PROSPECTS 5.0

D1.2 Industry 5.0 Community Trends and Status

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Short Description
Task 1.2 focuses on reviewing existing approaches and methodologies for the adoption and implementation of Industry 5.0. It will begin with a comprehensive review of relevant literature to identify key definitions related to Industry 5.0 and associated frameworks. Following this, a Delphi survey using industry input from all use-cases will be conducted to refine these definitions and propose future trends for use in Task 1.3. A Delphi survey will then be conducted, drawing on industry input from all use cases, to anticipate future trends for integration into the understanding of Industry 5.0 and following Task 1.3.

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Main Author(s):		Clara Herkenrath (FIR)	
Contributor(s):		Clara Herkenrath (FIR), Gerrit Hoeborn (FIR), Cansu Kanak (FIR), All Use-Case facilitators and providers	
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LIST OF ACRONYMS

ADAM	Aachen Digital Architecture Management
AI	Artificial Intelligence
CPS	Cyber-physical systems
CSR	Corporate Social Responsibility
EFQM	European Foundation for Quality Management
I5.0	Industry 5.0
I5.0 AF	Industry 5.0 Assessment Framework
I5.C	Industry 5.0 Community of Interest
IoE	Internet of Everything
IoT	Internet of Things
IQR	Interquartile range
KPIs	Key Performance Indicators
OEE	Overall equipment effectiveness
SCM	Supply Chain Management
SDGs	United Nations Sustainable Development Goals
SLR	Systematic Literature Review
T 1.2	Task 1.2
WP	Work Package

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1. EXECUTIVE SUMMARY

Task 1.2 aims to evaluate and refine existing approaches and methodologies for the adoption and implementation of Industry 5.0. This task will provide a foundational understanding necessary for subsequent tasks, particularly Task 1.3, by identifying key definitions and frameworks, and anticipating future trends.

The task begins with an extensive review of relevant literature to consolidate existing knowledge on Industry 5.0. This review will focus on identifying and clarifying key definitions, strategic objectives, and frameworks associated with Industry 5.0. The literature review will also assess the current understanding of Industry 5.0's core components, such as human centricity, sustainability, and resilience, as defined by leading authorities including the European Commission.

Building on the literature review, a Delphi survey will be conducted, engaging industry experts and stakeholders across various use cases. This survey aims to refine the definitions identified in the literature, ensuring they are aligned with practical industry perspectives. The survey will also gather insights into the challenges and opportunities associated with Industry 5.0 implementation, helping to anticipate and identify future trends.

The findings from the Delphi survey will be used to forecast future trends that are likely to influence the evolution and implementation of Industry 5.0. These trends will be critically analyzed to determine their implications for industry practices and their integration into the Industry 5.0 framework.

The refined definitions and anticipated trends identified through this task will serve as a base for Task 1.3. This next phase will leverage the insights from Task 1.2 to develop actionable strategies and methodologies for the broader adoption of Industry 5.0 across different sectors.

Task 1.2 will culminate in a detailed report that consolidates the literature review, Delphi survey results, and future trend analysis. This report will serve as a critical input for Task 1.3, providing a robust foundation for the continued exploration and implementation of Industry 5.0 principles and practices.

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2. INTRODUCTION

Task 1.2 aims to conduct a comprehensive review of existing methodologies and approaches of Industry 5.0 concepts. It will critically examine current literature and practices to identify gaps and limitations within the existing framework, paving the way for the development of a robust Industry 5.0 Assessment Framework (I5.0 AF).

Initially, the task will involve an extensive review of relevant literature and current practices related to Industry 5.0 across various sectors. This review will involve a critical analysis of the methodologies, tools, and frameworks currently in use, with the goal of identifying effective strategies and understanding the limitations of existing approaches. Key thematic areas will be identified, and specific gaps that need to be addressed will be delineated. A Delphi survey will follow, utilizing a structured communication technique to gather expert opinions and achieve consensus on critical issues related to Industry 5.0. This iterative process will involve two rounds of surveys, refining and building consensus on the most pertinent aspects of Industry 5.0 implementation.

Finally, insights from the literature review, Delphi survey, and case study analysis will be integrated to develop a comprehensive set of recommendations. These recommendations will address identified gaps and propose actionable strategies for the effective adoption and implementation of Industry 5.0 concepts. Additionally, the task will outline methodological approaches and tools necessary for assessing the feasibility and impact of these strategies, ensuring alignment with the overarching goals of the Industry 5.0 framework. This task is crucial in establishing a robust and adaptable Industry 5.0 Assessment Framework, enabling stakeholders to enhance their Industry 5.0 implementation effectively.

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3. UNDERSTANDING OF INDUSTRY 5.0

Industry 5.0 represents a significant evolution from Industry 4.0, aiming to create a more sustainable, human-centric, and resilient industrial framework. This new paradigm emphasizes the importance of incorporating human-centric approaches into technological advancements and production processes. Unlike its predecessor, which focused primarily on digital connectivity and efficiency through AI and IoT, Industry 5.0 prioritizes the integration of human values, environmental sustainability, and robust resilience in industrial operations (European Commission 2024). Industry 5.0 is built on the understanding that technological progress should not come at the expense of human well-being or environmental health. Instead, it seeks to harmonize technological innovation with societal needs and ecological constraints, creating an industrial landscape that is more attuned to the broader impacts of production activities. This approach addresses the growing concerns about the negative environmental, social, and economic consequences of unchecked industrialization.

