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Human-Centric Manufacturing Skills in Industry 5.0: A Systematic Review and Framework Proposal

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Abstract

This thesis addresses the gap between the theoretical concept of **Human-Centricity in Industry 5.0** and its practical implementation. While the importance of a human-centric approach is widely recognized, existing literature **lacks consolidated frameworks** to define the specific workforce skills required to operationalize it.

This thesis fills this void by reviewing scientific literature and developing a comprehensive Human-Centric Skills Framework that maps competencies across the life cycle of socio-technical systems.

To achieve these goals a systematic literature review was carried out following the **PRISMA** protocol. Furthermore, the study leverages an adapted version of Generalized Enterprise Reference Architecture and Methodology (**GERAM**) framework to construct a novel skill classification.

The **resulting matrix** dynamically intersects four **Organizational Entities** (i.e., Strategic Management, Production, Infrastructure, Data & AI) with four **Lifecycle Phases** (i.e., Concept & Design, Implementation, Operation & Management, End-of-Life). A key innovation is the redefinition of the **End-of-Life** phase, which shifts focus from asset disposal to the "lifecycle of the professional role," providing actionable competencies for managing workforce restructuring and ensuring long-term employability.

Practically, this study offers a reference model that can support industrial organizations in identifying skill gaps and planning workforce evolution. Simultaneously, it informs academic institutions by outlining the essential hybrid technical-ethical skills required to shape the profile of Industry 5.0 engineers.

Keywords: Industry 5.0, Human-Centricity, Skills Framework, GERAM, Technology Lifecycle, Workforce Transition

Abstract in italiano

Questa tesi affronta il divario tra il concetto teorico di **Human-Centricity** (centralità umana, antropocentrismo) **nell'Industria 5.0** e la sua implementazione pratica. Sebbene l'importanza di un approccio incentrato sull'uomo sia ampiamente riconosciuta, la letteratura esistente **manca di framework consolidati** per definire le competenze specifiche della forza lavoro necessarie per renderlo operativo. Questa ricerca colma tale vuoto sviluppando un Human-Centric Skills Framework completo che mappa le competenze lungo il ciclo di vita dei sistemi socio-tecnici.

Per raggiungere questi obiettivi è stata condotta una revisione sistematica della letteratura seguendo il protocollo **PRISMA**. Inoltre, lo studio sfrutta una versione adattata del framework Generalized Enterprise Reference Architecture and Methodology (**GERAM**) per costruire una nuova classificazione delle competenze.

La **matrice risultante** interseca dinamicamente quattro **Entità organizzative** (ovvero Gestione Strategica, Produzione, Infrastruttura, Dati e IA) con quattro Fasi del **Ciclo di Vita** (ovvero Ideazione e Progettazione, Implementazione, Operatività e Gestione, Fine Vita). Un'innovazione chiave è la ridefinizione della fase di **Fine Vita (End-of-Life)**, che sposta l'attenzione dallo smaltimento degli asset al "ciclo di vita del ruolo professionale", fornendo competenze operative per gestire la ristrutturazione della forza lavoro e garantire l'occupabilità a lungo termine.

In termini pratici, questo studio offre un modello di riferimento in grado di supportare le organizzazioni industriali nell'identificazione delle lacune di competenze e nella pianificazione dell'evoluzione della forza lavoro. Simultaneamente, fornisce indicazioni alle istituzioni accademiche delineando le competenze ibride tecnico-etiche essenziali richieste per plasmare il profilo degli ingegneri dell'Industria 5.0.

Parole chiave: Industria 5.0, Human-Centricity, Framework delle Competenze, GERAM, Ciclo di Vita della Tecnologia, Transizione della Forza Lavoro.

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1 Introduction

The concept of **Industry 5.0** has emerged not merely as a chronological successor to **Industry 4.0**, but as a necessary paradigm shift intended to reconcile the technological advancements of the last decade with human-centric, sustainable, and resilient values [57] [2].

While **Industry 4.0** focused heavily on automation, digitization, and efficiency through technologies like the Internet of Things (IoT) and Cyber-Physical Systems (CPS), it neglected the human element, treating workers as components to be optimized or replaced [27] [47]. Instead, **Industry 5.0**, as described by the European Commission, explicitly aims to place the well-being of the worker at the center of the production process [58].

It recognizes that true industrial resilience and long-term sustainability cannot be achieved through technology alone but require a symbiotic relationship between human ingenuity and machine efficiency [5]. Consequently, the **transition to Industry 5.0** necessitates a **re-evaluation of the skills** and competencies required by the workforce [46].

It is no longer sufficient for employees to possess only deep technical knowledge; they must now develop **hybrid skills** that allow them to collaborate effectively with intelligent machines (e.g., cobots, AI) while leveraging uniquely human attributes such as critical thinking, creativity, and empathy [21] [6].

However, **a significant gap exists** between the high-level policy goals of Industry 5.0 and the practical reality of workforce management and training [38]. Many organizations struggle to translate the abstract concepts of "human-centricity" into concrete job roles and training programs [20]. Additionally, the rapid pace of technological change often outpaced the ability of educational institutions and corporate training departments to update curricula, leading to a widening skills gap [44] [12].

This thesis aims to address this critical gap by analyzing the specific **human-centric Industry 5.0 skills** and proposing a structured framework for their identification and development throughout the life cycle of socio-technical systems.

The remainder of this thesis is organized as follows. **Chapter 2** establishes the theoretical context, analyzing the transition from Industry 4.0 to Industry 5.0 and defining the core pillars of the new paradigm, with a specific focus on the concept of

Human-Centricity. **Chapter 3** outlines the research methodology, detailing the Systematic Literature Review (SLR) process conducted according to the PRISMA protocol and introducing the GERAM framework adopted as the structural reference for the study. **Chapter 4** presents the consolidated results, illustrating the findings from the descriptive and content analyses and proposing the final Human-Centric Skills Framework. Finally, **Chapter 5** discusses the theoretical and practical contributions of the research, acknowledging its limitations and suggesting avenues for future developments.

2 Overview about Industry 5.0

2.1. Transition from I4.0 to I5.0

The fourth industrial revolution, known as **Industry 4.0**, aimed to create smart manufacturing by integrating advanced production systems with information technology [57] [2]. The goal was to make manufacturing processes more flexible, efficient, and capable of real-time communication between different systems [9]. This paradigm brought significant advancements in automation and data exchange, leading to optimized production and cost reductions [47]. By creating "smart factories" with cyber-physical systems and the Internet of Things (IoT), machines could communicate and make independent decisions, transforming value chains and business models [16] [27].

However, Industry 4.0 presented several **major challenges**. Its implementation is extremely expensive, creating a competitive gap between large corporations and small and medium-sized enterprises (SMEs) that cannot afford the new digital infrastructure [31]. The reliance on networked systems also increased the risk of cybersecurity threats like data breaches, which could disrupt operations and lead to financial loss [9] [13]. Furthermore, the focus on automation led to concerns about job displacement, as many workers lacked the technical skills to operate complex digital systems [19] [49]. This technology-centric approach often neglected social and environmental values, facing resistance from a workforce that saw technology as a threat to their jobs [47].

In response to these issues, **Industry 5.0** emerged as a corrective evolution. This new paradigm shifts the focus from pure automation to a more **human-centric, sustainable, and resilient model** [2] [49]. Instead of replacing human workers, Industry 5.0 seeks to integrate their creativity and critical thinking with the efficiency of advanced technologies [21] [13]. It promotes human-robot collaboration, using tools like collaborative robots (cobots) to work alongside employees, enhancing their capabilities rather than making them obsolete [23] [27]. This approach allows for mass customization, where products can be tailored to individual customer needs without losing efficiency [1] [20].

This **transition** requires a significant shift in workforce management, emphasizing the need for upskilling and reskilling employees to work effectively with new technologies [34] [44]. Under Industry 5.0, the role of technology is to support human labor, not to replace it [12] [4]. By automating repetitive, low-skill tasks, it frees up

workers to concentrate on more value-added work, such as problem-solving, creative design, and system optimization [51] [9]. The focus moves from a quest for full automation to a "human-labor centric" model, where people are once again at the heart of the production process, using technology to augment their skills and judgment [27] [22]. This creates a more balanced and sustainable industrial future that values both human ingenuity and machine efficiency [55].

2.2. Industry 5.0

Industry 5.0 represents the next stage in manufacturing, growing from the foundations of Industry 4.0: while Industry 4.0 was driven by automation, digitization, and optimizing efficiency, Industry 5.0 shifts to a more balanced approach with a change that isn't just about technology, but also about fundamental values [5]. Unlike its predecessor, Industry 5.0 builds principles like trust, security, openness, and inclusiveness directly into its design [19]. The ultimate vision is to create a future where industry isn't just intelligent and automated but is truly human-centric and sustainable [49] [1].

At the heart of this transformation lie three key pillars: the **human-centric** approach, **resilience**, and **sustainability** (see **Figure 1**) [2] [55]. These principles shape an industrial framework where technology and innovation go beyond mere production efficiency, actively contributing to human well-being, strengthening adaptability to global challenges, and fostering environmental responsibility [19] [49] [1].

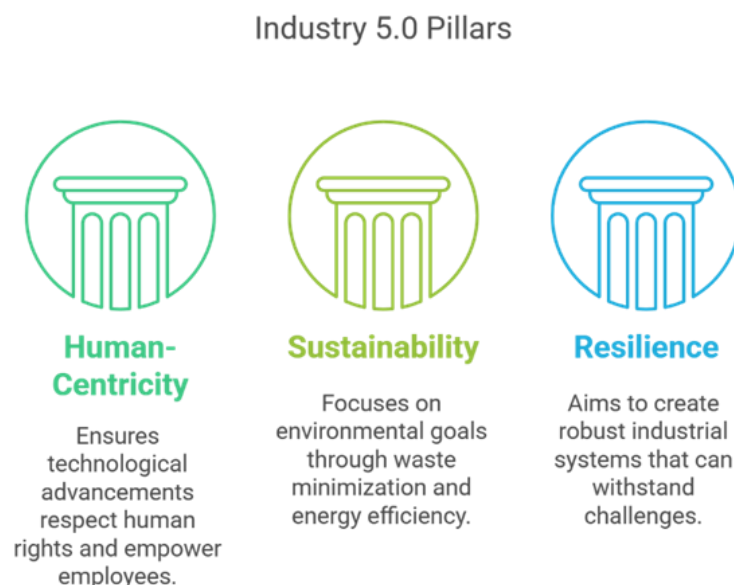


Figure 1: Industry 5.0 Pillars

Resilience focuses on making companies robust, ensuring they can absorb sudden shocks like market changes or supply issues while still operating smoothly [1] [9]. It uses smart technology and data to predict threats and adapt in real-time [49].

Similarly, **Sustainability** demands that industrial growth is responsible, it requires manufacturers to seriously cut waste, minimize their environmental footprint and use resources efficiently [55] [50]. This is about making business success and the long-term health of our planet inseparable [2].

While resilience and sustainability are both critical, this work will focus primarily on **Human-Centricity**. Human-centricity in Industry 5.0 focuses on integrating human intelligence, creativity, and decision-making with frontier technologies such as artificial intelligence, robotics, and automation [5] [21]. Human beings are at the core of the industrial ecosystem. Rather than replacing human labor, industry 5.0 seeks to enhance it by leveraging technology to amplify human capabilities [27].

The **human-centric goals** revolve around designing, developing, and implementing technological solutions and organizational practices that prioritize human needs, motivations, and experiences [22] [6]. This vision goes beyond merely meeting functional requirements; it aims to improve well-being, skills, competencies, and working conditions [47] [53]. Technologies like collaborative robots (cobots), virtual reality, and digital twins (which will be explored in greater detail in the following chapters) are used to support and empower workers rather than replace them, creating a workplace where human imagination and machine precision coexist harmoniously [45] [25].

Unlike previous industrial paradigms, **Industry 5.0** is not technology-driven but **value-driven**, fostering a synergy between humans and machines [19] [49]. Implementing human-centricity generates value at multiple levels: at the **micro level**, it enhances worker empowerment and job satisfaction; at the **business level**, it improves employee retention and business profitability; and at the **macro level**, it contributes to higher quality of life and sustainable growth [34] [12].

At the end of the day, human-centric technologies are designed to support and elevate the workforce, ensuring that all this industrial progress aligns with our ethical values and society's true needs [10]. This involves new ways of working, like co-creation, and inspires new business models that truly prioritize social and environmental considerations [48] [17].

3 Objective and Research Method

To rigorously identify, evaluate, and interpret the existing literature on the skills required by the Industry 5.0 paradigm, a **systematic literature review (SLR)** was conducted. The methodological process adopted follows the framework proposed by [59], an established approach to ensure transparency, rigor, and replicability in the analysis of scientific literature.

3.1. Defining the Research Questions

The starting point of the research is the **identification of a gap** in the current literature: despite a growing interest in Industry 5.0, there is a lack of systematic treatment and a consolidated framework for the competencies needed to support the transition towards a truly human-centric production model.

To fill this gap, this thesis adopts a predominantly inductive approach, which aims not to test an existing model, but to derive a competency framework directly from the analysis of applied literature.

This led to the formulation of the following research questions:

- **RQ1 (Exploratory):** Are there competency frameworks in the literature for classifying the skills required by the Industry 5.0 paradigm?
- **RQ2 (Descriptive):** What are the skills required for the implementation of a human-centric production system in Industry 5.0?
- **RQ3 (Constructive):** Is it possible to develop a framework to systematically and structurally classify these competencies, with a specific focus on the human-centric domain?

This sequence first allows for mapping the existing literature (RQ1), then collecting raw data from the literature (RQ2), and finally synthesizing them into an original and structured contribution (RQ3).

