, and mechatronics Prokopenko, et al. [4] intensifies the need for professional profiles capable of operating heterogeneous ecosystems while understanding organizational and safety implications.

Rapid transformations digitize and automate production, optimizing value chains and reconfiguring market relationships [38]. These changes alter interactions between suppliers, producers, customers, and humans and machines.

Professionals with advanced digital skills thus become central [39, 40]. Studies such as Guzmán Sánchez-Mejorada, et al. [11] reveal gaps between curricula and market needs, highlighting priority areas for updates.

In this sense, it is imperative to understand how education and training will be impacted by Industry 4.0. Technological innovations demand lifelong learning and models integrating practice, theory, and interdisciplinarity [41, 42]. Programs combining technical, digital, and socio-emotional skills, alongside partnerships between academia and industry, are promising to bridge gaps. Bayraktar and Ataç [43] stress reconceptualizing the human role as managers and orchestrators of technologies, decisive for competitiveness and innovation. Picinin, et al. [18] add that resilience and adaptability are crucial elements for ensuring that workers remain relevant in digitalized environments.

Therefore, this paper investigates the technical and interpersonal skills required for the labor market to Industry 4.0 in Portugal, proposing a future research agenda to prepare workers for the challenges of this digital era.

2. Industry 4.0 and Workers' Skills

Industry 4.0 is profoundly transforming the labor landscape in Portugal, requiring workers to develop diverse skills to adapt to an increasingly digitalized and automated environment [9]. This scenario redefines roles and demands capabilities that sustain competitiveness in the global market [44]. According to Prokopenko, et al. [4] integrating technologies such as IoT, cyber-physical systems, and mechatronics increases operational complexity, requiring professionals capable of managing interconnected industrial ecosystems.

Schwab [9] memphasizes that Industry 4.0 is not limited to technological transformations; it also involves reshaping the skills required of workers. The automation and digitization of production processes demand advanced technical skills, such as operating and managing information systems and conducting data analysis [45]. In Portugal, these changes are driven by initiatives aimed at modernizing the economy and aligning professional training with the new demands of the productive sector. Turcato, et al. [26] note that this requires not only technical training but also the integration of socio-emotional competencies such as creativity, adaptability, and teamwork.

Technical skills, effective communication, and collaboration in multidisciplinary teams are gaining strategic importance [44]. Production systems' horizontal and vertical integration requires professionals who can articulate information and build solutions collaboratively. Santa Rita, et al. [15] emphasize that using strategic metrics, such as patent counts, combined with collaborative skills, strengthens organizations' capacity for innovation. Amarante, et al. [32] reinforce that innovation competencies are strongly tied to human-centered approaches that ensure sustainable adaptation to technological changes.

Continuous training is essential for workers to keep pace with technological innovations [45]. Companies must invest in programs that update employees' skills by incorporating new tools and work methodologies [46]. Several institutions in Portugal offer training programs focused on digital competencies and technology management, increasing employability and innovation capacity. Belina, et al. [13] stress that continuous learning is a cornerstone for preparing professionals to face the constant reconfiguration of work environments in Industry 4.0.

Autonomy in the workplace requires professionals to make informed decisions based on real-time data, which demands a high sense of responsibility and initiative [45]. Furthermore, this scenario requires flexibility to respond quickly to changes and unforeseen operational events, a skill Guerlinguer, et al. [12] highlighted as critical for organizational performance in the digital era. Hamada [22] point out that this flexibility is only achieved when technical knowledge is complemented by interpersonal and collaborative skills.

This need for adaptability is directly linked to the value placed on well-being and job satisfaction. Companies that combine technological advancements with humanized work environments strengthen their teams' motivation and creativity [44]. As noted by Hamada [22] and Picinin, et al. [23] integrating technical and human skills fosters innovative and resilient production environments that are better prepared to face scenarios of accelerated transformation. Girardi, et al. [19] add that competencies related to quality of life and work balance are equally critical for sustaining innovation capacity.

In this context, models such as those proposed by Jerman, et al. [47] and Blayone and VanOostveen [48] offer a framework for classifying skills into technical, digital, methodological, social, personal, and managerial domains. This approach enables the mapping and development of skills that meet the demands of Industry 4.0, strengthening Portugal's competitiveness in the global arena.

Jerman, et al. [47] classify the skills required for Industry 4.0 based on the model shown in Figure 1. This model identifies six main domains encompassing the essential skills for modern workers in an advanced production context, promoting the efficient integration of new technologies and processes into operations.

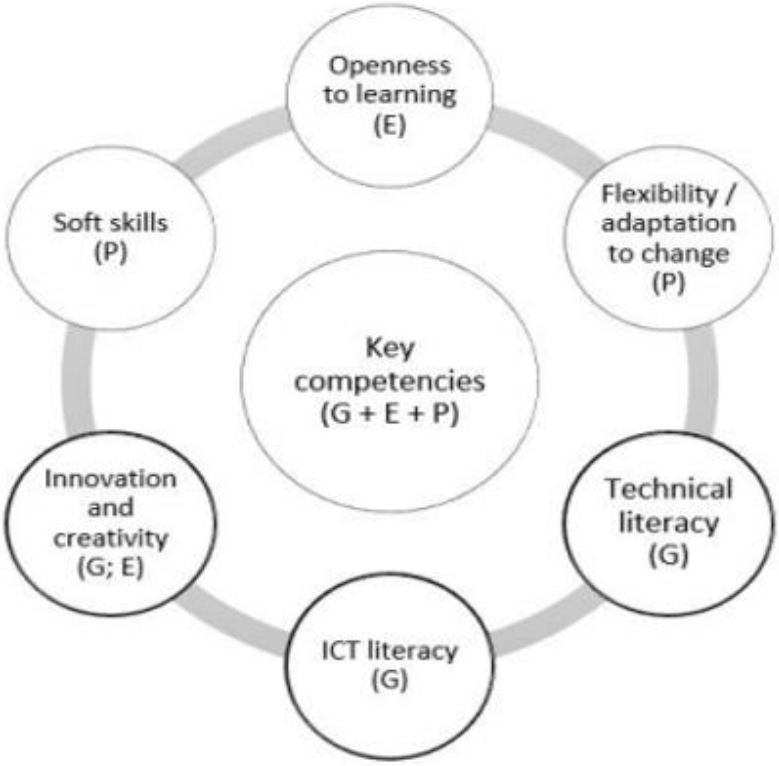

Figure 1.
Conceptual Model of Key Competencies.
Source: Jerman, et al. [47].