Different authors define Industry 5.0 in various ways. The following breakdown presents different perspectives, as illustrated in Table 1. This table highlights the diverse interpretations and focal points of Industry 5.0, providing a comprehensive overview of the current discourse in the field.

Table 1 Breakdown of Various Understandings of Industry 5.0 (own depiction)

Source	*Understanding*
Akundi, Euresti, Luna, Ankobiah, Lopes, Edinbarough (2022)	I5.0 is built on human centricity, environmental stewardship, and social benefit instead of solely technology.
Banholzer (2022)	I5.0 strikes a balance between techno-centric and human-centric approaches, requiring new governance tools to ensure sustainability.
Demir, Döven, Sezen (2019)	I5.0 extends the principles of robotics and artificial intelligence in I4.0, promoting human-machine collaboration as a key pillar.
European Comission (2021)	I5.0 goes beyond profit maximization and draws on the governance power of society to steer the industrial transformation toward environmental and human values.
Ghobakhloo, Iranmanesh, Mubarak, Mubarik, Rejeb, Nilashi (2022)	I5.0 manages digital industrial transformation to achieve sustainable economic and socio-environmental development.

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Ivanov (2023)	I5.0 aims to deliver sustainable and human-centered services by creating adaptable systems that quickly realign resources in response to shifting demand and supply conditions.
Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang (2022)	I5.0 prioritizes human-machine symbiosis for societal goals beyond economic growth, fostering a sustainable super-smart society.
Longo, Padovano, Umbrello (2020)	I5.0 is in the integration of cyber-physical systems and human operators in a symbiotic factory concept.
Lu, Zheng, Chand, Xia, Liu, Xu, Wang, Qin, Bao (2022)	I5.0 still relies on technological capabilities to deliver the envisioned values.
Maddikunta, Pham, B, Deepa, Dev, Gadekallu, Ruby, Liyanage (2022)	I5.0 emphasizes collaboration, where humans handle customization and critical thinking while cobots perform repetitive tasks.
Nahavandi (2019)	I5.0 aims to achieve a human-machine collaboration, leverage human cognitive abilities and creativity for increased process efficiency.
Pizoń, Cioch, Kański, Sánchez García (2022)	I5.0 involves collaborative robots or cobots, working alongside humans to optimize workflows.
Sindhwani, Afridi, Kumar, Banaitis, Luthra, Singh (2022)	I5.0 focuses on a digital bioeconomy for sustainable development.

Based on these varying understandings, the current definition by the European Commission (25 Mar. 2024) is utilized for this project, which identifies Industry 5.0 through three core competencies: Human centricity, sustainability, and resilience. The European Commission (25 Mar. 2024) defines Industry 5.0 through three core strategic objectives:

- **Sustainability**: Sustainability focuses on developing circular processes with r-strategies to re-use, repurpose, and recycle natural resources, minimizing waste and reducing environmental impact. Key measures include lowering energy consumption and greenhouse gas emissions to protect natural resources from

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depletion and degradation. This approach aims to foster a balanced and regenerative industrial ecosystem, respecting planetary boundaries (European Commission, 25 Mar. 2024). Advanced technologies like Artificial Intelligence (AI) and additive manufacturing enhance resource efficiency and minimize waste, supporting sustainable industrial practices (European Comission, 2021). Integrating these technologies promotes a circular economy and ensures sustainable industrial growth, as advocated by the European Commission.

- **Human centricity**: Human centricity in Industry 5.0 places core human needs and interests at the center of production processes. This approach emphasizes using technology to adapt production to workers' requirements, enhancing their well-being and productivity while respecting fundamental rights such as privacy, autonomy, and human dignity (European Comission, 2021, European Commission, 25 Mar. 2024). By prioritizing human needs over mere technological efficiency, Industry 5.0 promotes a more inclusive and equitable industrial environment.
- **Resilience:** Resilience in Industry 5.0 emphasizes creating robust industrial systems that can withstand disruptions. This includes developing resilient value chains, adaptable production capacities, and flexible business processes to ensure stability amid challenges like supply chain disruptions and economic fluctuations (European Commission, 25 Mar. 2024). The COVID-19 pandemic and geopolitical shifts have shown the fragility of globalized production, underscoring the need for increased resilience, especially in critical sectors like healthcare and security. By focusing on these areas, Industry 5.0 aims to ensure reliable operations during crises (European Comission, 2021).

The transition from Industry 4.0 to Industry 5.0 marks a critical shift in focus (Renda, Schwaag Serger, Tataj, Morlet, Isaksson, Martins, Mir Roca, Hidalgo, Huang, Dixson-Declève, Balland, Bria, Charvériat, Dunlop, Giovannini, 2021, pp. 5–7). Industry 4.0, despite its advancements, lacks crucial dimensions necessary for systemic change due to its adverse environmental, climate, and social impacts. It misses regenerative features that embrace a circular economy and positive restorative feedback loops in value chain design. Additionally, it lacks a focus on worker well-being, social inclusion, and technologies that complement human skills. Furthermore, a mandatory environmental dimension aimed at eliminating fossil fuels, promoting energy efficiency, and using nature-based solutions for regenerating carbon sinks and restoring biodiversity is needed (Renda, Schwaag Serger, Tataj, Morlet, Isaksson, Martins, Mir Roca, Hidalgo, Huang, Dixson-Declève, Balland, Bria, Charvériat, Dunlop, Giovannini, 2021, pp. 5–7).