3.2. Defining Inclusion and Exclusion Criteria

To ensure the relevance and high quality of the corpus of articles to be analysed, precise inclusion and exclusion criteria were defined a priori, as suggested by the SLR methodology.

Inclusion Criteria:

- **Thematic relevance:** Full adherence of articles to the concepts of Industry 5.0, competencies (skills), workforce, and the human-centric approach.

- **Recency:** Exclusive inclusion of articles published from 2019 onwards, to ensure the analysis is based on the most up-to-date knowledge in the field.
- **Source type:** Articles published in peer-reviewed academic journals (journal articles, conference papers) and documents from grey literature such as EU projects, and publications from industry associations and research institutes.
- **Language:** Articles written in the English language.

Exclusion Criteria: All articles that did not meet the criteria listed above were excluded, namely:

- Articles published before 2019.
- Articles written in languages other than English.
- Editorials, comments, blog articles, and other sources not supported by rigorous data or analysis.

3.3. Literature Search and Retrieval

The search for primary studies was conducted systematically on the **Scopus academic database**, chosen for its broad coverage in the fields of engineering, management, and social sciences.

To maximize the sensitivity and specificity of the search, the following **search string** was developed:

(TITLE-ABS-KEY ("Industry 5.0" OR human-cent*) AND TITLE-ABS-KEY (skill* OR competenc* OR workforce OR "human capital") AND TITLE-ABS-KEY (gap* OR mismatch* OR shortage* OR need* OR requirement* OR develop* OR training OR education OR "learning factor*" OR "teaching factor*" OR "didactic factor*") AND TITLE-ABS-KEY (manufacturing OR engineering)) AND PUBYEAR > 2019 AND PUBYEAR < 2027 AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "COMP") OR LIMIT-TO (SUBJAREA , "SOCI") OR LIMIT-TO (SUBJAREA , "BUSI") OR LIMIT-TO (SUBJAREA , "PSYC") OR LIMIT-TO (SUBJAREA , "NEUR")) AND (EXCLUDE (SRCTYPE , "b") OR EXCLUDE (SRCTYPE , "k"))

3.4. Selection of Relevant Literature

The article selection process followed the guidelines of the **PRISMA framework** (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to ensure transparency and replicability.

The process was divided into the following steps:

- **Identification:** The initial phase involved the extraction of 464 articles via the search queries run on the Scopus database.
- **Screening:** These were subjected to screening. Applying the inclusion and exclusion criteria to titles, abstracts, and keywords, 407 articles were excluded, resulting in a total of 57.
- **Eligibility:** These were assessed for eligibility through a careful full-text reading to verify their full adherence to the research objectives and criteria.
- **Inclusion:** All 57 articles passed the full-text assessment and were therefore included in the final corpus for qualitative analysis, as there were no exclusions at this stage. To these were added 9 articles, which were identified through a snowballing process, bringing the total to 66 articles overall.

The entire process is visually summarized in the PRISMA flow diagram shown in **Figure 2**.

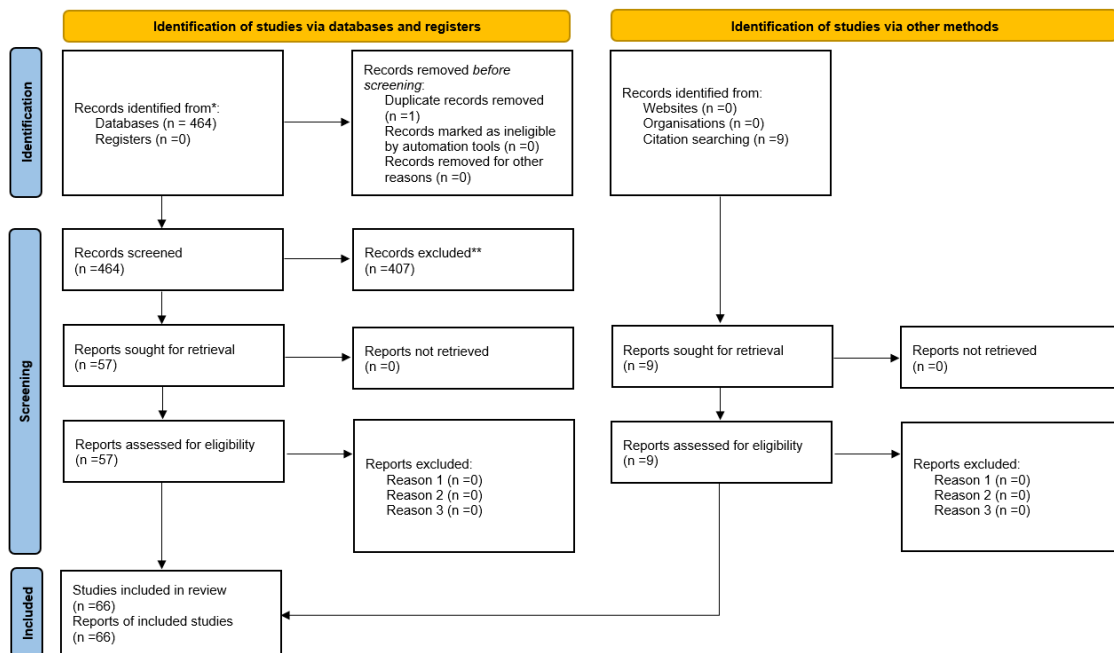


Figure 2: PRISMA Flow Diagram illustrating the Literature Selection Process.

3.5. Analysis

Following the selection of the final corpus of articles, the study proceeded with a structured analysis divided into two distinct phases. First, a **Descriptive Analysis** was conducted to map the bibliographic landscape, identifying key trends, temporal evolution, and prominent publication venues. This was followed by a comprehensive **Content Analysis**, which qualitatively examined the text to extract specific human-centric skill.

3.5.1. Descriptive Analysis

In the descriptive analysis phase, **VOSviewer** was used to analyze the keywords within the article dataset. To understand the scope of topics covered, a network visualization was created based on the co-occurrence of key terms in the literature. This **map** provides a clear overview of thematic clusters and the relationships between core concepts, highlighting both central areas and emerging trends.

In the **VOSviewer map**:

- **Nodes** (bubbles) represent keywords, with size indicating frequency.
- **Links** show co-occurrence of keywords in the same documents; stronger lines indicate stronger associations.
- **Colors** indicate clusters, grouping keywords that frequently appear together.

Subsequently, a **publication year chart** was designed to visualize how publication trends have changed over time, which helps identify peaks in research activity and trends. Complementing this temporal overview, the dataset was analyzed to **list the top publications**, thereby mapping the primary academic venues driving the discourse.

3.5.2. Content Analysis

After mapping the general research trends in the previous section, the focus shifted to a **qualitative content analysis**. The main objective of this phase was to deeply examine the selected literature to gather the foundational elements needed to build the final competency framework. To ensure a systematic approach, this qualitative analysis was divided into two main steps.

The first step consisted of a **direct review of the selected papers** to extract explicit data. Specifically, the focus was on identifying and cataloguing all the skills and competencies expressly cited and defined by the authors within the Industry 5.0 context. Concurrently, this stage mapped any existing frameworks, models, or taxonomies already proposed in the literature. This initial extraction provided a solid theoretical baseline grounded in established research.

However, a purely explicit extraction provided only a partial view of the human-centric capabilities required for the transition. Therefore, a second and deeper level of analysis was introduced: the **inferential derivation**. During this phase, the source texts were critically interpreted to formulate additional competencies. These were skills that, while not explicitly articulated in the documents, emerged as logical necessities or natural functional extensions of the established findings. This crucial step helped to bridge the gaps in the existing literature, defining the complete set of competencies needed to fully actualize the Human-Centric paradigm.

3.6. Skills Framework Development

3.6.1. The GERAM Framework Overview

To ensure a rigorous and systematic structuring of the competencies required for the Human-Centric transition, this thesis adopts the **GERAM** (Generalised Enterprise Reference Architecture and Methodology) framework as its methodological reference. Defined within the **ISO 15704:2000 standard** ("Requirements for enterprise-reference architectures and methodologies"), GERAM was developed by the **IFIP-IFAC Task Force** to address the increasing complexity that modern enterprises face.

This complexity stems from the rapidly changing environment in which today's enterprises operate, where they can no longer make predictable long-term provisions. To evolve and maintain competitiveness, organizations must embrace an adaptive approach, integrating operations with the discipline of **Enterprise Engineering**, which is dedicated to organizing the knowledge necessary to manage change. GERAM constitutes the reference framework for this discipline: it acts as a generalized architecture, that unifies the know-how of previous research models (such as CIMOSA, GRAI/GIM, and PERA), offering a conceptual toolkit applicable to any type of enterprise.

The fundamental reason why GERAM was selected as the basis for our framework lies in its Scope: by bridging distinct approaches of enterprise integration, specifically those based on product models and business process design, the framework encompasses the entire life history of the enterprise entity, spanning from the initial identification of needs to final decommissioning. This holistic lifecycle coverage is crucial for the industry 5.0 transition, as the implementation of a Human-Centric model extends beyond the mere operational use of technologies. It requires specific competencies as early as the Design phase, to create safe and inclusive systems, and ethical management skills during the **End-of-Life phase**. Consequently, adopting GERAM enables us to overcome a siloed vision, mapping human competencies not as isolated elements, but as integrated resources that interact with technology throughout the system's entire evolution.

3.6.2. Scope of Application

The GERAM framework constitutes a comprehensive architecture composed of nine distinct components designed to cover the entire process of enterprise engineering and integration. As illustrated in **Figure 3**, these components range from generic concepts and methodologies (**GERA**, **EEMs**) to specific modelling tools and operational systems (**EETs**, **EOSs**), creating a complete ecosystem for designing, implementing, and maintaining an integrated enterprise.

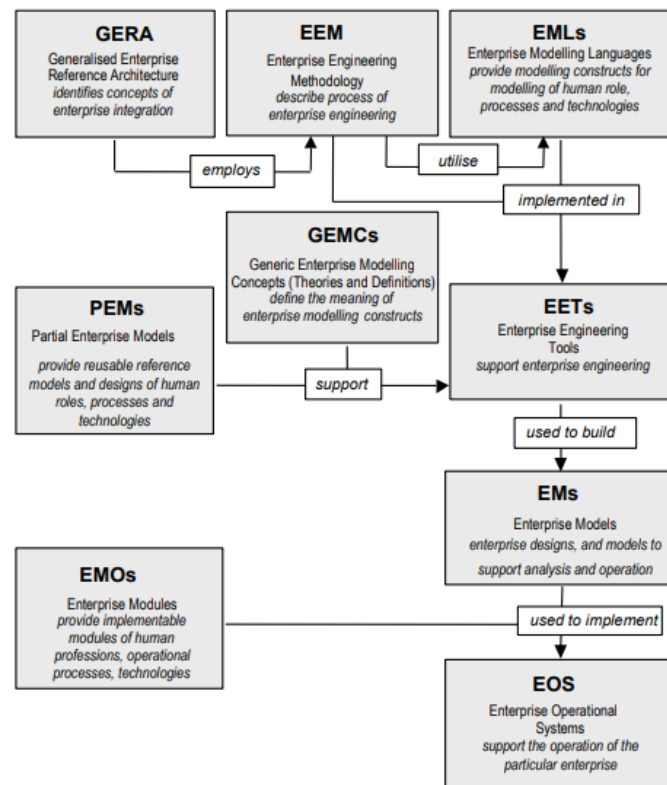


Figure 3: GERAM framework components (ISO 15704:2000)

However, given the specific nature of this research, which aims to define a theoretical competency framework rather than to implement a physical IT system, it is necessary to define the scope of application by selecting only the components relevant to our objectives.

3.6.2.1. Components Excluded from the Scope

In accordance with this theoretical focus, six out of the nine GERAM components fall outside the boundaries of this research. These components are excluded as follows:

- **Enterprise Engineering Methodologies (EEMs):** These describe the procedural process of enterprise engineering (the "how-to"). As this thesis focuses on the *content* of the competency framework rather than providing a step-by-step project management guide for its implementation, EEMs are not addressed.
- **Enterprise Modelling Languages (EMLs):** These provide the specific syntax and semantics for modelling. This research adopts standard conceptual representations and does not aim to develop or validate a new graphical modelling language.

- **Generic Enterprise Modelling Concepts (GEMCs):** These define the core semantic concepts (glossary and ontologies). While this thesis adopts the standard definitions provided by ISO 15704, it does not aim to formulate new theoretical modelling concepts.
- **Enterprise Models (EMs):** An EM represents the model of a specific enterprise entity. Since this thesis aims to create a generalized reference model applicable to the entire manufacturing sector (a PEM), the creation of a particular model for a single specific company is excluded.
- **Enterprise Engineering Tools (EETs):** These are the software tools used to support the engineering process. The development or testing of software tools is outside the boundaries of this theoretical framework.
- **Enterprise Operational Systems (EOSs):** These constitute the actual physical operation of the enterprise (hardware, software, and people in action). As this work is located at the design level and does not involve the physical operation of a manufacturing system, EOSs are excluded.

3.6.2.2. Components Adopted in the Framework

Conversely, the research focuses on three key components of the GERAM architecture which define the structure, nature, and content of the proposed model:

- **Generalised Enterprise Reference Architecture (GERA):** As the core of the framework, GERA defines the generic concepts of enterprise integration. In this thesis, it serves as the structural foundation, specifically through the definition of the Enterprise Entity Lifecycle and Enterprise Entity Types, which are used to organize the Human-Centric Skills Framework in a systematic way.
- **Partial Enterprise Models (PEMs):** PEMs are defined as reusable reference models that capture characteristics common to a specific industry sector, rather than a single enterprise. The framework developed in this thesis acts as a Human-Oriented PEM for Industry 5.0: a reference model defining competency requirements applicable to any manufacturing enterprise undergoing this transition, intended to be used as a basis for further specific modelling.
- **Enterprise Modules (EMOs):** EMOs represent the implementable building blocks of the enterprise, including physical equipment and human resources. In the context of this research, the identified human competencies constitute the essential attributes required to qualify the "Human Resource" EMOs within the future Industry 5.0 system.