The six competency domains proposed by Jerman, et al. [47] form a structure to prepare workers for Industry 4.0. These domains include technical, digital, methodological, social, personal, and managerial skills. These abilities enable workers to handle advanced technologies, work in teams, solve complex problems, and lead innovations in a digitalized production environment. Klafke, et al. [37] emphasize that these domains reflect the dynamic nature of industrial growth, demanding constant adaptability and innovation-driven skills.

The model proposed by Blayone and VanOostveen [48] presented in Figure 2, addresses five essential dimensions that help professionals adapt to this new work environment. These dimensions emphasize the importance of integrating technologies with human skills.

#	Readiness Factor	Readiness Subfactors (KSAs)	Contextual Considerations
1	Technological	(1) Foundational digital skills (2) Advanced IT skills (3) Attitudinal orientations and intrapersonal skills supporting enthusiastic IT use skill development	Level of Industry 4.0 technological maturity Presence of adaptive augmentation systems towards Operator 4.0
2	Flexibility	(1) Multidisciplinary knowledge (2) Openness to dynamically assigned roles and tasks (3) Tolerance of environmental dynamism and emergent problems	Stubbornness of traditional (hierarchical) organisational cultures Broader socioeconomic pressures on manufacturing operations Level of Industry 4.0 technological maturity
3	Inter-agent	(1) Attitudes of openness and comfort toward human-machine partnering (2) A well-calibrated level of trust toward technological agents and automation systems (3) Knowledge and skills for modelling, communicating and calibrating trust with machine agents/robots	Availability and sophistication of collaborative robots, adaptive augmentation systems, wearable tech, expert systems and machine agents Organisational decision-making protocols
4	Interpersonal	(1) Social-networking competencies (2) Communication and negotiation skills (3) Attitudes and skills supporting digital-mediated collaboration problem-solving in dispersed, cross-cultural teams	Distribution of responsibilities among agents in cyber-physical systems Location and diversity of teams Levels of interaction, ranging from coexistence to collaboration, required to achieve objectives
5	Innovation	(1) Creative and adaptive strategic-thinking skills (2) Data-analysis knowledge and software application skills	Creative capabilities of humans and other agents Organisational culture/rules related to conservatism and innovation Level of Industry 4.0 technological maturity

Figure 2.
Proposed Model of Five Dimensions of Worker Readiness for Industry 4.0.
Source: Blayone and VanOostveen [48].

This approach is fundamental to ensuring that workers become familiar with new tools and develop abilities that enhance their effectiveness and innovation in a constantly changing industrial setting [48] In this study, a hybrid approach combining the models of Jerman, et al. [47] and Blayone and VanOostveen [48] was used to classify domains as follows:

- Technical Domain: Encompasses the abilities and skills to perform specific tasks, such as solving complex problems.
- Flexibility Domain: Adapting industrial operations and processes quickly and efficiently to changes and flexible demands.
- Agent Interaction Domain: Assesses interactions and collaborations among autonomous agents to perform tasks and achieve common goals.
- Behavioral and Subjective Skills Domain (Soft Skills): Focuses on socio-emotional and behavioral skills valued and required for professional success in a highly technological and automated environment.
- Innovation Domain: Encompasses the capacity to adopt and develop advanced technological solutions, fostering a culture of innovation in processes, products, and services.
- Information Technology Domain: Assesses professionals' ability to effectively use information and communication technologies to improve productivity, efficiency, and innovation in industrial processes.

The models by Jerman, et al. [47] and Blayone and VanOostveen [48] provide a solid foundation for identifying and developing critical skills for Industry 4.0. These frameworks make it possible to map the required abilities and establish a roadmap for worker training and upskilling, preparing them to face the challenges and seize the opportunities of this new industrial era. In Portugal, aligning with these models is essential for ensuring the country's competitiveness in the global Industry 4.0 landscape.

3. Methodology

The methodology of this study was designed to ensure scientific rigor in analyzing the professional skills required by Industry 4.0 in Portugal. The research was based on a systematic literature review, using the Scopus database as a source, which is recognized for its comprehensiveness and academic quality. Data collection took place on August 7, 2025, involving original and review papers that addressed the topic of skills in Industry 4.0 in an innovative or in-depth manner. After selecting the papers, a detailed bibliometric analysis was conducted to identify research trends and patterns.

3.1. Definition of Search Parameters

The search parameters were established to ensure a precise and relevant selection of documents. The Scopus database was chosen due to its reputation and inclusion of peer-reviewed journals, ensuring the quality and relevance of the analyzed papers.

The search was limited to documents published up to 2025, prioritizing papers that offered new perspectives on professional skills in Industry 4.0 in Portugal. Additionally, conference papers were excluded, focusing exclusively on articles published in academic journals.

3.2. Definition of Keywords

The search strategy was built using combinations of keywords that reflected the breadth of the research topic. The following terms were used:

"Fourth Industrial Revolution" OR "Industry 4.0" AND "Skill" OR "Competenc*" AND "Portugal"*

These keywords were selected to capture relevant publications addressing the relationship between professional skills and Industry 4.0 requirements in the Portuguese context. The initial search result identified 19 papers, which underwent a rigorous screening process described below.

3.3. Refinement and Filtering

After the initial identification of papers, a refinement and filtering process was applied to ensure the quality of the selected documents. The analysis began by evaluating the titles to exclude irrelevant publications. When necessary, abstracts were reviewed to confirm adherence to the topic. One conference paper was excluded, resulting in a final set of 18 articles.

This study sought to analyze the skills required in the context of Industry 4.0 in Portugal based on a comprehensive review of the existing literature. The search strategies employed are detailed in Table 1.

Table 1.
Search documents.

Keywords	Number of papers
"Fourth Industrial Revolution" OR "industry 4.0" AND "Skill*" OR "Competenc*" AND "Portugal"	19

The selected documents were categorized into thematic areas to provide a comprehensive and structured view of the skills needed in the Industry 4.0 context. These steps ensured a solid methodological approach, delivering consistent data for subsequent analyses and contributing to understanding emerging demands in the Portuguese industrial landscape.

The study analyzed 19 documents exported from the Scopus database to perform a bibliometric analysis. For this purpose, RStudio, a free, open-source development environment that allows for R script execution and data visualization, was used. The Biblioshiny graphical interface, which facilitates using the Bibliometrix package, was also employed to manage references and conduct detailed analyses.