By integrating these competencies, Industry 5.0 aims to create a balanced approach where technological innovation and human-centric values coexist harmoniously. This approach addresses the shortcomings of Industry 4.0 by fostering an industrial ecosystem that is not only efficient but also equitable and sustainable. The emphasis on sustainability ensures that industrial activities contribute positively to the

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environment, while the focus on human centricity ensures that technological advancements enhance human well-being. Additionally, the resilience component ensures that the industrial system remains robust and adaptable in the face of various challenges, thus securing long-term stability and growth (European Commission, 25 Mar. 2024, p. 14). As shown in Figure 1, the evolution of industrial paradigms from Industry 1.0 to Industry 5.0 highlights the progressive enhancements in technological capabilities and the increasing emphasis on sustainability, human centricity, and resilience.

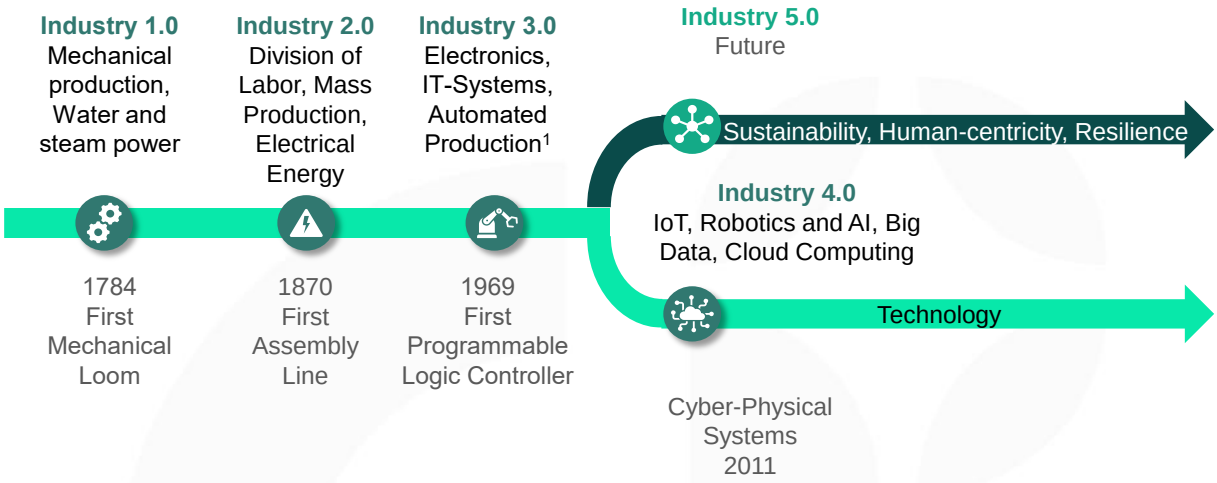

Figure 1 The evolution of industrial paradigms from Industry 1.0 to Industry 5. 0 (adapted and expanded from Demir, Döven, Sezen, 2019, p. 689, Renda, Schwaag Serger, Tataj, Morlet, Isaksson, Martins, Mir Roca, Hidalgo, Huang, Dixson-Declève, Balland, Bria, Charvériat, Dunlop, Giovannini, 2021, pp. 5–7)

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4. SYSTEMATIC LITERATURE REVIEW: RESEARCH RELATED TO INDUSTRY 5.0

4.1. Methodological Approach: Systematic Literature Review

To interpret existing approaches and strategies in Industry 5.0, with a focus on the major factors driving this transformation and its potential use cases, a systematic literature review (SLR) was conducted. This method is particularly suitable for exploring emerging fields or topics, as it relies on a comprehensive analysis of existing literature and research findings. By thoroughly analyzing the literature, commonalities and trends across various studies can be identified. This rigorous and structured approach ensures a systematic, repeatable, and transparent process for identifying, selecting, and critically evaluating relevant research, thereby providing an unbiased assessment and highlighting gaps and limitations in current research (Snyder, 2019, p. 336).

The systematic literature review follows the PRISMA method outlined by Page, McKenzie, Bossuyt, Boutron, Hoffmann, Mulrow, Shamseer, Tetzlaff, Akl, Brennan, Chou, Glanville, Grimshaw, Hróbjartsson, Lalu, Li, Loder, Mayo-Wilson, McDonald, McGuinness, Stewart, Thomas, Tricco, Welch, Whiting, Moher (2021) and Liberati, Altman, Tetzlaff, Mulrow, Gøtzsche, Ioannidis, Clarke, Devereaux, Kleijnen, Moher (2009). As depicted in Figure 2, the SLR process is structured into three phases and further divided into five steps according to the PRISMA method (Page, McKenzie, Bossuyt, Boutron, Hoffmann, Mulrow, Shamseer, Tetzlaff, Akl, Brennan, Chou, Glanville, Grimshaw, Hróbjartsson, Lalu, Li, Loder, Mayo-Wilson, McDonald, McGuinness, Stewart, Thomas, Tricco, Welch, Whiting, Moher, 2021, 5). An additional sixth step was included to address the specific research objectives of PROSPECTS 5.0. The first phase, Problem Definition, involves defining the problem to set the scope of the literature search based on specific research questions and objectives. This phase includes creating research parameters and developing a search string for querying databases. In the second phase, the literature search is conducted systematically. This phase consists of establishing formal research criteria to guide the search process, formulating and executing search queries in relevant databases, and conducting an initial review of the identified literature. The third phase, Analysis and Evaluation, focuses on analyzing and evaluating the gathered literature. This includes screening the identified publications and categorizing them based on relevance and content, followed by performing bibliometric and content analysis to reveal the characteristics of the publications, such as publication trends, and to provide a comprehensive assessment of the research field. Additionally, in Step 6, other media were included to incorporate developments from an industry perspective for the subsequent analysis. This analysis aims to explore the current state of Industry 5.0 research in depth and to highlight future research directions.