3.6.3. Process-Oriented Concepts: Lifecycle and Entities

Among the components selected in the previous section, **GERA** plays the most critical structural role. While PEMs define the nature of the model and EMOs its content, GERA provides the essential organizing principles to structure this content coherently.

According to the standard, the representation of an enterprise requires a **process-oriented approach**. This modelling aim is to describe the processes in the enterprise by capturing both their **operational functionality** and their **dynamic behaviour**.

To achieve a complete description of these processes, the architecture identifies specific concepts that must be recognized. The fundamental process-oriented concepts defined in GERA are the **Enterprise Entity Lifecycle** and the **Enterprise Entity Types**. These concepts constitute the structural backbone of the framework and will be analyzed in the following sections to define the temporal and structural coordinates of the research.

3.6.3.1. The GERA Lifecycle Phases

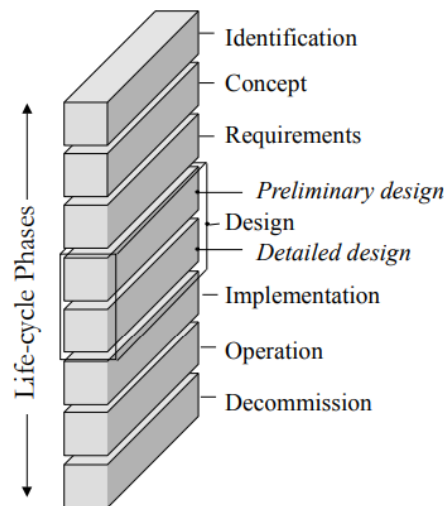


Figure 4: The GERA Lifecycle Phases

The Lifecycle is a fundamental concept of the architecture, applicable to any enterprise or any of its entities. It defines the generic types of activities pertinent during the entire life span of the entity, encompassing all activities from its initial identification to its final end-of-life.

As illustrated in the reference model (see **Figure 4**), GERA divides this lifecycle into seven distinct phases:

1. **Identification:** This phase encompasses the set of activities that identifies the contents of the particular entity in terms of its boundaries and its relation to the

environment. It defines the existence and nature of the business need or the need for change.

2. **Concept:** This phase involves the activities needed to develop the core concepts of the entity. This includes the definition of the mission, vision, values, strategies, and operational concepts required to meet the identified needs.
3. **Requirements:** This phase focuses on developing the descriptions of operational requirements needed to achieve the mission. It covers the collection of all functional, behavioural, and capability needs, regardless of whether they will be satisfied by humans or technology.
4. **Design:** This phase specifies the system components that satisfy the requirements, including the design of all human tasks and machine tasks. As illustrated in the reference model, this phase may be further subdivided into Preliminary Design (for overall specifications and management approval) and Detailed Design (for the complete system specification suitable for implementation).
5. **Implementation:** This phase defines the tasks necessary to build or re-build the entity. It comprises commissioning technology, hiring and training personnel, and testing and validating the system before its release into operation.
6. **Operation:** This represents the actual use of the system to perform the enterprise mission (producing products or delivering services). During this phase, resources are managed to fulfil the entity's goals, and feedback from operations may trigger continuous improvement or re-engineering cycles.
7. **Decommissioning:** This final phase includes the activities needed for the end of the system's useful life, such as re-missioning, retraining of personnel, recycling, or disposal of resources.

3.6.3.2. Recursive Enterprise Entity Types

While the lifecycle defines the temporal sequence of activities, the internal structure of the enterprise is defined by the concept of **Recursion**. GERA identifies a generic set of **Enterprise Entity Types**, where the operation of one entity enables the creation or functioning of the next.

This recursive structure establishes a hierarchical chain of development comprising five specific entity types:

1. **Strategic Enterprise Management Entity (Type 1):** This entity defines the necessity and the starting point of any enterprise engineering effort. It is responsible for identifying the goals and scope that trigger the creation of lower-level entities.
2. **Enterprise Engineering/Integration Entity (Type 2):** This entity provides the means to carry out the efforts defined by Type 1. Its specific role is to define, design, implement, and build the operation of the target enterprise entity (Type 3).
3. **Enterprise Entity (Type 3):** This is the result of the operation of the Engineering Entity (Type 2). It represents the operational system that, once implemented, is responsible for defining, designing, and manufacturing the products or services.
4. **Product Entity (Type 4):** This entity represents the result of the operation of Entity Type 3. It encompasses all products and customer services delivered by the enterprise to the market.
5. **Methodology Entity (Type 5):** This entity represents the methodology employed by the other entities during their operation. Specifically, both the Engineering Entity (Type 2) and the Enterprise Entity (Type 3) use a methodology to perform their respective tasks of designing systems or producing products.

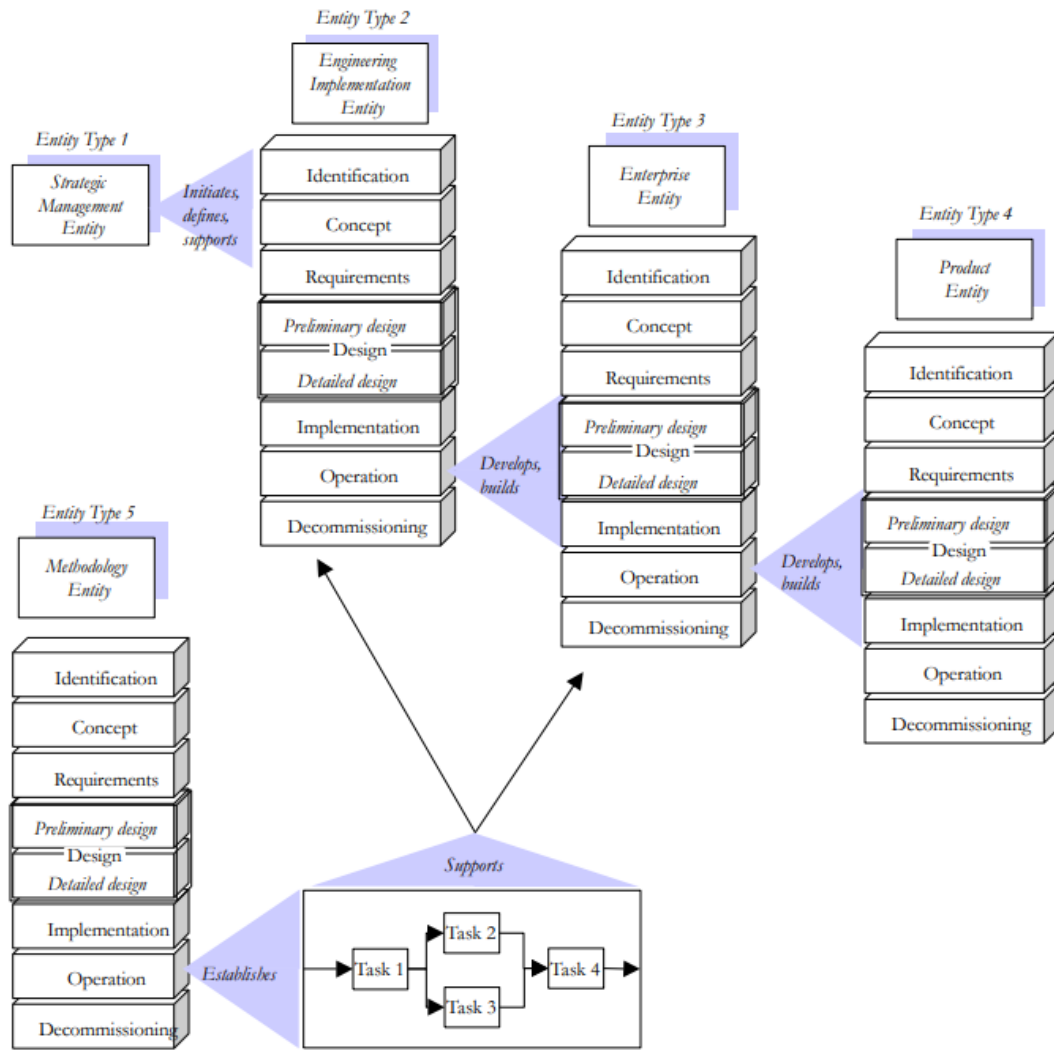


Figure 5: Relationships between lifecycles of GERA entity Types

As illustrated in **Figure 5**, this classification ensures that the enterprise is modelled not as a static set of functions, but as a dynamic chain of value creation, leading from strategic conception down to the final product.

4 Results

This chapter presents the **consolidated findings** of the Systematic Literature Review (SLR), structured sequentially to ensure a logical progression. First, it outlines the outcomes of both the **descriptive and qualitative content analyses**, providing a thematic overview of the research landscape and identifying the foundational competencies extracted from the literature. Building upon these initial results, the chapter then introduces the core contribution of this research: the structured Human-Centric Skills Framework. This final section details how the **GERAM architecture was adapted** to classify the inferentially derived skills, ultimately providing a comprehensive competency matrix for the Industry 5.0 transition.

4.1. Descriptive Analysis

The first step of the descriptive analysis was to use the software **VOSviewer** to create a co-occurrence network of keywords found in the analyzed papers. This visualization reflects a multidisciplinary perspective, showing Industry 5.0 as connected not only to technology (AI, automation, ergonomics) but also to education, skills, and human factors.

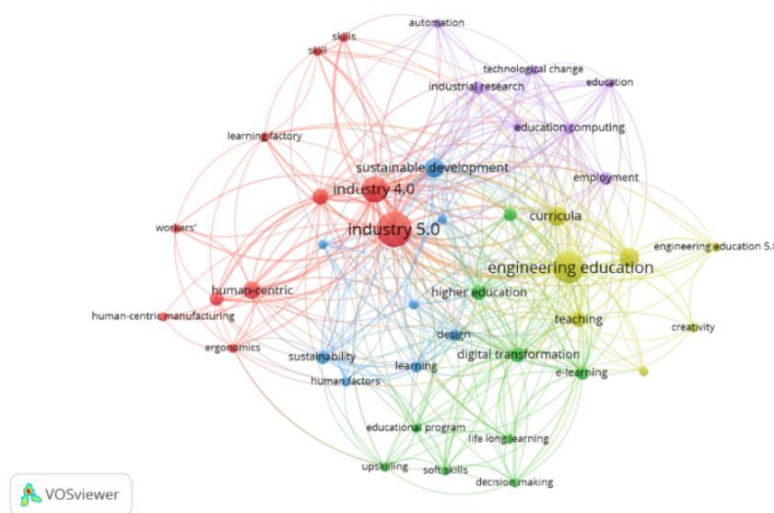


Figure 6: Co-occurrence Network of Keywords generated via VOSviewer.

As shown in **Figure 6**, at the center, the core themes include:

- **Industry 5.0**
- **Industry 4.0**
- **Engineering education**

The co-occurrence map reveals **five main clusters**, each representing a distinct thematic area within the literature. These clusters can be summarized as follows:

- **Red Cluster:** focuses on the technology of Industry 5.0 and its continuity with Industry 4.0 (AI, human-machine collaboration, ergonomics, learning factories).
- **Purple Cluster:** focuses on engineering education and curriculum reform (teaching, creativity, skills development, education 5.0).
- **Green Cluster:** focuses on learning processes and continuous competence development (lifelong learning, upskilling, digital transformation, soft skills, decision-making).
- **Yellow Cluster:** focuses on the link between education systems, research, and employment (automation, industrial research, higher education, computing in education).
- **Blue Cluster:** focuses on applied aspects of Industry 5.0 with emphasis on sustainability and human-centric design (sustainability, design thinking, CAD/CAI, digitization).

The analysis highlights the central role of Industry 5.0, closely connected to both Industry 4.0 and engineering education. This dual focus underscores that the competences required are both technology-driven and education-driven. At the same time, the prominence of keywords such as human-centric, ergonomics, sustainability and the others highlighted, signals a shift toward broader skills encompassing ethical responsibility, human factors, and sustainable practices. Lifelong learning, upskilling, and soft skills emerge as essential for adaptability in a rapidly evolving digital landscape, while the link between curricula, research, and employment points to the need for stronger collaboration between academia and industry to prepare engineers for the Industry 5.0 era.

4.1.1. Publication Years Analysis

As previously mentioned, the research database considers publications from the last decade, going from 2019 to 2025. This is based only on the papers that have been analysed in this thesis, though the same trend has been found in the same analysis conducted on all the articles found through the query previously mentioned.