The Bibliometrix package was configured to import data and generate graphs. The R version used was 2024.09.0+375, released on August 7, 2025. After preparation, the data were analyzed and visualized using various tools, resulting in charts and maps illustrating research on Industry 4.0.

The main results of the analysis include:

- Annual publication trends: The number of papers published since 2017 shows growing interest in the field.
- Geographic collaborations: Highlights partnerships between countries, with darker areas indicating stronger collaborations.
- Types of publications: Most analyzed documents are scientific papers and conference proceedings.
- Keyword analysis: Word clouds and keyword clusters reveal the most relevant themes in Industry 4.0 research.
- Thematic growth over time: Tracks the evolution of different topics based on frequently used keywords.
- Treemap analysis: Visualizes the frequency of words in publication abstracts.
- Thematic categorization: A two-dimensional map categorizes keywords into core, niche, emerging, or basic themes.
- Historical evolution: Shows trends and key topics over time.
- Qualitative domain analysis: Six main domains were identified, along with their respective skills, plus an additional category labeled “others.”

The next section of the paper presents detailed results from the Scopus data analysis, offering a comprehensive overview of Industry 4.0 publications in Portugal, including trends, collaborations, and the skills needed in the current context.

4. Findings

The research results on Industry 4.0, obtained through bibliometric analysis and literature review, revealed perspectives into the skills required for workers in Portugal. The main findings are presented below.

Figure 3 illustrates the evolution in the number of papers published annually on Industry 4.0. The temporal analysis reveals growth trends in academic output related to the subject, indicating increased interest and research in the area.

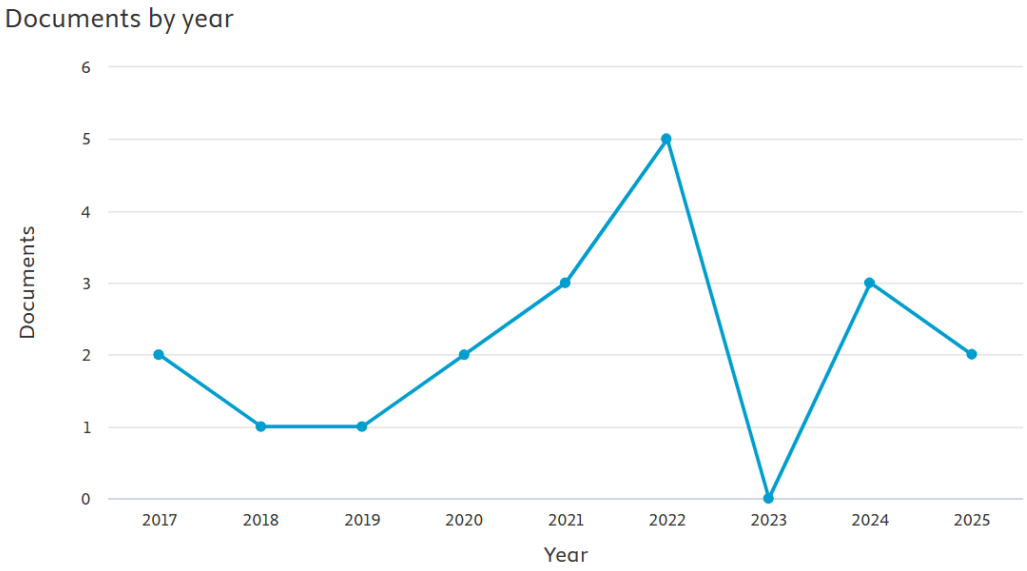

Figure 3.
Documents by year.

Figure 4 visually represents the study’s scope, highlighting the main themes and subthemes addressed in the literature on Industry 4.0. This visualization helps understand how different topics are interconnected and which areas are most explored. It also demonstrates the multidimensionality of the topic and the need for an integrated approach.

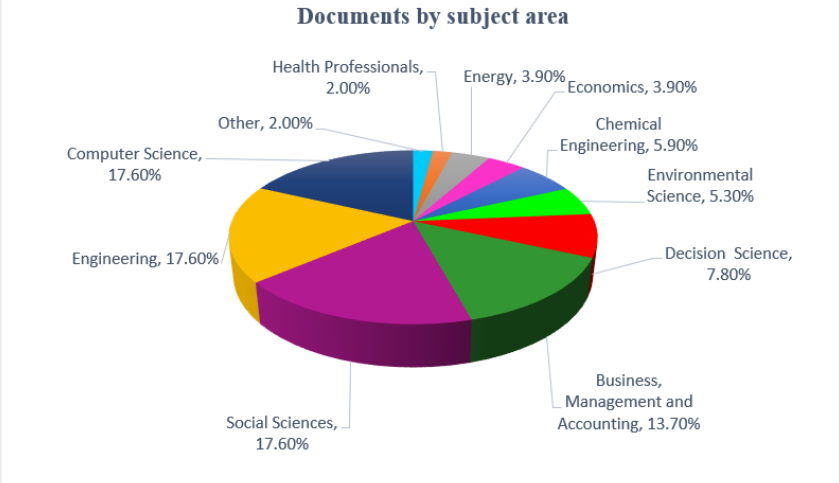

Figure 4.
Documents by subject area.

Figure 5 categorizes the documents analyzed in the research, showing the distribution between original articles, review papers, conference papers, and others. This categorization is essential to understanding the nature of publications and the depth of the existing research. The diversity of document types indicates a dynamic and evolving field of study.

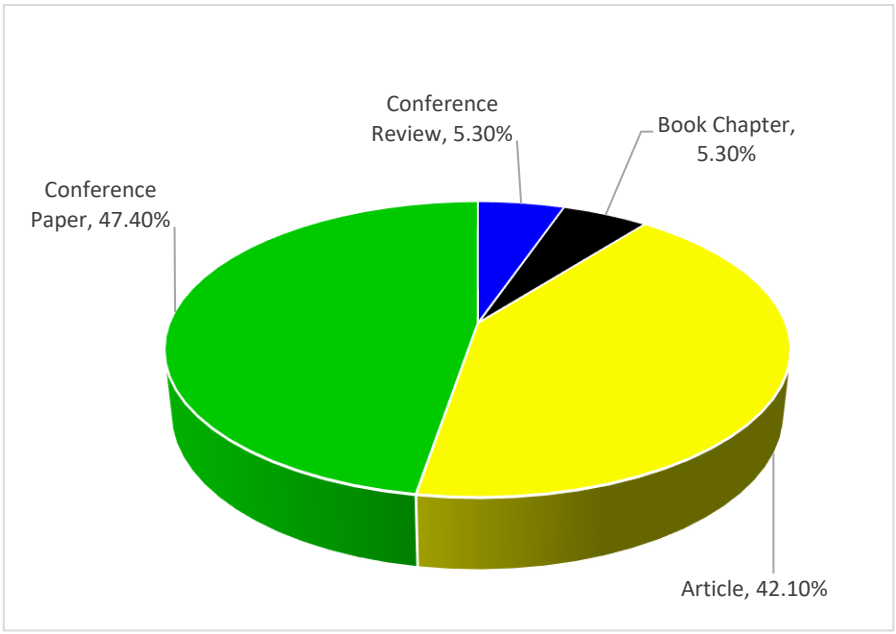

Figure 5.
Documents by type.