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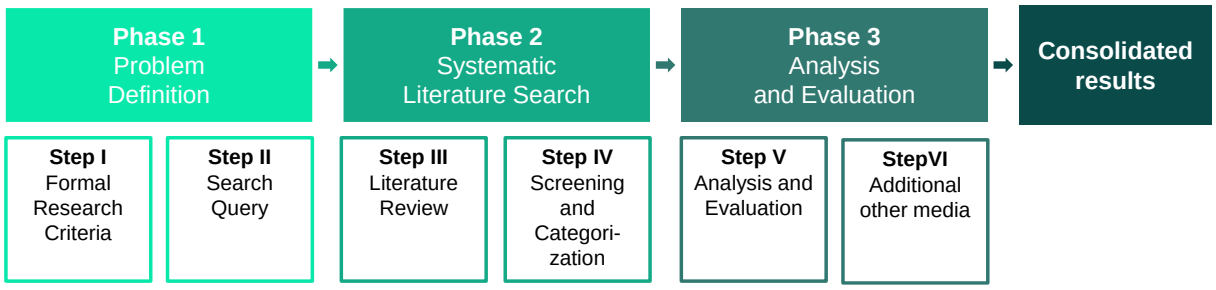

Figure 2 Methodological Approach: PRISMA Method for Systematic Literature Review with an Additional Step for PROCEPTS5.0 Research Objective (adapted and expanded from Page, McKenzie, Bossuyt, Boutron, Hoffmann, Mulrow, Shamseer, Tetzlaff, Akl, Brennan, Chou, Glanville, Grimshaw, Hróbjartsson, Lalu, Li, Loder, Mayo-Wilson, McDonald, McGuinness, Stewart, Thomas, Tricco, Welch, Whiting, Moher, 2021, 5)

The goals of this desk research are to collect information from literature and other media, with the expected outputs being a thorough analysis of the state of the art in scientific literature on existing frameworks for Industry 5.0, existing holistic Industry 4.0 frameworks as a basis for expansion to Industry 5.0, and other relevant media. These outputs will feed into project activities by connecting with the results of workshop Task 1.1 and the Delphi Study to identify similarities across different sectors and methodologies, and to address methodological gaps in comparison to existing models and frameworks. This will contribute to an Industry 5.0 framework and the definition of technological and non-technological trends in Industry 5.0 adoption and implementation. Through this systematic approach, the literature review not only ensures a thorough and unbiased assessment of existing research but also identifies critical gaps and limitations. These insights are crucial for guiding future research efforts and advancing the understanding and implementation of Industry 5.0.

4.2. Implementation and Analysis: Systematic Literature Review

The systematic literature review was executed through a structured, multi-step process to ensure comprehensive and objective analysis. Initially, predefined criteria for literature selection were documented (Page, McKenzie, Bossuyt, Boutron, Hoffmann, Mulrow, Shamseer, Tetzlaff, Akl, Brennan, Chou, Glanville, Grimshaw, Hróbjartsson, Lalu, Li, Loder, Mayo-Wilson, McDonald, McGuinness, Stewart, Thomas, Tricco, Welch, Whiting, Moher, 2021) to identify relevant and adequate literature and ensure the reproducibility and objectivity of the research. The search was unrestricted by specific research methodologies, publication periods, or geographic regions. Inclusion and exclusion criteria determined eligibility: Only studies with full texts available in English, and publications including research articles, review articles, and conference papers were considered. To guarantee the inclusion of all pertinent information concerning Industry 5.0, search terms were developed and linked with the Boolean operator OR with synonyms. The search query used was: (("Industry 5.0") OR ("fifth Industrial revolution") OR ("5IR")). The syntax was adapted for the TITLE-ABS-KEY database, with the predefined search strings. Bibliographic research was conducted using three internet databases: SCOPUS, Science Direct, and Web of Science. Additionally, the library catalogs of RWTH

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Aachen and Google Scholar were utilized to gather academic publications and conference papers.

The query yielded a total of 879 publications: 358 from SCOPUS, 242 from Science Direct, and 279 from Web of Science, forming the basis for investigation. Using the selection criteria defined initially, a flow diagram depicting the data collection process is presented in Figure 3. Titles and abstracts were reviewed, resulting in 284 articles remaining after the first exclusion (Q1). Full-text examination further excluded 177 articles that did not align with the research goals, leaving 107 publications that provided insights into Industry 5.0. Through forward and backward analysis, 15 sources were identified that provided critical insights and foundational knowledge for the research on Industry 5.0. Duplicates or triplicates among these sources were excluded. Excluded studies were re-examined to ensure the quality of the review. Ultimately, 61 sources were included for further evaluation. The comprehensive list of literature is provided in Figure 3.