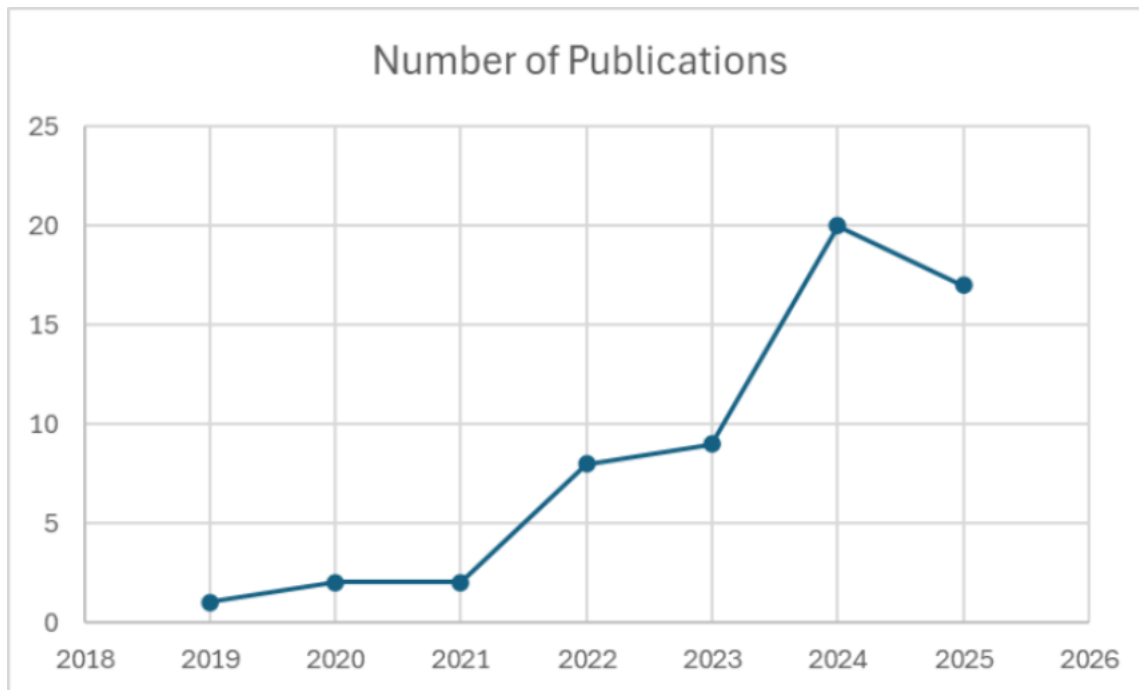


Figure 7: Annual Scientific Publications.

The chart in **Figure 7** highlights a marked increase in publications from 2022 onward, with 2024 showing the largest rise and reaching a peak that continues into 2025. The slight decline observed in 2025 compared to 2024 is likely due to the fact that the year was not yet complete at the time of data extraction. This upward trend reflects considerable academic attention toward Industry 5.0. This interest lays the groundwork for addressing one of its most direct consequences: the need to update engineering education and skill development. Research therefore becomes the key instrument to inform the development of curricula and competency frameworks that prepare the workforce for the challenges of a human-centric and technologically advanced industry.

4.1.2. Key Publication Sources

Among the papers analyzed for this study, the journals that appeared most frequently as publication sources are reported in **Table 1**.

Table 1: Key Publication Sources

Sources	Articles
IEEE Global Engineering Education Conference (EDUCON)	6
IFAC-PapersOnLine	4
Procedia Computer Science	5

Several authors and journals contribute to the growing body of research on Industry 5.0 and its implications for engineering education and skill development. This highlights the overall commitment and diversity of sources where emerging ideas on human-centric manufacturing, curriculum adaptation, and skill development are being shared.

4.2. Content Analysis

The results of the content analysis show that the transition toward Industry 5.0 represents a significant paradigm shift compared to the pillars of Industry 4.0. Previously, the main objective was the continuous search for efficiency, automation, and digitization, sometimes completely replacing the role of workers. This was possible through the integration of technologies like Artificial Intelligence (AI), the Internet of Things (IoT), Big Data analytics, robotics, and Cyber-Physical Systems (CPS).

With the I5.0 paradigm, however, technology does not seek to replace the human role but rather to enhance it. As stated by the European Commission, I5.0 combines technology, research, and innovation to guide this transition toward a model defined by three fundamental pillars: **sustainability, resilience, and human-centricity**.

This new human-centric approach is reshaping workforce requirements, demanding the integration of technical knowledge and transversal skills. Research highlights an urgent need for continuous education and skills development to adapt to these technological advances and the resulting changes in the labor market.

However, a significant "skills gap" threatens this transition. Several factors contribute to this gap:

- **Rapid Obsolescence:** The fast acceleration of technical revolutions and a Volatile, Uncertain, Complex, and Ambiguous (VUCA) global environment mean that educational content quickly becomes outdated [42] [7].
- **Industry Misalignment:** There is a significant lack of alignment between the curricula offered by higher education and the actual requirements of the industry [11] [20] [31].
- **Impact of AI:** The integration of AI is automating tasks, leading to job displacement risks and a fundamental re-evaluation of required skills [19] [34].
- **The Scale of the Challenge:** It is estimated that 40% of core skills will change within five years, and 50% of all employees will require retraining [34].

To mitigate these risks and ensure the workforce can effectively navigate this shift, a focus on substantial reskilling, upskilling, and lifelong learning is required.

4.2.1. First step: Industry 5.0 Skills and Framework cited in papers

To address this challenge, the following phase of the content analysis focused on identifying the specific skills and competencies necessary for the industry 5.0 paradigm. **Table 2** lists the skills explicitly mentioned within the analyzed literature. To provide a clearer structure, the skills have been organized into two main specific groups:

Technical Skills / Hard Skills: These relate to the knowledge and practical abilities linked to specific technologies, tools, and production processes. They are further divided into:

- **Digital and Data:** Skills related to managing, analyzing, and protecting data and using enabling digital technologies.
- **Engineering and Production:** Technical skills related to mechanics, automation, and manufacturing processes.
- **Design and Development:** Abilities to create and develop specific interfaces and systems.

Transversal Skills / Soft Skills: Abilities that are not tied to a single discipline but are crucial for interacting, thinking critically, and adapting in a complex, human-centric work environment. They are broken down into:

- **Cognitive and Methodological:** Abilities related to thinking, reasoning, and work organization.
- **Social and Interpersonal:** Abilities to interact effectively with other people and with machines.
- **Personal and Creative:** Individual attitudes related to proactivity, ethics, and self-management.

Additionally, the table includes an '**Application Focus**' column. This column specifies the business context in which each skill is primarily applied:

- **Design/Development:** This context involves the planning and creation of new products, systems, or processes.
- **Operation/Management:** This context involves the day-to-day execution, maintenance, and oversight of tasks and teams.

Table 1: Industry 5.0 skills cited in papers

Main Category	Sub-cluster	Skill	Application Focus (Design/Development vs. Operation/Management)
Technical Skills	Digital and Data	Data Skills (Analysis, Management, Literacy) Digital skills (ICT, Digital literacy) Cybersecurity Artificial Intelligence (AI) Internet of Things (IoT) Programming / Software development Machine Learning Blockchain Digital Twin literacy Extended reality literacy Ability to use data-driven technologies to design and evaluate complex systems	Both (Fundamental in developing solutions and crucial for operational management and optimization)
	Engineering and Production	Technical Engineering skills Robotics Automation Production / Manufacturing skills Ergonomics	Both (Central to designing plants and systems, but also in daily operations and maintenance)
	Design and Development	Human-Machine Interface (HMI) development	Primarily Design/Development

Transversal Skills	Cognitive and Methodological	Problem Solving / Troubleshooting Critical thinking / Analytical skills Strategic thinking / Digital strategy Decision-making capabilities Change management Time and task management 3Ss (Searching, Sharing, Simulation) Interdisciplinarity Transversal competencies	Both (Necessary for defining strategies and projects, but also for solving operational problems)
	Social and Interpersonal	Collaboration / Teamwork Human-Robot Collaboration Communication Leadership Empathy / Emotional intelligence Language skills	Both (Essential in the collaborative phase of a project as well as in the daily management of the team and interactions)
	Personal and Creative	Creativity / Ingenuity Adaptability / Flexibility Innovation / Innovative thinking Ethics / Ethical responsibility Design / Human-Centered Design Self-awareness / Self-management	Both (Creativity and innovation drive design, while adaptability and ethics are vital in continuous operation)

As we can see from **Table 2**, the move to Industry 5.0 requires a mix of soft and hard skills. While technical knowledge in areas like AI, machine learning, robotics, and data analysis is still essential, the real change is blending this know-how with key soft skills like creative problem-solving, critical thinking, and collaboration. This blend is vital for building a work environment where people and machines can work well together, allowing humans to add the unique value that machines can't.

A perfect example of this is how the word "**collaboration**" is changing. It no longer just means people working together; it now also includes human-machine collaboration. In these new hybrid systems, workers must be able to interact smoothly with "cobots" (collaborative robots) and other smart platforms. This new requirement highlights a key point: this teamwork is only possible if the machines themselves are programmed to be safe and easy-to-use partners. This is precisely why those advanced hard skills are still so necessary.

This **combined skill set** is important in every part of the business, from strategy to daily operations. It is especially critical in the design phase, where professionals must know how to design safe, collaborative layouts and program cobots to work smoothly and safely alongside human teams.

After identifying the necessary skills for Industry 5.0, we then searched the literature to find any **existing classification frameworks**. In this section, we will review the specific frameworks that were identified within the analyzed literature.

4.2.1.1. Framework 1

This framework identifies nine critical skills necessary for the digital workplace, organizing them into three distinct categories:

- **Cognitive & Metacognitive Skills:** These abilities relate to processing language and numbers through logical, intuitive, and creative thinking.
- **Social-Emotional Skills:** These are the abilities that shape thoughts, feelings, and behaviors, enabling individuals to develop themselves, build relationships, and navigate social contexts effectively.
- **Practical Skills:** This category covers the ability to apply specific tools, procedures, and functions.

Table 2: Adapted from "Hey Leaders, It's Time to Train the Workforce: Critical Skills in the Digital Workplace".

Cognitive & Metacognitive Skills	Social-Emotional Skills	Practical Skills
• Entrepreneurial Mindset • Digital Responsible Thinking • Digital Literacy	• Transformative Skills • Communication Skills • Personal Development Skills	• Community Management Skills • Data Analytic Skills • Web Development Skills

4.2.1.2. Framework 2

This framework divides the skills for employment 5.0 into 2 categories:

- **Core skills**, which are considered fundamental for effective knowledge work (complex, non-routine, and knowledge-intensive activity that requires unique human capabilities)
- **Contextual skills**, which are considered necessary for knowledge workers (individuals who use information to develop innovative outcomes) to navigate the modern work environment

Table 3: Adapted from “Employment 5.0 The work of the future and the future of work “.

Core Skills	Contextual Skills
• Technical • Information Management • Communication • Collaboration • Creativity • Critical Thinking • Problem Solving	• Ethical Awareness • Cultural Awareness • Flexibility • Self-direction • Lifelong Learning

4.2.1.3. Framework 3

This framework systematically identifying and categorizing essential competencies into four key areas:

Table 4: Adapted from “Preparing Students for Industry 5.0: Evaluating the Industrial Engineering and Management Education “.

Professional Competences	Core IEM technical knowledge, from STEM application and system design to specialized operational fields like robotics and lean manufacturing.
Digital Competences	Advanced digital literacy, content creation, and the ability to manage ICT resources securely and ethically.
Sustainability Competences	Capacity to evaluate environmental, social, and economic impacts to ensure industrial alignment with global sustainability goals.
Transversal Competences	Refers to essential soft skills (critical thinking, empathy, and communication) that enable effective collaboration and ethical decision-making.

4.2.1.4. Framework 4

This framework systematically identifies and categorizes the essential competencies into five key areas:

Table 5: Adapted from “The Role of Competence Profiles in Industry 5.0-Related Vocational Education and Training: Exemplary Development of a Competence Profile for Industrial Logistics Engineering Education “

Special Competencies	Relate to specific topics or subject areas, covering methodical, theoretical, and practical basic knowledge based on the latest scientific findings.
Transversal Competencies	Competencies necessary and beneficial across several areas of life, encompassing methodological, interpersonal, and intrapersonal skills.
Intrapersonal Competencies	The dispositions of self-assessment, value attitudes, motivation, and recognizing one’s talents, essential for personal responsibility, independence, and professional self-management.
Methodological Competencies	The ability to work in a goal-oriented manner, analyze processes, react flexibly to general conditions, and reflect on work steps.
Interpersonal Competencies	The abilities to understand, cooperate, and act responsibly with other people, including conflict and communication skills, and leadership.

Based on the papers analyzed, it's clear that a wide variety of skills are necessary for Industry 5.0, making a classification framework essential. However, this review found that very few articles actually provide such frameworks. Most papers tend to simply mention relevant competencies or compile them into short lists rather than organizing them structurally.

The few frameworks that were identified in the literature appear designed for academic or **high-level categorization**, not for direct industrial application. They generally focus on describing broad types of skills needed, such as "Cognitive Skills," "Core Skills," or "Transversal Competences"; rather than providing comprehensive, specific lists of the skills themselves. This **highlights a gap** between the academic discussion and the practical need for a detailed framework that companies can use to up-skill and re-skill their workforce. Additionally, there is a **lack of focus** on the management of the personnell at the end of their career within their company, which is another relevant theme of the human-centricity pillar of indutry 5.0.

4.2.2. Second step: Industry 5.0 Skills derived from papers

Completing the explicit extraction of skills and frameworks from the literature, the research progressed to the **inferential derivation phase**, where the papers were critically analyzed to articulate additional competences, utilizing the initially identified skills as a baseline.

This is essential for guaranteeing the framework's completeness and logical coherence. These derived skills bridged specific gaps that would have otherwise been present in the framework and will be presented directly in the final model presented in the following sections.

4.3. Proposed Skills Framework

Building upon the outcomes of the descriptive and qualitative content analyses and leveraging the theoretical foundations of the **GERAM** framework detailed in the previous sections, this chapter details the construction of the final framework. Specifically, all the skills resulting from the inferential derivation process have been systematically grouped and organized to construct a functional **Human-Centric Skills Framework**.

The architecture of this framework is fundamentally based on the intersection of two primary process-oriented dimensions provided by GERA. The GERA Lifecycle constitutes the temporal dimension (**Horizontal Axis**), mapping the dynamic evolution of the system from conception to end-of-life, while the GERA Enterprise Entity Types constitute the structural dimension (**Vertical Axis**), identifying the functional areas where competencies must be applied.