Figure 6 highlights the types of documents analyzed by country, evidencing the academic production related to Industry 4.0. In this context, it shows that Portugal participates significantly in research, revealing the country's interest in understanding and developing professional skills for adopting Industry 4.0 technologies. Portugal's presence in the distribution of documents demonstrates that the government is keeping pace with international trends and contributing actively to knowledge production in the field, strengthening its position in the academic and industrial landscape regarding the skills required in this new industrial phase.

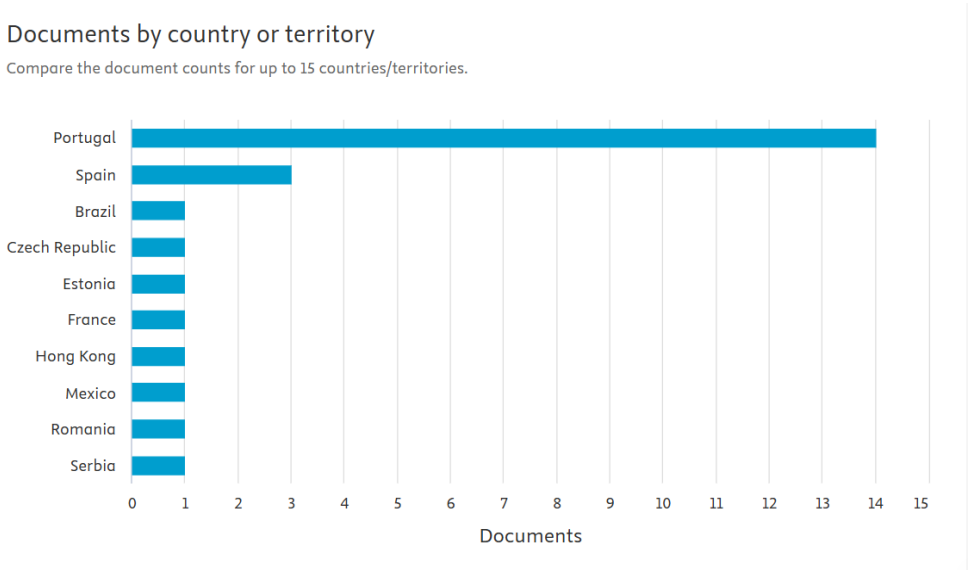

Figure 6.
Documents by country or territory.

Figure 7 displays a word cloud illustrating the most frequent terms found in the analyzed papers keywords, titles and abstracts. This visualization highlights the most relevant and recurring words, indicating the main research foci in the area. The predominance of specific terms reflects the current priorities in Industry 4.0 research.

Figure 7.
Displays a word cloud illustrating the most frequent terms found in the analyzed papers keywords, titles and abstracts.

Figure 8 presents the keyword cluster analysis, helping to identify the most relevant themes in Industry 4.0 research. The clusters reveal how digital skills, such as programming and data analysis, are becoming central and highlight the connection between automation and interpersonal skills. These perspectives are essential for training professionals to adapt to evolving market demands.

Figure 8.
Clusters of keywords.

Figure 9 illustrates the growth of keywords over time, showing which terms have been gaining relevance in the literature. This temporal analysis is critical for understanding emerging trends and rapidly developing areas. The growth of specific keywords may signal new research areas worthy of attention.

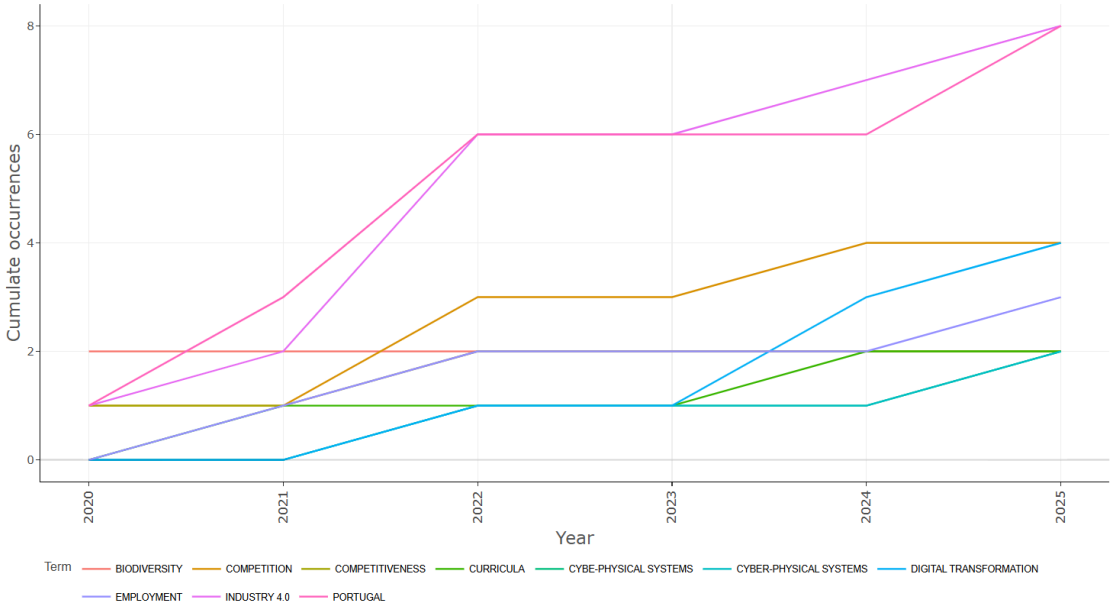

Figure 9.
The growth of keywords over time.