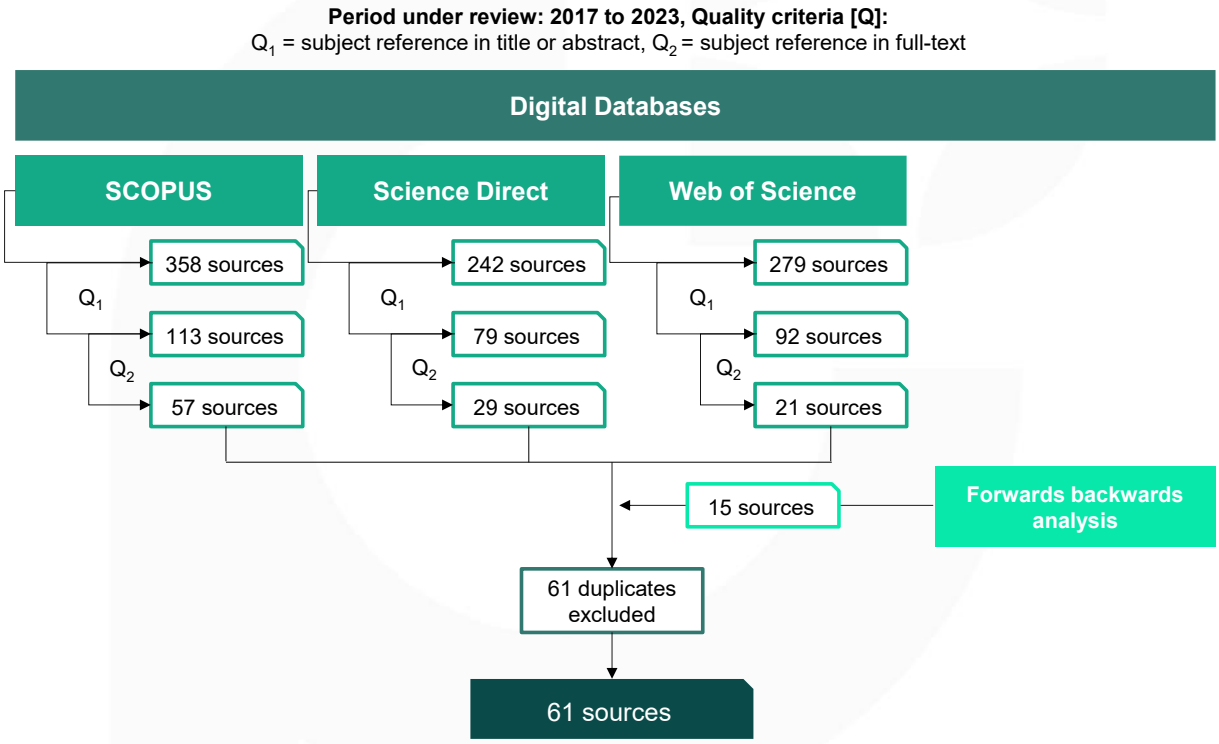

Figure 3 Selection Process Literature (own depiction)

Subsequently, the assessment took place, analyzing several key aspects. Focus areas of the literature were identified and categorized. Various triggers were analyzed, such as acute crises, market changes, talent recruiting and retention, political volatility and crises, planetary boundaries, and ethical and social responsibilities. Additionally, several enablers were examined: anchoring I5.0 objectives, upskilling and enablement, leveraging interdisciplinary synergies, deployment of enabling technologies, and implementing enabling technologies. In the following, these fields are analyzed in detail. Figure 4 provides an overview of the focus areas. The analysis includes a comprehensive examination of each field, highlighting their specific contributions and interrelations within the broader context of Industry 5.0.

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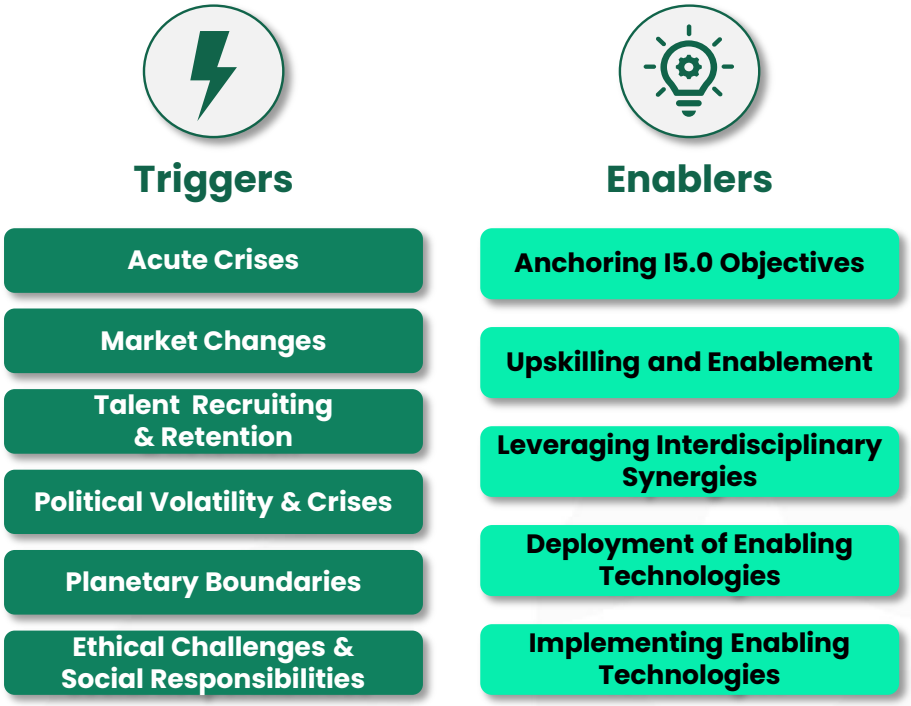

Figure 4 Identified focus areas from systematic literature review (own depiction)

4.2.1. Triggers

The industry is constantly evolving, and crises along with societal changes require adaptation to current trends. A detailed analysis and a deep understanding of the changes the industry faces are essential for developing concepts that enable the industry to navigate these challenges confidently. The current changes and the resulting triggers that necessitate a rethinking of Industry 5.0 in the industrial sector will be presented and defined in the following sections: Acute Crises, Market Changes, Talent Recruiting & Retention, Political Volatility & Crisis, Planetary Boundaries, and Ethical Challenges & Social Responsibilities.