Methodologically, the resulting framework is defined as a **Human-Oriented Partial Enterprise Model (PEM)**. According to the GERAM architecture, a PEM serves as a reusable reference model that captures characteristics common to a specific industry sector rather than a single enterprise. Consequently, this framework does not aim to describe the unique organizational chart of a specific company, but rather provides a generalized "blueprint" for the Industry 5.0 transition, designed to be instantiated and adapted by individual manufacturing organizations according to their specific needs.

Within this architecture, the content populating the matrix, specifically the skills, knowledge, and attitudes identified through the literature review, is methodologically classified as **Enterprise Modules (EMOs)**. In the GERA context, EMOs represent the implementable building blocks of the enterprise. In this framework, human competencies are treated as the essential "Human Resource modules" required to build the future system. By mapping these EMOs within the coordinates of the PEM, the framework ensures that every competency is contextually located, clarifying not only

what skill is needed, but when it is required during the lifecycle and where it creates value within the organizational structure.

4.3.1. Overview of the Skills Framework

Having established the theoretical foundations of the Human-Oriented Partial Enterprise Model (PEM) and its building blocks (EMOs), this section outlines how the **final skills framework** is structured and presented.

Before detailing its specific architecture and contents, a fundamental premise regarding the **nature of the results** is necessary. The framework maintains a strict **Focus on Human-Centricity**. The competencies populating the matrix represent the cognitive, behavioural, technical, and ethical skills required of the workforce. While the framework structurally references technological areas (such as infrastructure or production systems), the attributes described refer exclusively to the human capability to interact with, design, or manage these systems, distinctly separating them from the technical specifications of the machinery or software itself.

To ensure clarity, usability, and a logical progression of concepts, the presentation of the framework follows a hierarchical approach, moving from the definition of its structural elements to a granular description of the competencies:

1. **Axis Description:** First, the specific dimensions, adapted from the GERAM framework, are presented. This section defines the horizontal axis (the Lifecycle Phases) and the vertical axis (the Organizational Entities), establishing the coordinates of the framework.
2. **Global Quantitative Overview:** Following the definition of the axes, a preliminary summary table is provided. This illustrates the total number and distribution of skills mapped across each intersection of the matrix, offering an immediate visual representation of the competency density across the entire system.
3. **Detailed Analysis by Entity:** Finally, the qualitative results are explored in depth, organized by the individual Organizational Entities that constitute the vertical axis. For each specific area, the findings are presented using a dual format to facilitate both high-level understanding and granular analysis:
 - **Core Concepts Table:** An executive summary highlighting the dominant themes and "Core Concepts" required for each lifecycle phase, providing an immediate overview of the entity's role.
 - **Comprehensive Competency List:** A detailed breakdown listing the specific actionable skills and knowledge units, categorized by phase, constituting the granular operational content of the Human-Oriented PEM.

4.3.2. Axis Description

4.3.2.1. The Horizontal Axis: Lifecycle Macro-Phases

The Horizontal Axis of the competency matrix represents the **Time** dimension. It is derived directly from the GERA lifecycle concept, which describes the history of an enterprise entity from its inception to its decommissioning. However, to create a functional framework focused on human competencies rather than granular engineering steps, the original seven phases of the standard have been aggregated into four logical **Macro-Phases**.

This aggregation aligns with the systematic approach of Industry 5.0, grouping activities that require similar competency clusters. The four macro-phases are defined as follows:

1. Concept & Design

- **GERA Source Phases:** *Identification, Concept, Requirements, Design.*
- **Definition:** This phase represents the genesis of the system. It encompasses the translation of high-level strategic goals and human-centric needs into detailed functional specifications and system architectures.
- **Competency Focus:** In this stage, competencies are not operational but analytical and creative. The focus is on "**Human-Centricity by Design**": designing organizational, physical, and digital solutions where technical performance is structurally integrated with operator well-being and ethical constraints from the very outset.

2. Implementation

- **GERA Source Phase:** *Implementation.*
- **Definition:** This phase focuses on the concrete realization, installation, and **human-centric configuration** of the system.
- **Competency Focus:** This stage requires technical and pedagogical competencies. It entails not only the physical deployment of assets but also their **active calibration** to operator biometrics and cognitive needs. Furthermore, it involves the **empowerment** of the workforce through practical training and validation loops to ensure smooth adoption and safety compliance.

3. Operation & Management

- **GERA Source Phase:** *Operation.*

- **Definition:** This phase encompasses the daily execution and **dynamic optimization** of processes. It is the longest phase of the lifecycle, where the system must continuously **adapt** to the workforce's evolving condition.
- **Competency Focus:** The competencies here are dynamic and relational. The focus is on maintaining a **sybiotic feedback loop**, monitoring real-time physical and psychological states to proactively adjust operational parameters. It involves actively managing ethical compliance, skill evolution, and the long-term sustainability of the human-machine collaboration.

4. End-of -Life

- **GERA Source Phase:** *Decommissioning*.
- **Definition:** This final phase manages the **ethical transition and professional continuity** of the workforce when a system or technology reaches the end of its utility.
- **Competency Focus:** Unlike the technical dismantling of machinery, the human focus here is on **long-term employability**. Competencies are required to manage proactive reskilling and guided redeployment strategies, actively mitigating the **psychological impact** of restructuring through transparent social dialogue and support.

4.3.2.2. The Vertical Axis: Organizational Entities

The Vertical Axis of the competency matrix represents the **Structural** dimension. It is derived from the GERA concept of **Enterprise Entity Types**, which classifies the internal elements of an organization based on their recursive role within the system (e.g., management, operation, product).

To strictly align the framework with the requirements of the Industry 5.0 transition, the generic entity types defined by the standard have been instantiated into four specific **Functional Areas**. These areas represent the organizational layers where human competencies must be applied to ensure a successful human-centric transformation.

The four entities are defined as follows:

1. Strategic Management (GERA Type 1)

- **GERA Source Entity:** *Strategic Enterprise Management Entity (Type 1)*.
- **Definition:** This entity is responsible for defining the enterprise's vision, strategy, governance, and high-level goals. It ensures the strategic alignment between technological adoption, human-centric values, and workforce evolution.

- **Competency Focus:** The competencies mapped here are required to design transition roadmaps, orchestrate workforce evolution (reskilling/upskilling), and guarantee long-term workforce sustainability and psychological well-being during the transformation.

2. Production System (GERA Type 3)

- **GERA Source Entity:** *Enterprise Entity (Type 3) – Operational Aspect.*
- **Definition:** This entity represents the execution of physical production operations, encompassing both individual workstations and the integrated system level. Its goal is to ensure a symbiotic collaboration between human operators and intelligent assets, balancing operational efficiency with human-centricity.
- **Competency Focus:** The competencies here focus on engineering **adaptive workstations** optimized for physical and cognitive ergonomics (e.g., intuitive HMI, safety protocols) and managing **production flows** that integrate human factors (e.g., fatigue, age-inclusive models) into dynamic scheduling.

3. I5.0 Infrastructure System (GERA Type 3)

- **GERA Source Entity:** *Enterprise Entity (Type 3) – Technology & Support Aspect.*
- **Definition:** This entity is responsible for the technological backbone (IT/OT) that enables the symbiosis between physical assets and human operators. It moves beyond simple connectivity to provide a **bio-responsive and cognitive-aware environment**, where systems adapt in real-time to the worker's state.
- **Competency Focus:** The competencies in this area relate to the design of **Human Digital Twins** that model operator characteristics and the deployment of **bio-responsive architectures** (e.g., adaptive Cobots, wearables) capable of reacting to fatigue or stress.

4. Data & AI Service (GERA Type 4)

- **GERA Source Entity:** *Product Entity (Type 4).*
- **Definition:** This entity manages the lifecycle of Data and Artificial Intelligence assets, treating them as internal products that function as **transparent, ethical co-pilots** for the workforce. It shifts the focus from pure automation to **human augmentation**, prioritizing explainability, fairness, and privacy protection.
- **Competency Focus:** The competencies here are required to develop **human-centric AI solutions** (designed to augment rather than replace), implement **bias**

mitigation protocols to ensure equitable outcomes, and manage secure data architectures that prevent surveillance abuse.

4.3.3. Global Quantitative Overview

Table 6: Quantitative distribution of mapped skills

Dimensione 1: Entità	Dimensione 2: Fasi del Ciclo di Vita			
TOT: 105	1. Concept & Requirements	2. Design & Implementation	3. Operation & Management	4. End-of-Life
1. Strategic Management (28)	11	4	5	9
2. Production System (33)	13	9	9	2
3. I5.0 Infrastructure System (28)	12	5	10	1
4. Data & AI Service (16)	9	3	4	0

4.3.4. Detailed Analysis by Entity

4.3.4.1. Strategic management

The entity within the company which is responsible for defining the enterprise's vision, strategy, governance, and high-level goals, ensuring the alignment between technological adoption, human-centric values, and workforce evolution.

Table 7: Core concepts for Strategic Management.

Concept & Design	Implementation	Operations & Management	End-of-Life
Ability to design Industry 5.0 transition roadmaps and ethical policies that align technology adoption with diverse internal	Ability to execute transformation roadmaps that synchronize technological adoption	Capability to balance conflicting goals, such as cost-effectiveness versus human-centricity, and align individual worker	Capability to manage workforce reductions and restructuring with radical transparency, equity, and verifiable

stakeholder perspectives and the protection of vulnerable workers. Capability to design new hybrid roles and learning pathways based on predictive skill gap analysis and the distinction between automatable and human-essential tasks. Ability to evaluate infrastructure and retrofitting projects by integrating metrics for worker well-being, safety, and human-machine interaction rather than purely financial goals. Capability to strategize for long-term workforce sustainability by proactively identifying and mitigating negative impacts of technology.	with necessary personnel training. Capability to introduce digital changes and new organizational roles in a way that prevents workforce stress and protects job identity	needs with organizational objectives. Ability to utilize sentiment analysis and semantic technologies to monitor workforce morale and identify tacit employee skills for optimal role assignment. Expertise in modeling skill acquisition and decay to manage learning curves and commission proactive training interventions.	adherence to ethical standards. Ability to maintain psychological safety and mitigate distress or identity crises caused by job loss and organizational changes. Capability to forecast skill obsolescence and leverage partnerships or AI matching to transition at-risk employees into new internal or external roles.
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Concept & Design

- Ability to strategically navigating the lack of standards and policies for emerging human-centric technologies.
- Ability to understand and integrate the viewpoints of various internal stakeholders into decision-making.
- Knowing how to evaluate infrastructure investments while also integrating metrics for worker well-being, safety and job satisfaction.
- Ability to design new specialized internal roles necessary for the new technologies & human-centric principles.
- Strategic capability to map workforce needs and design learning pathways (reskilling/upskilling) that transition employees from traditional tasks to hybrid human-technology roles.

- Expertise in retrofitting existing brownfield facilities to avoid total replacement and designing specifications for improved human-machine interaction.
- Ability to create Strategic Industry 5.0 Transition Roadmaps that combine technology adoption and workforce training.
- Ability to identify which human jobs must be preserved and which should be augmented by technology.
- Expertise in utilizing predictive technologies like Cognitive Digital Twins to identify current internal skill gaps.
- Capability to identify and reduce the negative impact of technology on the workforce (e.g. unemployment) to ensure the long-term workforce sustainability.
- Capability to define ethical company policies to protect vulnerable workers (elderly, neurodivergent individuals...) from job disruption and abilitate them for new hybrid I5.0 roles.

Implementation

- Ability to implement the transformational roadmap which requires both technological adoption and proper personell training.
- Capability to carefully implement digital technological changes to prevent collective workforce stress and confusion.
- Capability to introduce new roles inside the company structure, withouth causing Job Identity Threat to the current personell.

Operations & Management

- Capability to understand and balance often conflicting objective functions, such as cost-effectiveness versus human-centricity.
- Ability to use sentiment analysis tools to gauge collective workforce morale and anxiety levels during changes, enabling proactive human support interventions.
- Ability to utilize semantic technologies and NLP to identify and value “tacit” employee skills emerging from daily interactions, optimizing role assignment and knowledge transfer to maximize individual human potential.
- Ability to manage individual worker needs (e.g. flexible scheduling, ethical offboarding) while still being aligned with the organizational goals, ensuring sustainable labor.
- Expertise in utilizing modified learning curves to dynamically model both skill acquisition and "decay" and commission proactive training interventions, to avoid quality loss and job disruption.

End-of-Life

- Ability to recognizing and mitigating signs of psychological distress caused by organizational change and job loss.
- Ability to empathically communicate difficult news (layoffs, closures) with radical transparency and emotional intelligence.
- Ability to include in the planning of workforce reductions equity, long-term employability, and proactive social dialogue.
- Ability to maintain psychological safety during restructuring, ensuring employees can safely voice their concerns.
- Capability to forecast workforce skill obsolescence before the role becomes redundant.
- Capability to establish and manage partnerships with external training entities and universities to create direct "hiring corridors" for exiting employees.
- Ability to use ML insights and talent matching algorithms to map skills of at-risk employees against open roles, prioritizing internal redeployment over layoffs.
- Ability to use monitoring systems to ensure that restructuring or dismissal processes adhere to ethical standards, preventing discriminatory biases and ensuring verifiable fairness in decisions.
- Preventing identity crises during restructuring by helping employees redefine their roles alongside emerging technologies.
- Ability to cultivate deep expertise that expands into adjacent fields, enabling rapid adaptation to industrial changes.

4.3.4.2. Production

The entity responsible for executing physical production operations, encompassing both individual workstations and the integrated system level. It ensures the symbiotic collaboration between human operators and intelligent assets, balancing operational efficiency with human-centricity.

4.3.4.3. Production – workstation level

Table 8. Core concepts for Production - workstation level.