Figure 10 provides a visual summary of scientific publications, using the TreeMap technique to categorize and display the number of publications in different Industry 4.0 subtopics. This visualization helps identify which areas are more saturated with research and which may be considered niches. These findings can inform future investigations and academic collaborations. Terms such as *Industry 4.0*, *Portugal*, *competition*, *curriculum*, and *students* were among the most frequent in abstracts, indicating their relevance in this context.

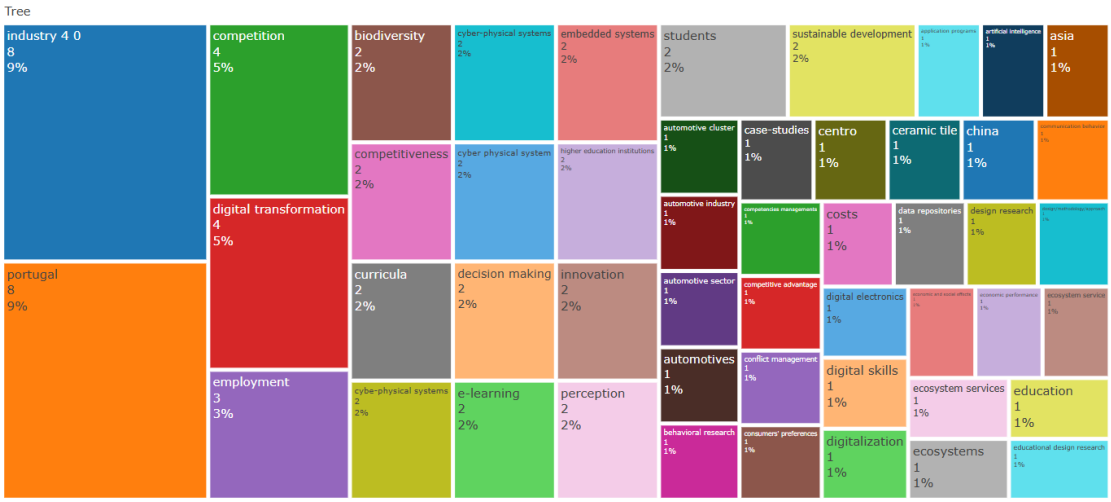

Figure 10.
TreeMap the number of publications in different Industry 4.0 subtopics.

Figure 11 shows a thematic map that categorizes keywords into quadrants, indicating the relevance and development of these themes in research. The quadrants are classified as driving, niche, emerging, declining, and basic or transversal themes, allowing for a deeper analysis of focus areas. This categorization is key to guiding research efforts and skills development.

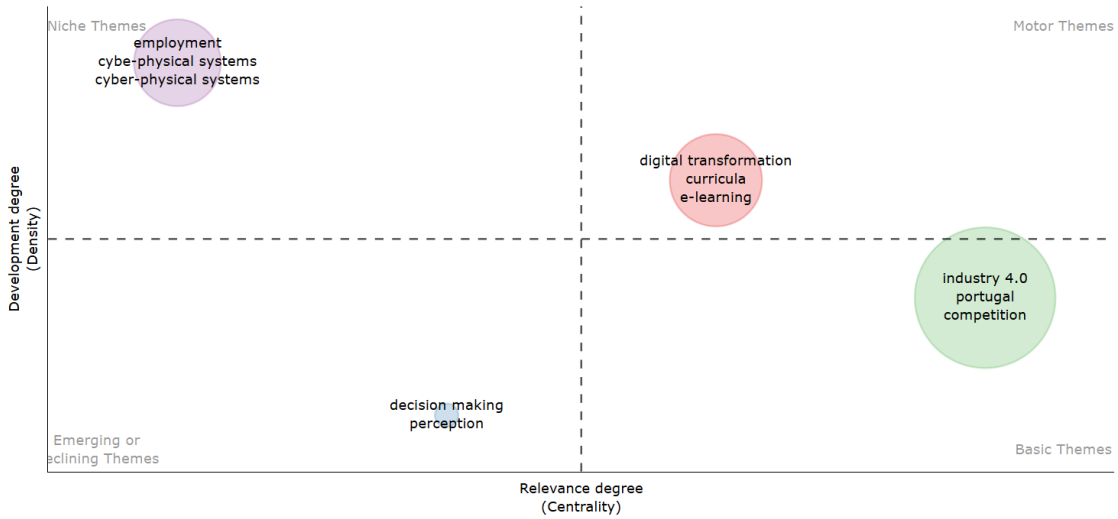

Figure 11.
Thematic map of keywords categorizes.

Figure 12 depicts the thematic growth and evolution of articles on Industry 4.0. The analysis shows a significant increase in the number of publications, reflecting the growing importance of the subject in academic research. This thematic evolution clearly indicates how Industry 4.0 is shaping the future of skills required in the industrial sector.

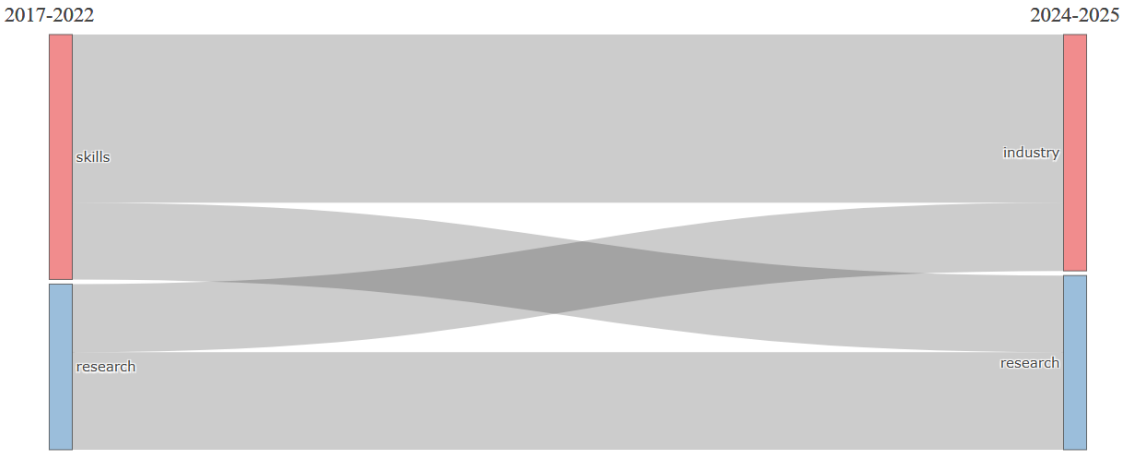

Figure 12.
The thematic growth and evolution of articles on Industry 4.0 over time.