ACUTE CRISES

Acute crises describe situations that occur suddenly and demand immediate change. These situations are fraught with uncertainty, as the probability of occurrence and environmental conditions are either completely unknown or only partially understood. Examples of *acute crises* include sudden disruptions in the supply chain resulting in production losses, natural disasters, cyberattacks, or the outbreak of infectious diseases.

The literature repeatedly identifies acute crises as triggers for rethinking within the industry. For example, the COVID-19 pandemic is frequently mentioned by numerous sources as a turning point that exposed the fragility of companies. The COVID-19 crisis demonstrated that the resilience of supply chains can quickly collapse, highlighting the urgent need for innovative solutions to prevent such failures (Zizic, Mladineo, Gjeldum, Celent, 2022, Sarfraz, Sarfraz, Iftikar, Akhund, 2021). Furthermore, it became evident that traditional machines, despite their productivity and efficiency, face significant

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challenges in effectively responding to acute crises (European Comission, 2021, Aheleroff, Huang, Xu, Zhong, 2022). In this context, the lack of resilience in companies is frequently discussed, emphasizing the necessity of protecting production from disasters like the COVID-19 pandemic (Adel, 2022b, Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang, 2022). Decision-making in uncertain environments, such as during an *acute crisis*, poses a significant challenge for companies (Chandel, Sharma, 2023, Sindhwani, Afridi, Kumar, Banaitis, Luthra, Singh, 2022, Zizic, Mladineo, Gjeldum, Celent, 2022). Additionally, the crucial importance of employees became evident, underscoring the urgency of refocusing on their needs and roles within the organization (Zizic, Mladineo, Gjeldum, Celent, 2022). The challenges that acute crises bring affect a wide range of industries. In addition to manufacturing companies, retailers and service providers also faced changed market conditions triggered by the COVID-19 crisis (Noble, Mende, Grewal, Parasuraman, 2022).

MARKET CHANGES

The market is fundamentally an economic arena where supply and demand intersect, facilitating pricing and exchange (Woll, 2008). Consequently, *market changes* denote alterations in these dynamics, including shifts in consumer behavior and modifications in the competitive landscape. These changes significantly impact market equilibrium, requiring businesses to adopt adaptive strategies to sustain their competitive advantage and address evolving consumer demands.

In a rapidly changing world, market conditions are evolving at an unprecedented pace, compelling companies to adapt swiftly. One of the primary challenges for businesses is to respond effectively to these market changes. A significant market shift in the context of Industry 5.0 is the increasing demand for personalized products (Aheleroff, Huang, Xu, Zhong, 2022). Personalization involves tailoring products precisely to individual customer needs, thereby evoking emotions and a sense of identity (Doyle-Kent, Kopacek, 2020, Lu, Zheng, Chand, Xia, Liu, Xu, Wang, Qin, Bao, 2022). This level of personalization significantly influences customers' purchasing decisions (Mishra, Paul, 2023). Companies that successfully implement personalization strategies gain a competitive advantage and see increased customer loyalty (Aheleroff, Huang, Xu, Zhong, 2022).

However, while machines and robots excel at producing standardized products, they face considerable challenges in manufacturing personalized items (Chandel, Sharma, 2023). Current technologies often fall short in meeting the demands for personalization (Adel, 2022a, Maddikunta, Pham, B, Deepa, Dev, Gadekallu, Ruby, Liyanage, 2022). To address this growing demand, companies must invest in advanced technologies and machinery that enable cost-effective personalization (Adel, 2022a). Furthermore, involving consumers in the development phase is crucial to achieving resilience and human centricity within the organization (Costa, Amorim, Reis, Melão, 2023). By adopting these strategies, businesses can not only satisfy market demands but also

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foster customer loyalty and secure a competitive edge in the evolving landscape of Industry 5.0.

TALENT RECRUITING & RETENTION

Talent Recruiting & Retention refer to the imperative for companies to attract and retain employees with the requisite qualifications over the long term. This necessity is driven by several factors, including the increasing complexity of job roles, the rapid pace of technological advancement, and the competitive nature of the global market.

The shortage of skilled employees compels employers to create attractive incentives for potential candidates. Particularly for younger generations, such as Millennials and Generation Alpha, companies that prioritize employee autonomy, well-being, and societal contributions are more appealing (Lu, Zheng, Chand, Xia, Liu, Xu, Wang, Qin, Bao, 2022). An issue vastly overlooked in Industry 4.0 is employee well-being, which has become increasingly relevant in today's society. This encompasses various aspects: workplace safety, ergonomics, mental health, and self-realization. Companies must address these safety demands to ensure a secure working environment (Alves, Lima, Gaspar, 2023). Ergonomics is equally critical, particularly in settings where humans and robots collaborate, to prevent long-term health issues such as musculoskeletal disorders (Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang, 2022). Beyond physical well-being, mental health and self-realization are now recognized as essential components of employee satisfaction. Aheleroff, Huang, Xu, Zhong (2022) utilize Maslow's hierarchy of needs to illustrate that fulfilling both lower and higher-level needs is crucial for workplace satisfaction. Job satisfaction positively impacts overall company performance (Frutos-Bencze, Sokolova, Zubr, Mohelska, 2022), and improving mental health can mitigate productivity losses caused by disorders like depression and anxiety (European Comission, 2021).