Concept & Design	Implementation	Operations & Management	End-of-Life
Ability to design interfaces and select machinery that prioritize intuitive interaction and filter non-essential data to minimize operator mental strain. Capability to design workstation geometries, safety protocols, and assistive technologies to minimize physical strain and eliminate hazards. Ability to design human-machine interaction sequences that offload heavy or repetitive physical burdens to automation systems. Capability to design workstations that facilitate peer support and team cohesion, avoiding operator isolation.	Ability to test and validate workstation setups, ranging from digital dashboards to physical workflows, in simulated or real-time environments to ensure they minimize cognitive overload and physical strain. Capability to physically fit and calibrate assistive technologies, to individual worker biometrics during deployment.	Capability to regulate workstation pace based on real-time wearable data to proactively prevent safety incidents. Capability to operate heavy machinery or robots in hazardous zones remotely using low-latency interfaces to ensure operator safety. Ability to continuously refine workstation ergonomics and design by integrating human feedback and real-time validation to improve interaction.	

Concept & Design

- Ability to design the physical geometry and safety logic of individual collaborative cells to minimize physical strain (e.g., reaching distances, posture).
- Ability to configure adaptive sensor systems and safety protocols to eliminate hazards in collaborative environments.
- Ability to design the step-by-step interaction sequence between operator and machine, strategically allocating heavy and repetitive physical burdens to the automation system.
- Ability to evaluate and select machinery based on its "intrinsic cognitive load," prioritizing assets with intuitive interfaces and simplified control logic to minimize the mental effort and learning curve required for the operator.
- Ability to apply cognitive psychology principles to centralized process dashboards filtering non-essential data to prevent information overload and reduce decision fatigue.
- Ability to analyze workforce load-handling tasks and select the appropriate exoskeleton models based on biomechanical compatibility, prioritizing long-term musculoskeletal health.
- Capability to engineer workstation layouts that structurally facilitate peer-to-peer mentoring and mutual support.

Implementation

- Ability to test and refine ergonomics in real-time to ensure the new setup actively improves human-machine interaction before full operational use.
- Ability to implement validation loops to analyze workstations' workflows and confirm the minimization of operator physical strain.
- Ability to test interfaces (dashboards) in a simulated environment to validate that they display only context-relevant information and prevent cognitive overload before deployment on the shop floor.
- Ability to physically fit and calibrate exoskeletons to individual worker biometrics during deployment.

Operations & Management

- Capability to include human feedback about the workstation ergonomic's desing to continuously improve it
- Capability to regulate workstation pace based on real-time wearable data to proactively prevent safety incidents.
- Capability to operate heavy machinery or robots in hazardous zones remotely using low-latency interfaces.

4.3.4.4. Production – system level

Table 9: Core concepts for Production - system level.

Concept & Design	Implementation	Operations & Management	End-of-Life
Ability to integrate human factors such as well-being, skills, and fatigue directly into production scheduling algorithms. Capability to engineer production flows and asset arrangements that minimize psychological pressure and frustration through dynamic task allocation and intuitive standardization.	Capability to validate task allocation and scheduling algorithms via simulation to ensure they align with worker fatigue levels and minimize stress before deployment. Capability to lead practical workshops that instruct operators on digital tools, ensuring confidence and safe adoption on the production line.	Competence in utilizing real-time health data and Digital Twin simulations to dynamically rotate tasks and identify psychological stressors, ensuring long-term well-being. Capability to improve AI accuracy through active feedback loops and construct semantic networks that optimize resource allocation based on human skills.	Capability to design adaptive work models that accommodate diverse physical needs, ensuring the retention of senior expertise and preventing workforce exclusion. Capability to transform individual problem-solving procedures into permanent corporate assets via digital twin interfaces.

Concept & Design

- Ability to integrate human factors (e.g. well-being, skills, fatigue) directly into scheduling algorithms.
- Capability to engineer production flow, integrating buffers and dynamic task allocation, preventing bottleneck, therefore minimizing workforce psychological pressure.
- Capability to engineer logical asset arrangements that eliminate search friction through intuitive standardization, preventing loss and minimizing operator frustration.

- Capability to design communication channels (digital platform) that instantly route issues to the correct owner, eliminating the stress of searching for support and ensuring clear accountability.
- Capability to engineer production layouts that enable visual contact and safe interaction, preventing operator isolation and fostering team connection.
- Capability to design inclusive feedback loops that allow operators to report insights and process improvements directly from the line, ensuring their voice is heard and valued in system optimization.

Implementation

- Capability to test the impact of shift patterns and task allocation on worker fatigue and stress, optimizing scheduling algorithms before full implementation.
- Capability to validate and calibrate dynamic task allocation via simulation, ensuring alignment with worker fatigue and skill levels, before production deployment.
- Capability to lead practical technology workshop to instruct operators on the practical application of digital tool, ensuring confidence and safe adoption before full adoption on the production line.
- Capability to implement the communication platform by instructing staff on its usage and demonstrating its value in reducing daily friction, ensuring full adoption and clear role understanding.
- Capability to implement the feedback channel by instructing operators on its usage and demonstrating how their input directly resolves daily friction, ensuring they feel heard and empowered.

Operations & Management

- Competence in interpreting aggregated data from the "Healthy Operator" infrastructure to dynamically rotate workers between heavy and light tasks during the shift.
- Competence in using the Digital Twin interface to simulate "what-if" scenarios on the production line in real-time regarding operators' physical conditions.
- Capability to actively curate communication flows by filtering noise, purging obsolete updates, and tracking resolution status, ensuring the stream remains relevant and clutter-free for all users.

- Ability to construct semantic networks that link operator skills and process requirements to facilitate resource allocation and enable complex querying of human-machine collaboration data.
- Capability to use monitoring datas to identify phsycological factor stressors, implementing intervention to safeguard long term workforce mental well-being.
- Capability to actively curate the feedback channel through periodic reviews, validating valuable insights for implementation while systematically archiving resolved or non-applicable entries to maintain system clarity.

End-of-Life

- Capability to digitize personal expertise problem-solving procedures, via digital twin interfaces, transforming individual knowledge into a permanent corporate asset.
- Capability to engineer age-inclusive work models and adaptive roles that accommodate different physical needs, ensuring the retention of senior expertise and preventing workforce exclusion.

4.3.4.5. I5.0 Infrastructure System

The entity responsible for the technological backbone (IT/OT) that enables the symbiosis between physical assets and human operators. Its core focus is creating environments where technology adjusts to the human rather than the reverse.

Table 10: Core concepts for Infrastructure System.

Concept & Design	Implementation	Operations & Management	End-of-Life
Ability to engineer bio-responsive Digital Twins that integrate human physical and cognitive parameters for ergonomics and trigger automatic safety protocols.	Capability to calibrate Digital Twins with individual operator physiological baselines and real-time sensor connections while ensuring cyber-physical security.	Capability to use real-time health data and feedback to dynamically adapt Digital Twins and cobot behavior to the worker's current condition.	Capability to ensure the permanent and secure deletion of sensitive operator biometric and behavioral data when decommissioning Digital Twins and other systems.

Capability to design cobot systems that dynamically adjust cycle times, hand-over positions, and safety zones based on real-time operator fatigue and proximity. Ability to select accessible XR hardware and design interface layouts that prevent cognitive overload and ensure physical safety within the workspace. Capability to select wearable technologies that accurately monitor physiological metrics without obstructing worker movement.	Ability to deploy and validate interactive technologies (AR, Cobots, Wearables) by translating operator feedback into technical adjustments to ensure comfort and usability.	Ability to monitor physiological data and usage patterns to identify fatigue trends and trigger interventions that prevent burnout. Capability to manage the psychological aspects of human-machine interaction, ensuring appropriate trust levels, cognitive engagement, and situational awareness. Ability to maintain device hygiene and real-time data synchronization to ensure safe and accurate operator actions.	
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Concept & Design

- **Digital Twin – CPS**
 - Capability to create and calibrate Human Digital Twins that model the operator physical and cognitive characteristics to validate ergonomic and task feasibility before physical prototyping.
 - Capability to design Digital Twin data structures that integrate human cognitive variables as core parameters, enabling the system to process operator mental states alongside machine data.
 - Capability to engineer bio-responsive safety protocols within the Digital Twin that automatically trigger protective machine reactions when operator health anomalies are detected.
 - Capability to configure cyber-fail-safe parameters that trigger automatic physical stops during network attacks to guarantee operator safety.

- **IoT & Sensors**
 - Capability to evaluate and select non-invasive wearables that monitor physiological metrics without obstructing movement.
- **Cobots**
 - Capability to evaluate cobot specifications, prioritizing intuitive interfaces and sensory feedback, to minimize cognitive load and maximize safety.
 - Capability to configure ergonomic parameters into robot hand-over positions that ensure optimal exchange heights, to prevent operator bending and strain.
 - Capability to design control logic that dynamically modulates cobot cycle times to synchronize with the operator's physiological state and fatigue levels.
- **Augmented Reality (AR) & XR**
 - Capability to evaluate and select AR/XR devices based on their adaptability to diverse anthropometric profiles (e.g., adjustable IPD, prescription lens compatibility).
 - Capability to design the visual interfaces that display only essential task-specific data, preventing information overload and operator fatigue.
 - Capability to design workstation lighting and background contrast to ensure optimal digital text legibility on AR tool and prevent operator eye strain.
 - Capability to design safe AR walking paths by designating permitted and prohibited zones to ensure full situational awareness.

Implementation

- **Digital Twin – CPS**
 - Capability to capture and calibrate unique physiological baselines for each operator within the Digital Twin to accurately distinguish between healthy exertion and personal distress signals.
 - Capability to implement OT-specific cybersecurity protocols to prevent cyber-physical incidents and ensure workforce safety.
- **IoT & Sensors**
 - Capability to deploy wearable sensors to monitor real-time operator health, physical movement, and fatigue.
- **Cobots**
 - Capability to translate operator feedback regarding proximity anxiety and stress into technical adjustments that ensure the cobot adapts to the human's comfort zone.

- **Augmented Reality (AR) & XR**
 - Capability to validate AR layout and content usability through operator feedback, ensuring the experience reduces cognitive effort and aligns with worker needs.

Operations & Management

- **Digital Twin – CPS**
 - Capability to dynamically update Human Digital Twins datas to reflect physiological / physical changes over time, ensuring safety models remain accurate.
 - Capability to integrate real-time operator feedback and health data into the Digital Twin's decision-making to dynamically adapt system settings to the worker's current condition.
 - Capability to analyze aggregated Digital Twin data to identify cumulative mental fatigue trends and proactively intervene to prevent operator burnout.
- **IoT & Sensors**
 - Capability to monitor wearable data streams to identify worker fatigue trends and maintain device calibration.
- **Cobots**
 - Ability to analyze operator-cobot interaction patterns to detect overly confident behavior and implement active strategies to maintain operators' cognitive engagement.
 - Capability to monitor operator trust levels towards the cobot and implement post-error transparency protocols to restore psychological safety and prevent technology misuse.
- **Augmented Reality (AR) & XR**
 - Capability to continuously monitor and validate the synchronization between the headset datas and production status to ensure operators act on valid, up-to-date data.
 - Capability to monitor physiological signals and headset usage to detect fatigue, scheduling mandatory screen-free breaks to prevent burnout and protect operator health.
 - Capability to analyze usage patterns to detect when operators focus too much on the screen and trigger active alerts to restore focus to the physical environment.
 - Capability to manage hygiene and maintenance protocols for shared wearable devices, ensuring sanitization to prevent health risks and maintain operator safety.

End-of-Life

- **Digital Twin – CPS**
 - Capability to ensure the permanent and secure deletion of sensitive operator biometric and behavioral data upon Digital Twin decommissioning.

4.3.4.5.1. Data & AI Service

The entity responsible for the lifecycle management of data and Artificial Intelligence assets, ensuring they function as co-pilots for the workforce, prioritizing explainability, fairness, and the strict protection of operator privacy.

Table 11: Core concepts for Data & AI Service

Concept & Design	Implementation	Operations & Management	End-of-Life
Capability to develop transparent, interpretable AI solutions designed to augment human skills rather than replace them, facilitating seamless collaboration. Ability to design AI pipelines with built-in bias mitigation techniques and anomaly reporting channels to ensure equitable performance across demographics. Capability to design strict protocols and access controls to prevent data leakage and ensure the responsible, private	Ability to implement feedback channels and override mechanisms that prioritize human judgment, ensuring AI functions as a co-pilot and can be recalibrated or halted by operators. Capability to deploy robust security measures that strictly isolate sensitive operator data from developers and unauthorized systems.	Capability to audit AI models and datasets to detect and eliminate biases (e.g., age, gender, race), ensuring equitable outcomes in critical decisions. Ability to derive health and well-being models by analyzing data collected from wearable technology. Capability to enforce strict privacy standards and prevent surveillance abuse through continuous operational audits. Ability to ensure the accuracy of worker skill profiles within	

use of operator personal data. Ability to design data models that integrate social vulnerability metrics for ethical restructuring and graph-based skill networks for internal resource mapping.		knowledge graphs via continuous data ingestion.	
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Concept & Design

- **Artificial Intelligence**

- Ability to develop AI-enabled solutions in manufacturing that are designed around human skills, aiming to augment rather than replace workers.
- Ability to develop interfaces and interaction methods for AI systems that facilitate seamless collaboration between humans and machines.
- Proficiency in integrating interpretability libraries to design AI systems that are transparent and interpretable, so that the decision logic is clear to human users.
- Developing AI training pipelines that integrate specific bias mitigation techniques to ensure equitable performance across demographics.
- Ability to design protocols to prevent sensitive data leakage to external APIs and enforcing least-privileged access.
- Designing structured communication channels that enable production-line operators to report system anomalies and inconsistencies of AI performance.

- **Data**

- Ability to design technical measures and protocols to ensure privacy, security, and responsible use of operators' personal data.
- Ability to design data models for workforce reduction that weigh tenure, social impact, and vulnerability alongside financial metrics to ensure equitable restructuring.
- Ability to design relational and graph-ready data models for employee skills to enable the implementation of internal semantic networks.