These figures provide a comprehensive view of the skills demanded in the context of Industry 4.0 in Portugal, guiding professionals, educational institutions, and companies in developing talent aligned with market needs.

Table 2 presents a synthesis of the skills identified in the literature on Industry 4.0, categorized by domain and number of papers. However, technical skills, such as integrating different technologies and interpreting data, are essential for technological innovation. In addition, the ability to lead and manage innovation-oriented projects is fundamental for success in the contemporary industrial environment. These skills preparing workers for the challenges of Industry 4.0 and ensuring organizational competitiveness. The qualitative analysis indicated that market needs are rapidly changing due to Industry 4.0. Six main domains were identified.

Table 2.
Domain and skills identified in the literature on Industry 4.0.

Domain / Number of Papers	Author / Year	Title
Technical Domain (7 papers)	Faria, et al. [49]; Campos and Silva [50]; Savu and Dumitrescu [51]; Alexandre, et al. [52]; Moniz, et al. [2]; Prokopenko, et al. [4] and Guzmán Sánchez-Mejorada, et al. [11]	- Impact of Governmental support for the implementation of Industry 4.0 in Portugal; - Synergies between Quality Management and knowledge Management: 4.0 shop floor competency management model; - Knowork-in-Progress: developing a master programme for specialists in Industry 4.0: how an international Partnership of Universities developed the curricula for a master programme for specialists in Industry 4.0; - Application of industry 4.0 technologies to the design and manufacturing of handicraft products; - Changes in productivity and labour relations: Artificial intelligence in the automotive sector in Portugal; - The convergence of IoT, cyber-physical systems, and mechatronics in Industry 4.0 digitalization; - *Industry 4.0 skills assessment: A case study of students' perceptions in computer science postgraduate programs.*
Flexibility Domain (2 papers)	Mesquita, et al. [53] and Neves, et al. [54]	- Did AI Kill My Job?: Impacts of the Fourth Industrial Revolution in Administrative Job Positions in Portugal; - The competences in the digital era in the tourism and hospitality sector.
Inter-Agency Domain (1 paper)	Teixeira, et al. [55]	- How Higher Education Institutions Are Driving to Digital Transformation: A Case Study.
Behavioral and Subjective Skills Domain (Soft Skills) (3 papers)	Cunha, et al. [56]; Dié guez [57] and Mazurchenko and Maršíková [58]	- Not Practicing What You Preach: How Is Accounting Higher Education Preparing the Future of Accounting; - Digital Transformation and Organizational Challenges. An Exploratory Study; - Digitally-powered human resource management: Skills and roles in the digital era.
Innovation Domain (4 papers)	Santos, et al. [14]; Santa Rita, et al. [15];Alexandre, et al. [52] and Da Silva and Almeida [59]	- New needed quality management skills for quality managers 4.0; - Application of industry 4.0 technologies to the design and manufacturing of handicraft products; - Towards INDUSTRY 4.0 a case STUDY in ornamental stone sector; - Digital transformation: patents as a determinant proxy for Industry 4.0.
Information Technology Domain (1 paper)	Jeranoski and Leitão [60]	- Development of stem curriculum for digital electronics education in secondary school.

Source: Authors (2025).

Summary of Findings by Domain:

- Technical Domain: Automation and digitalization are replacing some functions, requiring new technical skills that enable professionals to operate and manage complex systems.
- Flexibility Domain: The ability to adapt to new technologies and processes is increasingly valued, reflecting the need for workplace flexibility.
- Inter-Agency Domain: Companies seek professionals with communication and collaboration skills essential for working in dynamic, multidisciplinary teams.
- Behavioral and Subjective Skills Domain (*Soft Skills*): There is growing demand for interpersonal skills such as empathy, resilience, and critical thinking, which are key to success in a constantly changing work environment.
- Innovation Domain: Innovating and adopting sustainable practices is necessary, as organizations must adjust to new market demands and societal expectations.
- Information Technology Domain: Competence in IT, including programming and data analysis, is essential for efficient operation in a digital environment.

The research results highlight the significant transformation Industry 4.0 is bringing to professional skills in Portugal. New technologies require technical expertise, interpersonal skills, and multidisciplinary training. The bibliometric analysis and literature review revealed a growing academic output on the subject, reflecting the increasing relevance of Industry 4.0 in the contemporary context. Therefore, educational institutions and companies must align their training and talent development strategies with new market demands, preparing professionals for an increasingly digital and automated future.

5. Practical Implications

5.1. Industry 4.0 Skills in the Technical Domain in Portugal

Analyzing the skills required in Industry 4.0 revealed a diversity of domains for training a qualified workforce. The technical domain is fundamental, encompassing specific abilities related to technology and automation [2, 4, 11, 49-52].

Faria, et al. [49] discuss the policies and initiatives implemented by the government to facilitate the digital transition of industries, highlighting challenges and opportunities in this context. The research emphasizes the importance of financial and technical support for small and medium-sized enterprises and addresses the need for an integrated strategy to maximize the benefits of Industry 4.0.

Campos and Silva [50] explore synergies between quality management and knowledge management, proposing a competency management model for the shop-floor environment in the 4.0 era. The authors discuss how integrating these two areas can improve industry efficiency and innovation. The model presented aims to empower employees through knowledge sharing and applying quality practices, highlighting the importance of a collaborative environment adaptable to new technologies.

Savu and Dumitrescu [51] detail the curriculum development process to meet market demands and prepare students for the challenges of digital transformation in industries. The focus is on integrating technical knowledge and practical skills to enable graduates to operate effectively in advanced industrial settings.

Alexandre, et al. [52] explore the application of Industry 4.0 technologies in designing and manufacturing artisanal products. The paper addresses how integrating advanced technologies such as 3D printing and automation can enhance efficiency and customization in artisanal production.

Moniz, et al. [2] analyze the impact of artificial intelligence (AI) on productivity and labor relations in Portugal's automotive sector. The authors examine how AI technologies are altering production processes and work dynamics, highlighting both the benefits and challenges companies and workers face.

Prokopenko, et al. [4] highlight the strategic convergence of IoT, cyber-physical systems, and mechatronics, emphasizing that integrating these technologies is vital for the efficient digitalization of industrial processes, which requires professionals with broad, multidisciplinary technical skills capable of operating and innovating in complex and interconnected environments.