Another significant challenge is the skills gap, where employees often lack the qualifications necessary for modern workplaces (Trstenjak, Hegedić, Tošanović, Opetuk, Đukić, Cajner, 2023). This gap affects both shop floor workers and managers, hindering the adoption of new technologies due to reliance on outdated practices (Ramachandran, Nagarjuna, Akram, Bhalani, Raju, Ponnusamy, 2023). Employees frequently lack proficiency with technologies such as AI and robotics (Suciu, Plesea, Petre, Simion, Mituca, Dumitrescu, Bocaneala, Moroianu, Nasulea, 2023, Trstenjak, Hegedić, Tošanović, Opetuk, Đukić, Cajner, 2023). Additionally, soft skills like critical thinking and creativity, which are increasingly vital, are not adequately addressed by employers or academic institutions (Suciu, Plesea, Petre, Simion, Mituca, Dumitrescu, Bocaneala, Moroianu, Nasulea, 2023). To address these issues, companies must develop effective strategies for Talent Recruiting & Retention. This includes creating incentives to attract employees, fostering long-term relationships, and providing the necessary training to equip employees with essential skills. By doing so, companies can meet the demands of the evolving workplace and maintain a competitive edge.

POLITICAL VOLATILITY & CRISES

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Political volatility and crises refer to political events that significantly impact the economy. Volatility involves fluctuations and uncertainties due to changes in legislation, trade agreements, or regulatory frameworks. Crises are dramatic events indicative of political instability, such as political upheavals, civil unrest, and diplomatic tensions. These conditions necessitate that companies develop strategies to mitigate risks and adapt swiftly to changing political landscapes.

Organizations are facing a rapidly changing geopolitical situation, which presents a significant challenge for many businesses (Alojaiman, 2023, Huang, Wang, Li, Zheng, Mourtzis, Wang, 2022, Saniuk, Grabowska, Straka, 2022). Political volatility refers to the potential fluctuations and uncertainties introduced by changes in policy, such as alterations in legislation, trade agreements, or regulatory frameworks. *Crises*, on the other hand, are dramatic events indicative of political instability, including political upheavals, civil unrest, and diplomatic tensions. The ability to swiftly adapt to a changing political landscape is regarded as a crucial factor in achieving resilience (Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang, 2022).

Political volatility and crises have a direct impact on organizations, compelling them to navigate unpredictable and often disruptive events. In response, organizations must cultivate a range of skills and devise robust strategies to maintain their success. This necessitates an ongoing commitment to adaptability, resilience, and strategic planning to effectively navigate and thrive in a constantly shifting environment. By understanding and anticipating these political dynamics, businesses can better ensure their resilience and sustainability in the global market.

PLANETARY BOUNDARIES

Planetary Boundaries delineate a safe operating space across nine interconnected environmental dimensions, the transgression of which could have severe repercussions for both humanity and the Earth system (Leitschuh, Michelsen, Simonis, 2015)

One of the greatest current societal challenges, which stands out from the crises mentioned in the previous section and is therefore considered separately, is the widespread transgression of planetary boundaries (Sindhwani, Afridi, Kumar, Banaitis, Luthra, Singh, 2022). A framework that defines and partially quantifies planetary boundaries is provided by (Rockström, Steffen, Noone, Persson, Chapin, Lambin, Lenton, Scheffer, Folke, Schellnhuber, Nykvist, Wit, Hughes, van der Leeuw, Rodhe, Sörlin, Snyder, Costanza, Svedin, Falkenmark, Karlberg, Corell, Fabry, Hansen, Walker, Liverman, Richardson, Crutzen, Foley, 2009). This framework outlines nine boundaries that must be respected to prevent catastrophic consequences for humanity. In 2023, six of these nine boundaries were crossed, highlighting an urgent societal need to correct this imbalance (Richardson, Steffen, Lucht, Bendtsen, Cornell, Donges, Drüke, Fetzer, Bala, Bloh, Feulner, Fiedler, Gerten, Gleeson, Hofmann, Huiskamp, Kummu, Mohan, Nogués-Bravo, Petri, Porkka, Rahmstorf, Schaphoff, Thonicke, Tobian, Virkki, Wang-Erlandsson, Weber, Rockström, 2023). Industry plays a significant role in this context, as it is among

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the largest contributors to environmental degradation. In Industry 4.0, there was insufficient focus on addressing this issue. The increasing demand from consumers for environmentally friendly products, coupled with growing regulation by governments and international organizations such as the United Nations, is driving sustainability to become an increasingly important aspect of industrial practices (Costa, Amorim, Reis, Melão, 2023). Sustainable manufacturing is increasingly being recognized as a key priority for both industry and government (Peças, John, Ribeiro, Baptista, Pinto, Dias, Henriques, Estrela, Pilastri, Cunha, 2023).

ETHICAL CHALLENGES & SOCIAL RESPONSIBILITIES

Ethical challenges and social responsibilities are concerned with the moral and ethical dilemmas that arise in business activities. These challenges encompass a wide range of considerations, including corporate social responsibility (CSR), ethical conduct in research and development, and a steadfast commitment to integrity and transparency in all business practices. Addressing these challenges requires businesses to not only comply with legal and regulatory standards but also to proactively engage in practices that promote social good, environmental sustainability, and ethical behavior throughout their operations.