Implementation

- **Artificial Intelligence**
 - Ability to implement “override mechanisms” and human-validation stages in automated workflows to ensure the AI acts as a co-pilot rather than a replacement.
 - Ability to implement feedback channels that empower production-line operators to report system anomalies and data inaccuracies, ensuring human judgment is prioritized in guiding AI recalibration.
- **Data**
 - Ability to deploy security measures to ensure sensitive operator data is never exposed to developers or unauthorized systems.

Operations & Management

- **Artificial Intelligence**
 - Capability to audit AI models and data sets used in restructuring decisions to detect and eliminate biases (e.g., age, gender, race) ensuring equitable outcomes.
- **Data**
 - Ability to gather & analyze data from wearable technology to derive models for workers’ health and well-being.
 - Ability to conduct audits to ensure that data privacy and ethical standards are strictly maintained during daily operations, preventing surveillance abuse.
 - Ability to manage continuous data ingestion pipelines to ensure real-time accuracy of worker skill profiles within the knowledge graph.

5 Discussion & Conclusions

The transition from Industry 4.0 to Industry 5.0 represents far more than a mere technological upgrade; it marks a fundamental philosophical shift in how value is created. While the Fourth Industrial Revolution focused on efficiency, interconnectivity, and automation, the Fifth introduces a critical counterweight: the **return of the human being to the center of the production process**. Nevertheless, a critical challenge remains moving beyond the theoretical definition of human-centricity to establish the tangible workforce requirements and actionable organizational strategies needed for its execution.

The starting point of this thesis was a clear gap identified in the scientific literature: while the "what" of Industry 5.0 (resilience, sustainability, human-centricity) was well-defined, the "how", specifically regarding the skills and competencies required to sustain this paradigm, remained fragmented and abstract.

Through a Systematic Literature Review and subsequent content analysis, this research has responded to the three initial research questions. Starting from RQ1, it was found that multiple papers describe competency frameworks and list the skills needed for human-centricity in Industry 5.0. However, as shown in the literature review, they often discuss them superficially or within very high-level and abstract frameworks. Following this, RQ2 was answered by extracting skills that were explicitly stated within the papers and the ones that were logically derived. This led to answering the RQ3 by creating a framework that intersects four key organizational Entities: Strategic Management, Production System, Infrastructure, and Data & AI; with the four phases of the Technology Lifecycle. The results demonstrate that the skills required for Industry 5.0 are not static; they evolve as technology matures. It was found that:

- **In the Concept & Design phase**, competencies represent a critical fusion of technical proficiency and ethical foresight. The research highlights that human-centricity must be architected into the system from the start, requiring the ability to integrate workforce well-being metrics and ethical constraints directly into functional specifications and data architectures.
- **In the Implementation phase**, the focus shifts to the concrete deployment and calibration of technology. Critical skills involve technical expertise for system configuration alongside the capability to establish feedback channels, ensuring the workforce can actively guide the system's calibration and alignment with operator needs.

- **In the Operations & Management phase**, the required skills centre on continuous auditing and dynamic interaction. The framework highlights the need for concrete capabilities to manage real-time data flows and maintain ethical standards during daily operations, ensuring the technology continues to support worker health and autonomy rather than simply tracking productivity.
- In the **End-of-Life** phase, it was identified that it requires specific competencies to drive upskilling and reskilling initiatives that allow the workforce to adapt rather than be replaced, as well as to manage workforce displacement, ethical offboarding, and the psychological impact of technological obsolescence and restructuring.

5.1. Contribution to State-of-the-Art Literature

Grounded in a systematic analysis of the current state of the art, this research aims not only to consolidate existing knowledge but to **actively enrich it** through the proposal of a new, structured framework. The primary contribution of this work is the expansion of the literature regarding the Human-Centric pillar of Industry 5.0, shifting the focus from abstract concepts to the **tangible skills** required to both execute the transition to a human-centric environment and effectively maintain it over time.

Furthermore, the developed framework addresses a significant gap in the current academic landscape: the scarcity of practical, granular tools for industry application. Unlike the few existing frameworks, which often remain at a high theoretical level, this research offers a **specific, operationally oriented guide** designed for real-world applicability.

Another innovation of this framework is that it does not limit itself to implementation; it includes the **entire lifespan** of industrial technology, from the earliest stages of conception and design through to operational usage and management. Crucially, it introduces a **novel perspective on the "End-of-Life" phase**. While existing literature typically analyzes this phase through the Sustainability pillar (focusing on material disposal and recycling), this research reinterprets it through a strictly "Human-Centric" lens. The primary focus is placed on the strategic management of workforce displacement to ensure **long-term employability**. This is operationalized through specific framework competencies that enable the proactive identification of skill gaps and the anticipation of new technological requirements. By utilizing these insights to drive targeted **upskilling and reskilling initiatives**, the framework ensures that the decommissioning of legacy systems serves as a catalyst for professional evolution rather than workforce obsolescence. Additionally, the framework addresses the ethical necessity of ensuring that **sensitive operator data** is rigorously protected when obsolete machinery is finally decommissioned, as well as guaranteeing equity in

restructuring decisions and maintaining full transparency throughout the workforce transition process.

5.2. Practical Contribution

The framework emerging from this research extends beyond theoretical novelty to offer substantial practical utility for two distinct but interconnected stakeholders: industrial organizations and educational institutions.

For the **corporate sector**, the framework serves as a versatile strategic instrument for **Human Resource Management** and **Strategic Workforce Planning**. Companies can leverage these findings to modernize professional profiles descriptions to define roles that truly reflect the requirements of Industry 5.0. Furthermore, the framework acts as a **diagnostic tool**, enabling managers to conduct comprehensive assessments of their current workforce. By mapping existing employee capabilities against the proposed framework, organizations can identify critical skill gaps and evaluate their overall readiness for the human-centric transition.

Simultaneously, for universities and training entities, the framework provides a blueprint for curriculum alignment. Academic institutions can utilize these insights to update and redesign educational modules, ensuring they remain relevant to market needs. This involves not only the integration of specific technical competencies but, crucially, the inclusion of the soft skills and human-centric perspectives identified as essential in this study. By doing so, educators can better prepare the next generation of engineers to navigate and lead within the complex, human-focused environment of Industry 5.0.

5.3. Limitations

While this study provides a robust theoretical contribution to the paradigm of Industry 5.0, it is strictly necessary to acknowledge certain **methodological limitations** that frame the scope of our findings.

First, regarding the literature selection, the research was restricted exclusively to papers published in the English language. Consequently, relevant insights, frameworks, or case studies published in other languages may have been excluded, potentially introducing a **linguistic bias** that overlooks specific regional or cultural approaches to human-centricity.

Secondly, the construction of the framework itself carries an **inherent degree of subjectivity**: in complex industrial environments, competencies often overlap across boundaries; therefore, the allocation of a specific skill to a single category is a discretionary choice that may be interpreted differently by other researchers or practitioners.

Finally, and perhaps most significantly, the proposed framework remains a **theoretical construct**. While it is grounded in a rigorous analysis of existing literature, it has not yet been subjected to empirical validation through testing within a real-world operational environment.

5.4. Future Developments

Considering the above-mentioned limitations, the most immediate avenue for future work is the **empirical validation** of the framework. This could be achieved by applying the model in the field through pilot projects or longitudinal case studies across various industrial sectors. Such applications would test whether the theoretical allocation of skills holds true in practice and allow for iterative refinement of the framework.

Additionally, this framework provides the architectural basis to develop specific operational tools. Future research could translate these theoretical requirements into **practical diagnostic instruments**, such as automated skill-gap analysis software, allowing companies to measure their workforce readiness quantitatively.

Finally, there is a significant opportunity for educational integration as the framework can be utilized to design **specialized modules and curricula** for universities and professional training entities. By translating the identified skills into learning outcomes, educational institutions can ensure that the next generation of professionals enters the workforce not just with engineering know-how, but with the specific human-centric mindset and soft skills that modern industry actually demands.

5.5. Conclusions

Ultimately, the success of Industry 5.0 will not be determined by the sophistication of the technology, but by the **workforce's ability** to accept, manage, and thrive alongside it. The framework developed in this thesis is a step toward formalizing this readiness, acknowledging that while technology accelerates, the '**human factor**' remains the true variable dictating the speed of adoption and probability of success. As industries move forward, competitive advantage will belong to organizations that view their people not as a cost to be minimized, but as an investment to be maximized; and this thesis hopes to serve as a foundational guide for that necessary evolution.

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7 Appendix A

This appendix **documents the complete set of competencies** explicitly extracted from the analyzed literature. The following table maps each skill directly to its corresponding academic references, providing the raw empirical evidence that grounds the subsequent framework development.

Table 13: Skill mentioned in the articles with references.

Skill	References
Creativity / Creative thinking / Ingenuity	[1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28]
Problem Solving / Troubleshooting	[7, 29, 8, 30, 10, 31, 11, 12, 13, 14, 16, 17, 18, 20, 21, 22, 23, 25, 32, 26, 27, 33, 34]
Collaboration (human) / Teamwork / Human interaction	[35, 36, 2, 3, 37, 6, 7, 29, 8, 38, 39, 10, 31, 11, 13, 16, 20, 21, 23, 32]
Critical thinking / Analytical skills	[36, 2, 37, 6, 7, 29, 8, 10, 31, 13, 15, 17, 20, 21, 23, 24, 25, 34, 28]
Communication (including online/offline and with humans/robots)	[2, 37, 7, 29, 8, 10, 31, 13, 16, 17, 19, 20, 23, 42, 24, 32, 34]
Adaptability / Flexibility / Agility / Versatility / Cognitive flexibility	[1, 4, 5, 7, 38, 30, 10, 31, 15, 17, 19, 20, 26]
Innovation / Innovative thinking / Ethical innovation	[1, 9, 10, 31, 11, 12, 13, 43, 15, 16, 17, 18, 20, 21, 26]
Human-Robot Collaboration / Human-Machine Interaction	[2, 5, 6, 8, 39, 9, 40, 13, 41, 14, 15, 20, 24]
Data Skills (Analysis, Management, Literacy, Science) / Analyze and interpret data	[7, 8, 44, 31, 11, 41, 14, 16, 19, 20, 21, 45, 24, 46, 33]
Ethics / Ethical and social responsibility / Data ethics / Ethical reasoning / Safety and ethics with robots	[37, 6, 40, 10, 43, 16, 17, 19, 21, 23, 46, 28]
Digital skills / ICT / Digital literacy / Digital and technological competence	[36, 7, 38, 40, 10, 31, 11, 12, 19, 21, 25, 26, 28]
Cybersecurity / Data security	[2, 7, 31, 11, 13, 41, 14, 24]
Artificial Intelligence (AI) / AI literacy	[2, 37, 7, 8, 31, 11, 18, 19, 27, 28]
Technical / Engineering skills (including mechanics, electronics, computer science)	[35, 7, 38, 10, 44, 31, 43, 23]
Design / Human-Centered Design	[2, 6, 29, 41, 16, 17, 20, 26]
Leadership	[2, 29, 16, 17, 18, 25, 34]
Empathy / Emotional intelligence	[3, 37, 7, 38, 26]
Internet of Things (IoT)	[2, 8, 31, 20]
Robotics / Technical skills in cobot management, programming, and design	[7, 41, 19, 20, 23]
Programming / Software development	[2, 7, 11, 12]

Automation	[11, 14]
Strategic thinking / Digital strategy	[2, 31]
Ergonomics	[6, 44]
Machine Learning	[2, 8]
Production / Manufacturing skills	[35, 2, 4, 12, 43]
Change management	[10]
Blockchain	[41]
Digital Twin / Digital twin literacy	[20, 27]
Self-awareness / Self-management	[6, 34]
Transversal competencies	[21, 42]
Ability to use data-driven technologies to design and evaluate complex systems	[45]
Interdisciplinarity	[23, 26, 45]
Decision-making capabilities	[42, 33]
3Ss (Searching, Sharing, Simulation)	[46]
Human-Machine Interface (HMI) development	[25]
Extended reality literacy	[27]
Language skills	[34]
Time and task management	[34]

8 Appendix B

In the following pages there's a list of the skills elaborated in the results & findings, associated with the sources they were extracted from.

8.1. Strategic Management

Table 14: Strategic Management skill extracted in the articles with references.