In this context, Guzmán Sánchez-Mejorada, et al. [11] in a study with computer science graduate students, identify gaps between the skills taught and the demands of the market, stressing the need for continuous curriculum updates to prepare professionals to meet Industry 4.0's technological challenges.

This technical domain underscores the importance of skills such as programming, automated systems maintenance, and the ability to work with emerging technologies. These abilities are essential to ensure workers can operate and innovate in an increasingly digitalized industrial environment.

5.2. Industry 4.0 Skills in the Flexibility Domain in Portugal

The flexibility domain is a critical skill set in rapid technological and market changes. Two studies, Mesquita, et al. [53] and Neves, et al. [54] discuss the need for professionals to adapt quickly to new conditions and demands. The ability to adjust to different contexts and lead organizational change processes is vital for the survival and success of companies in the Industry 4.0 era.

Mesquita, et al. [53] examine the impacts of the Fourth Industrial Revolution, particularly automation and artificial intelligence, on administrative jobs in Portugal. The authors analyze how these technologies transform administrative functions, leading to shifts in the demand for skills. The paper also addresses workers' fears and concerns about job displacement, and proposes strategies for workforce adaptation and retraining to mitigate the adverse effects of automation.

Neves, et al. [54] address the skills required for professionals in the tourism and hospitality sector in the digital era. The authors explore how new technologies shape customer expectations and operations in the industry, requiring workers to acquire specific digital skills. They further stress the importance of continuous training and developing competencies in digital marketing, data management, and customer service, emphasizing the need for adaptation to ensure competitiveness and service excellence.

In the flexibility domain, adaptability is relevant in rapid technological and market changes. The studies by Mesquita, et al. [53] and Neves, et al. [54] demonstrate how this skill allows professionals to face unpredictable challenges and lead organizational transformations, thus fostering business resilience and success in the digital era.

5.3. Industry 4.0 Skills in the Inter-Agency Domain in Portugal

In the Inter-Agency domain, Teixeira, et al. [55] address the need for effective communication and teamwork skills. In a work environment that values multidisciplinary collaboration, conveying information clearly and working with others toward common goals is essential.

Teixeira, et al. [55] examine specific cases where partnerships between universities and companies have driven digital initiatives, highlighting the importance of academic training aligned with market needs and regional economic development.

The study emphasizes that collaboration and clarity in communication are key to achieving common goals and success in digital projects.

5.4. Industry 4.0 Skills in the Behavioral and Subjective Skills Domain (Soft Skills) in Portugal

Behavioral and subjective skills, commonly called soft skills, are increasingly recognized as essential for professional success. Cunha, et al. [56]; Dié guez [57] and Mazurchenko and Maršíková [58] stress the importance of abilities such as emotional intelligence, empathy, and relationship management. These skills are fundamental for building collaborative and innovative work environments.

Cunha, et al. [56] argue that, despite contemporary guidelines and theories on accounting practices, university curricula often fail to reflect the skills needed for future accountants. The study highlights the gap between theoretical training and the practical skills required in the field, suggesting the need for curricular reforms that better integrate current practices and technologies.

Dié guez [57] examines how companies must adapt to new technologies and processes, analyzing organizational culture, resistance to change, and leadership. The exploratory approach identifies key barriers and enablers of digital transformation, offering perspectives into how organizations can navigate this complex process.

Mazurchenko and Maršíková [58] discuss the evolution of human resource (HR) management in the digital era, focusing on the new skills and roles HR professionals must develop. They analyze how digitalization transforms recruitment, training, and talent development practices, underscoring the importance of digital competencies for HR team effectiveness.

All three studies highlight that these soft skills are essential for creating collaborative, innovative, and adaptable workplaces capable of meeting the demands of Industry 4.0.

5.5. Industry 4.0 Skills in the Innovation Domain in Portugal

Innovation is a central pillar of Industry 4.0. The innovation domain was addressed by four papers Santos, et al. [14]; Alexandre, et al. [52]; Da Silva and Almeida [59]; Santa Rita, et al. [15] all emphasizing the need to foster an innovative mindset among workers. The ability to develop new ideas, products, and processes is vital for organizations to remain competitive in a constantly evolving market.

Santos, et al. [14] examine the new skills required for quality managers in the Industry 4.0 era. The authors discuss how digitalization and automation are transforming the role of quality managers, requiring abilities in areas such as data analysis, process management, and leadership in technological environments. They emphasize the importance of continuous training and adaptive skill development so that these professionals can meet contemporary challenges and contribute effectively to constant improvement in organizations.

Alexandre, et al. [52] investigate new design and manufacturing technologies applied to artisanal products. The authors discuss how integrating advanced Technologies, such as 3D printing and automation, can optimize the creation and production process, enabling greater customization and efficiency.

Da Silva and Almeida [59] present a case study on transitioning to Industry 4.0 in the ornamental stone sector. They examine how companies in this industry adopt digital and automated technologies to improve production efficiency and quality. They also discuss the opportunities Industry 4.0 presents for enhancing competitiveness and sustainability in the sector.

Santa Rita, et al. [15] reinforce the importance of innovation as a competitive differentiator, highlighting patents as a key indicator for measuring an organization's innovative capacity. This finding underscores the need to cultivate an organizational culture oriented toward continuous innovation to ensure long-term business sustainability.

Across these studies, the authors agree that an innovative mindset is indispensable for companies to remain competitive in constantly transforming markets.

5.6. Industry 4.0 Skills in the Information Technology Domain in Portugal

Finally, the information technology domain is essential for integrating and effectively using new technologies. Jeranoski and Leitão [60] discuss the importance of data analysis, information security, and IT systems management skills. As companies increasingly depend on data and technology, IT training becomes a priority to ensure operational efficiency and security.

Jeranoski and Leitão [60] focus on developing a STEM (Science, Technology, Engineering, and Mathematics) curriculum aimed at digital electronics education at the secondary school level. The authors stress the importance of integrating digital electronics concepts into the school curriculum to prepare students for future technological challenges.

According to Jeranoski and Leitão [60] data analysis, information security, and IT systems management are fundamental to ensuring the effectiveness and security of industrial operations. This domain reinforces the need for continuous training that is aligned with Industry 4.0's technological and digital demands.

5.7. Theoretical Implications of the Study

This study shows that Industry 4.0 requires a profound reassessment of professional skills, going beyond the technical domain to encompass complex interpersonal and cognitive abilities, as discussed byFaria, et al. [49]. The authors highlight that traditional theories on skills development must be updated to reflect this multidimensionality, which mirrors the complexity and interconnectedness of modern industrial environments.