Skill	Reference
Ability to strategically navigate the lack of standards and policies for emerging human-centric technologies.	[42], [9], [47]
Ability to create Strategic Industry 5.0 Transition Roadmaps that combine technology adoption and workforce training. Ability to implement the transformational roadmap which requires both technological adoption and proper personell training.	[12], [50], [31], [47]
Ability to design new specialized internal roles necessary for the new technologies & human-centric principles.	[50], [11], [48], [49]
Capability to identify and reduce the negative impact of technology on the workforce (e.g. unemployment) to ensure the long term workforce sustainability.	[19], [50], [44], [12], [47], [16]
Ability to understand and integrate the viewpoints of various internal stakeholders into decision-making. Ability to manage individual worker needs(e.g. flexible scheduling, ethical offboarding) while still being aligned with the organizational goals, ensuring sustainable labor.	[6], [48], [31], [40]

Skill	Reference
Expertise in retrofitting existing brownfield facilities to avoid total replacement and designing specifications for improved human-machine interaction.	[41], [47], [22]
Knowing how to evaluate infrastructure investments while also integrating metrics for worker well-being, safety and job satisfaction.	[20], [52], [50], [13], [1]
Ability to identify which human jobs must be preserved and which should be augmented by technology.	[48], [19], [27], [2], [44], [28]
Expertise in utilizing predictive technologies like Cognitive Digital Twins to identify current internal skill gaps.	[50], [4], [27], [16]
Strategic capability to map workforce needs and design learning pathways (reskilling/upskilling) that transition employees from traditional tasks to hybrid human-technology roles. Expertise in utilizing modified learning curves to dynamically model both skill acquisition and "decay" and commission proactive training interventions, to avoid quality loss and job disruption.	[44], [12], [11], [38], [16], [5]
Capability to define ethical company policies to protect vulnerable workers (elderly, neurodivergent individuals...) from job disruption and abilitate them for new hybrid I5.0 roles.	[52], [41], [19], [47], [50]
Capability to introduce new roles inside the company structure, without causing Job Identity Threat to the current personnel.	[51], [50], [28], [5], [38]
Capability to carefully implement digital technological changes to prevent collective workforce stress and confusion. Ability to use sentiment analysis tools to gauge collective workforce morale and anxiety levels during changes, enabling proactive human support interventions.	[51], [47], [38], [12], [50], [19]
Capability to understand and balance often conflicting objective functions, such as cost-effectiveness versus human-centricity.	[1], [10], [9], [6], [38], [19]

Skill	Reference
Ability to utilize semantic technologies and NLP to identify and value “tacit” employee skills emerging from daily interactions, optimizing role assignment and knowledge transfer to maximize individual human potential.	[44], [22], [19], [40]
Ability to recognizing and mitigating signs of psychological distress caused by organizational change and job loss.	[51], [52], [36], [19], [6], [46], [44]
Ability to empathically communicate difficult news (layoffs, closures) with radical transparency and emotional intelligence.	[36], [46], [19], [10], [7], [13], [6], [38]
Ability to include in the planning of workforce reductions equity, long-term employability, and proactive social dialogue.	[19], [52], [44], [46], [55]
Ability to maintain psychological safety during restructuring, ensuring employees can safely voice their concerns.	[6], [19], [2], [38]
Capability to forecast workforce skill obsolescence before the role becomes redundant.	[3], [4], [52], [44]
Capability to establish and manage partnerships with external training entities and universities to create direct "hiring corridors" for exiting employees.	[6], [54], [45], [20]
Ability to use ML insights and talent matching algorithms to map skills of at-risk employees against open roles, prioritizing internal redeployment over layoffs.	[40], [44], [4], [22]
Ability to use monitoring systems to ensure that restructuring or dismissal processes adhere to ethical standards, preventing discriminatory biases and ensuring verifiable fairness in decisions.	[46], [36], [19], [53]
Ability to cultivate deep expertise that expands into adjacent fields, enabling rapid adaptation to industrial changes.	[3], [54], [16], [45]

8.2. Production

8.2.1. Workstation Level

Table 15: Production-Workstation level skill extracted in the articles with references.

Skill	Reference
Ability to design the physical geometry and safety logic of individual collaborative cells to minimize physical strain (e.g., reaching distances, posture). Ability to test and refine ergonomics in real-time to ensure the new setup actively improves human-machine interaction before full operational use. Capability to include human feedback about the workstation ergonomic's desing to continuously improve it	[6], [27], [47], [48], [52], [54]
Ability to configure adaptive sensor systems and safety protocols to eliminate hazards in collaborative environments.	[9], [16], [22], [47], [53], [55]
Ability to design the step-by-step interaction sequence between operator and machine, strategically allocating heavy and repetitive physical burdens to the automation system.	[11], [40], [47], [48], [54]
Ability to evaluate and select machinery based on its "intrinsic cognitive load," prioritizing assets with intuitive interfaces and simplified control logic to minimize the mental effort and learning curve required for the operator.	[4], [6], [22], [47], [48], [53]
Ability to apply cognitive psychology principles to centralized process dashboards filtering non-essential data to prevent information overload and reduce decision fatigue. Ability to test interfaces (dashboards) in a simulated environment to validate that they display only context-relevant information and prevent cognitive overload before deployment on the shop floor.	[14], [22], [27], [48], [53]
Ability to analyze workforce load-handling tasks and select the appropriate exoskeleton models based on biomechanical compatibility, prioritizing long-term musculoskeletal health.	[6], [47], [52], [53]
Capability to engineer workstation layouts that structurally facilitate peer-to-peer mentoring and mutual support.	[4], [13], [17], [47], [52], [54]

Skill	Reference
Ability to implement validation loops to analyze workstations' workflows and confirm the minimization of operator physical strain. Capability to regulate workstation pace based on real-time wearable data to proactively prevent safety incidents.	[1], [4], [47], [52], [53], [56]
Capability to operate heavy machinery or robots in hazardous zones remotely using low-latency interfaces.	[2], [9], [16], [41], [45], [47]

8.2.2. System Level

Table 16: Production-System level skill extracted in the articles with references.

Skill	Reference
Ability to integrate human factors (e.g. well-being, skills, fatigue) directly into scheduling algorithms. Capability to test the impact of shift patterns and task allocation on worker fatigue and stress, optimizing scheduling algorithms before full-implementation. Competence in interpreting aggregated data from the "Healthy Operator" infrastructure to dynamically rotate workers between heavy and light tasks during the shift.	[52], [1], [4], [22]
Capability to engineer production flow, integrating buffers and dynamic task allocation, preventing bottleneck, therefore minimizing workforce psychological pressure.	[52], [1], [5], [51], [53], [22]
Capability to engineer logical asset arrangements that eliminate search friction through intuitive standardization, preventing loss and minimizing	[54], [6], [25], [48], [27], [44]

Skill	Reference
operator frustration. Capability to validate and calibrate dynamic task allocation via simulation, ensuring alignment with worker fatigue and skill levels, before production deployment. Competence in using the Digital Twin interface to simulate "what-if" scenarios on the production line in real-time regarding operators' physical conditions.	
Capability to design communication channels (digital platform) that instantly route issues to the correct owner, eliminating the stress of searching for support and ensuring clear accountability. Capability to implement the communication platform by instructing staff on its usage and demonstrating its value in reducing daily friction, ensuring full adoption and clear role understanding. Capability to actively curate the feedback channel through periodic reviews, validating valuable insights for implementation while systematically archiving resolved or non-applicable entries to maintain system clarity.	[44], [22], [2]
Capability to engineer production layouts that enable visual contact and safe interaction, preventing operator isolation and fostering team connection. Capability to actively curate communication flows by filtering noise, purging obsolete updates, and tracking resolution status, ensuring the stream remains relevant and clutter-free for all users.	[54], [6], [47], [17], [16], [13]
Capability to design inclusive feedback loops that allow operators to report insights and process improvements directly from the line, ensuring their voice is heard and valued in system optimization. Capability to implement the feedback channel by instructing operators on its usage and demonstrating how their input directly resolves daily friction, ensuring they feel heard and empowered.	[27], [44], [19], [14], [20], [17]
Capability to lead practical technology workshop to instruct operators on the practical application of digital tool, ensuring confidence and safe adoption before full-adoption on the production line.	[54], [45], [38], [20], [18], [13]
Competence in using the Digital Twin interface to simulate "what-if" scenarios on the production line in real-time regarding operators' physical conditions.	[30], [27], [4], [45], [50], [53]

Skill	Reference
Ability to construct semantic networks that link operator skills and process requirements to facilitate resource allocation and enable complex querying of human-machine collaboration data.	[22], [44], [4], [40], [52]
Capability to use monitoring datas to identify phsycological factor stressors, implementing intervention to safeguard long term workforce mental well-being.	[47], [53], [30], [51], [50], [6]
Capability to engineer age-inclusive work models and adaptive roles that accomodate different physical needs, ensuring the retention of senior expertise and preventing workforce exclusion.	[52], [14], [53], [16], [54]
Capability to digitize personal expertise problem-solving procedures, via digital twin interfaces, transforming individual knowledge into a permanent corporate asset.	[22], [30], [40], [44], [4], [45]

8.3. I5.0 Infrastructure System

Table 17: I5.0 Infrastructure System skill extracted in the articles with references.

Skill	Reference
Capability to create and calibrate Human Digital Twins that model the operator physical and cognitive characteristics to validate ergonomic and task feasibility before physical prototyping. Capability to dynamically update Human Digital Twins datas to reflect physiological / physical changes over time, ensuring safety models remain accurate. Capability to ensure the permanent and secure deletion of sensitive operator biometric and behavioral data upon Digital Twin decommissioning.	[22], [30], [27]

Capability to capture and calibrate unique physiological baselines for each operator within the Digital Twin to accurately distinguish between healthy exertion and personal distress signals.	
Capability to design Digital Twin data structures that integrate human cognitive variables as core parameters, enabling the system to process operator mental states alongside machine data.	[22], [27], [30]
Capability to engineer bio-responsive safety protocols within the Digital Twin that automatically trigger protective machine reactions when operator health anomalies are detected.	[47], [50], [53]
Capability to configure cyber-fail-safe parameters that trigger automatic physical stops during network attacks to guarantee operator safety. Capability to implement OT-specific cybersecurity protocols to prevent cyber-physical incidents and ensure workforce safety.	[13], [2], [14]
Capability to evaluate and select non-invasive wearables that monitor physiological metrics without obstructing movement. Capability to deploy wearable sensors to monitor real-time operator health, physical movement, and fatigue. Capability to monitor wearable data streams to identify worker fatigue trends and maintain device calibration.	[53], [47], [27]
Capability to evaluate cobot specifications, prioritizing intuitive interfaces and sensory feedback, to minimize cognitive load and maximize safety.	[47], [15], [49]
Capability to configure ergonomic parameters into robot hand-over positions that ensure optimal exchange heights, to prevent operator bending and strain.	[6], [47], [22]
Capability to design control logic that dynamically modulates cobot cycle times to synchronize with the operator's physiological state and fatigue levels.	[47], [27], [39]
Capability to evaluate and select AR/XR devices based on their adaptability to diverse anthropometric profiles (e.g., adjustable IPD, prescription lens compatibility).	[6], [47], [41]
Capability to design the visual interfaces that display only essential task-specific data, preventing information overload and operator fatigue.	[47], [6], [48]

Capability to design workstation lighting and background contrast to ensure optimal digital text legibility on AR tool and prevent operator eye strain.	[6], [27], [47]
Capability to design safe AR walking paths by designating permitted and prohibited zones to ensure full situational awareness.	[22], [38], [47]
Capability to translate operator feedback regarding proximity anxiety and stress into technical adjustments that ensure the cobot adapts to the human's comfort zone.	[22], [27], [47]
Capability to validate AR layout and content usability through operator feedback, ensuring the experience reduces cognitive effort and aligns with worker needs.	[6], [27], [47]
Capability to integrate real-time operator feedback and health data into the Digital Twin's decision-making to dynamically adapt system settings to the worker's current condition.	[20], [27], [47]
Capability to analyze aggregated Digital Twin data to identify cumulative mental fatigue trends and proactively intervene to prevent operator burnout.	[27], [47], [50]
Ability to analyze operator-cobot interaction patterns to detect overly confident behavior and implement active strategies to maintain operators' cognitive engagement.	[14], [27], [47]
Capability to monitor operator trust levels towards the cobot and implement post-error transparency protocols to restore psychological safety and prevent technology disuse.	[7], [14], [28]
Capability to continuously monitor and validate the synchronization between the headset datas and production status to ensure operators act on valid, up-to-date data.	[16], [22], [50]
Capability to monitor physiological signals and headset usage to detect fatigue, scheduling mandatory screen-free breaks to prevent burnout and protect operator health.	[27], [47], [53]
Capability to analyze usage patterns to detect when operators focus too much on the screen and trigger active alerts to restore focus to the physical environment.	[19], [27], [47]
Capability to manage hygiene and maintenance protocols for shared wearable devices, ensuring sanitization to prevent health risks and maintain operator safety.	[6], [7], [47]

8.4. Data&AI Service

Table 18: Data&AI Service skill extracted in the articles with references.

Skill	Reference
Ability to develop AI-enabled solutions in manufacturing that are designed around human skills, aiming to augment rather than replace workers.	[48], [27], [5]
Ability to develop interfaces and interaction methods for AI systems that facilitate seamless collaboration between humans and machines.	[7], [34], [40]
Proficiency in integrating interpretability libraries to design AI systems that are transparent and interpretable, so that the decision logic is clear to human users.	[9], [24], [28]
Developing AI training pipelines that integrate specific bias mitigation techniques to ensure equitable performance across demographics. Capability to audit AI models and data sets used in restructuring decisions to detect and eliminate biases (e.g., age, gender, race) ensuring equitable outcomes.	[28], [34], [24]
Ability to design protocols to prevent sensitive data leakage to external APIs and enforcing least-privileged access.	[13], [2], [31]
Designing structured communication channels that enable production-line operators to report system anomalies and inconsistencies of AI performance. Ability to implement feedback channels that empower production-line operators to report system anomalies and data inaccuracies, ensuring human judgment is prioritized in guiding AI recalibration.	[44], [27], [38]
Ability to design technical measures and protocols to ensure privacy, security, and responsible use of operators' personal data. Ability to deploy security measures to ensure sensitive operator data is never exposed to developers or unauthorized systems.	[13], [20], [46]
Ability to design data models for workforce reduction that weigh tenure, social impact, and vulnerability alongside financial metrics to ensure equitable restructuring.	[52], [19], [50]

Ability to design relational and graph-ready data models for employee skills to enable the implementation of internal semantic networks.	[44], [22], [40]
Ability to implement “override mechanisms” and human-validation stages in automated workflows to ensure the AI acts as a co-pilot rather than a replacement.	[13], [27], [48]
Ability to gather & analyze data from wearable technology to derive models for workers’ health and well-being.	[47], [50], [53]
Ability to conduct audits to ensure that data privacy and ethical standards are strictly maintained during daily operations, preventing surveillance abuse.	[13], [20], [28]
Ability to manage continuous data ingestion pipelines to ensure real-time accuracy of worker skill profiles within the knowledge graph.	[4], [22], [44]

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