Moreover, the research points to the need for an interdisciplinary approach to professional training, aligning with the perspective of Campos and Silva [50] who propose integrating quality management, knowledge management, and innovation as central elements for skills development in Industry 4.0. This perspective broadens the understanding of how

different fields of knowledge interact to form adaptable, resilient professionals capable of thriving in dynamic technological environments.

Prokopenko, et al. [4] also contribute by stressing the technological convergence between IoT, cyber-physical systems, and mechatronics, underscoring the need for skills development theories to incorporate multidisciplinary technical abilities and cognitive flexibility. This reinforces the importance of theoretical models integrating technical, behavioral, and strategic dimensions to explain how workers can be prepared for Industry 4.0 challenges.

Thus, the theoretical implications of this study contribute to advancing academic knowledge by proposing a more holistic and integrated framework that considers the multiple demands of a highly digitalized and automated industrial context.

5.8. Practical Implications of the Study

The practical implications of this study are especially relevant for educational institutions and companies that must quickly adapt to the demands of Industry 4.0. Campos and Silva [50] highlight the importance of revising curricula to include updated technical skills, interpersonal skills, and knowledge management, fostering a balanced training approach aligned with market needs. Adopting active learning methodologies, practical training, and partnerships with the productive sector is recommended to better prepare students for real industrial environments.

Neves, et al. [54] also indicate that specific sectors (such as tourism and hospitality) must develop training programs focused on digital skills and customer service, adapting to new technological and behavioral demands. The implementation of continuous and personalized training is presented as an effective path for organizational adaptation.

Finally, organizations should create work environments that value continuous learning, innovation, and flexibility, as Dié guez [57] suggested, so professionals are prepared to lead digital transformation processes and address the cultural barriers associated with change. This practical guidance calls for collaboration between businesses and educational institutions to build professional development ecosystems aligned with Industry 4.0 trends.

5.9. Study Limitations

Despite its significant contributions, this study has some limitations that must be acknowledged.

First, the research is primarily based on a literature review and analysis of selected studies, which may limit the generalization of results to specific contexts or industrial sectors.

Second, although comprehensive, the diversity of domains analyzed may not encompass all emerging skills that will arise with the rapid advancement of technologies.

Third, the lack of primary empirical data, such as interviews or field surveys with professionals and managers, limits the depth of analysis of skills in practice.

Finally, the rapid technological evolution of Industry 4.0 may render some identified skills obsolete in the short term, requiring frequent updates in future research. The intersection between technical and behavioral skills still lacks integrated and empirically validated models, posing a challenge for developing educational and corporate policies based on solid evidence.

5.10. Proposed Future Research Agenda for Industry 4.0 in Portugal

Industry 4.0 represents a major transformation of the industrial environment, requiring constant reassessment of skills and practices. Based on the analyses conducted, seven research agendas are proposed for Portugal:

1. Curriculum update aligned with emerging technical skills: Considering the mismatch between taught skills and market demands identified by Guzmán Sánchez-Mejorada, et al. [11] future studies should explore innovative methods for curriculum revision, including IoT and cyber-physical systems Prokopenko, et al. [4] promoting agile and multidisciplinary training.
2. Impact of artificial intelligence on productivity and labor relations: Building on Moniz, et al. [2] research should deepen understanding of AI's effects on production and socio-emotional skills, exploring strategies to mitigate challenges and maximize benefits.
3. Integrated models for soft skills training: As highlighted by Cunha, et al. [56]; Dié guez [57] and Mazurchenko and Maršíková [58] future research should validate pedagogical models that integrate emotional intelligence, empathy, and change management to prepare professionals for digital transformation.
4. Synergies between knowledge management and quality: Inspired by Campos and Silva [50] studies could analyze how collaborative environments and integrated management of these domains promote innovation and organizational flexibility, especially in SMEs.
5. Cultural and organizational barriers to technology adoption: Following Dié guez [57] it is important to investigate resistance to change and cultural factors that hinder digital transformation, developing strategies for adaptation and acceptance.
6. University–industry partnerships in training: Based on Teixeira, et al. [55] future studies could examine effective cooperation models between academia and industry to accelerate training aligned with technological and economic demands.
7. Strategies for sustainable innovation and patents as indicators: Considering [15] research should explore how to foster a culture of sustainable innovation in Portuguese organizations, using patents as indicators of technological and environmental progress.

These research agendas are essential for preparing Portugal for Industry 4.0. Collaboration among academia, industry, and government is key to developing solutions and training professionals capable of driving a sustainable and innovative future.

6. Conclusion

The analysis from the 18 selected papers and the reviewed literature shows that Industry 4.0 is more than a mere technological upgrade; it is a structural transformation that profoundly redefines the profile and skills professionals require. The demand for advanced technical skills and interpersonal skills reveals that modern workforce training must be holistic, encompassing operational and strategic dimensions. Integrating technical knowledge with creative problem-solving becomes a competitive advantage in this scenario.

In the technical sphere, consolidating skills in automation, robotics, data analysis, and artificial intelligence is imperative for effective performance in increasingly data-driven and interconnected industrial environments. However, the pace of innovation requires that these abilities be constantly updated through lifelong learning, reinforcing the concept of continuous education. In parallel, interpersonal skills, such as communication, collaboration, adaptability, and leadership, are central, enabling professionals to deal with uncertainty and lead teams through structural, cultural, and technological changes.

Furthermore, the integration of technology and sustainability emerges as a non-negotiable requirement. Incorporating sustainable practices and adopting circular economy principles are no longer differentiators but strategic imperatives for companies committed to competitiveness and socio-environmental responsibility. The literature indicates that when combined with Industry 4.0 technologies, sustainable innovation enhances efficiency gains and reduces environmental impact, creating a virtuous cycle between industrial development and resource preservation. This convergence reinforces the need for professionals to apply technological solutions without losing sight of sustainability principles.

Finally, building a workforce capable of meeting the demands of Industry 4.0 will depend on consistent collaboration between academia, industry, and government. This cooperation must be guided by long-term strategies that promote talent training in a way aligned with contemporary technological and socio-environmental requirements. The creation of research agendas, investment in capacity building, and implementation of public policies focused on innovation will be decisive in positioning countries like Portugal competitively in the global arena. Developing adaptable, innovative professionals committed to sustainability is the key to ensuring that organizations thrive in an increasingly dynamic and challenging environment.

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