There is a growing societal demand for a greater emphasis on ethical considerations in industry (Pang, Lee, Murshed, 2023). Ethical aspects are becoming increasingly important in academic research and public discourse, as well as entrepreneurship. Research on Industry 4.0 has often overlooked the effects on society, leading to a focus primarily on shareholders that reinforces socio-ecological inequality and the vulnerability of the global economy (Özdemir, Hekim, 2018, Ghobakhloo, Iranmanesh, Mubarak, Mubarik, Rejeb, Nilashi, 2022). This raises serious societal concerns about the potential for high unemployment due to new technologies. Furthermore, there is an increasing demand for technology that is not solely used for economic growth but also aims to improve the quality of life (Petrescu, Neacșa, Laudacescu, Tănase, 2023). The goal is to create a world in which essential goods and services are accessible to everyone, regardless of region, age, gender, language, or other constraints (Saniuk, Grabowska, Straka, 2022). Social development, equal job opportunities, income equality, and autonomy are also crucial (Ghobakhloo, Iranmanesh, Tseng, Grybauskas, Stefanini, Amran, 2023). While productivity and technology were the primary focus of Industry 4.0, there is an increasing demand for an industry that prioritizes the role of humans and their needs.

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4.2.2. Enablers

To achieve the Industry 5.0 transformation, companies require well-defined strategies and tools. The following outlines the focus areas of action essential for attaining these strategic objectives:

ANCHORING I5.0 OBJECTIVES

Anchoring Industry 5.0 Objectives into corporate strategy underscores the imperative of integrating these goals comprehensively within business frameworks. Formulating strategies that fortify resilience, prioritize human-centric approaches, and promote sustainability across all facets of business models and operations is crucial.

To achieve the transformation towards Industry 5.0, companies must develop agile business models to support this evolution. Trstenjak, Hegedić, Tošanović, Opetuk, Đukić, Cajner (2023) emphasize that innovation management is crucial for addressing rapidly changing market conditions. Resilience in this context requires smart production systems that can flexibly analyze data and make agile decisions (Huang, Wang, Li, Zheng, Mourtzis, Wang, 2022). Big data analytics are instrumental in predicting customer behavior and improving decision-making (Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang, 2022), while real-time data technologies enhance and expedite these processes (Zizic, Mladineo, Gjeldum, Celent, 2022). Consequently, future business strategies will increasingly rely on data, software, and analytics (Huang, Wang, Li, Zheng, Mourtzis, Wang, 2022). Implementing Industry 5.0 principles necessitates redesigning existing business models and creating new ones (Ivanov, 2023, Möller, Vakilzadian, Haas, 2022). This shift will lead companies to become more service-oriented (Majerník, Daneshjo, Malega, Drábik, Barilová, 2022). Digital transformation requires changes in processes and management (De Felice, Petrillo, 2023) and an organizational structure that supports human-human, human-machine, and machine-machine interactions (Simion, Avasilcai, Alexa). Effective strategic planning and management of these interactions are crucial (Chandel, Sharma, 2023).

Lean management methods can foreground human influence on process improvement (Zizic, Mladineo, Gjeldum, Celent, 2022, Demir, Döven, Sezen, 2019). The European Foundation for Quality Management (EFQM) Model 2020 emphasizes sustainability (Zizic, Mladineo, Gjeldum, Celent, 2022) while the Human-Centric Single-Minute Exchange of Die (H-SMED) model focuses on human centricity in lean management (Alves, Lima, Gaspar, 2023). Strategies such as job rotation and diverse working hours can enhance employee well-being (Alves, Lima, Gaspar, 2023). Value stream mapping aids sustainability by reducing waste and resource consumption (Pizoń, Cioch, Kański, Sánchez García, 2022). Transitioning to a circular economy is crucial for improving environmental impact while maintaining profitability (Iqbal, Lee, Ren, 7 Dec. 2022-10 Dec. 2022, Martín-Gómez, Agote-Garrido, Lama-Ruiz, 2024).

Overall, the focus of entrepreneurial action should shift from maximizing shareholder value to enhancing value for all stakeholders (Martín-Gómez, Agote-Garrido, Lama-Ruiz, 2024, Ghobakhloo, Iranmanesh, Tseng, Grybauskas, Stefanini, Amran, 2023). By embedding Industry 5.0 goals into corporate strategy, companies can set appropriate

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priorities, allocate resources effectively, and take necessary actions to successfully navigate the transformation towards Industry 5.0.

UPSKILLING AND ENABLEMENT

To meet the demands of a rapidly evolving workforce, it is essential to upskill and enable employees. *Upskilling* involves developing employees' competencies through courses, training programs, certifications, and other educational initiatives. This includes acquiring technical skills for new technologies, enhancing leadership abilities, and improving communication proficiencies. *Enablement* focuses on providing the necessary tools, resources, and support for employees to effectively utilize their skills. This includes modern work tools, a supportive work environment, and fostering a culture of continuous learning and collaboration. By integrating *upskilling and enablement,* organizations can ensure their workforce remains adaptable and proficient in the modern work landscape.

Industry 5.0 is expected to create more jobs that offer greater freedom, design thinking, and creativity (Alojaiman, 2023), shifting human labor towards more cognitive tasks (Chandel & Sharma 2023). With Industry 5.0 concepts placing humans at the center of the production system, there are new demands on employee skills (Jafari, Azarian, Yu, 2022). As machines increasingly take over repetitive and monotonous tasks, jobs that required low qualifications are disappearing (Adel, 2022b). Despite this, Suciu, Plesea, Petre, Simion, Mituca, Dumitrescu, Bocaneala, Moroianu, Nasulea (2023) argue that more jobs will be created in intelligent systems than will be lost. Similarly Saniuk, Grabowska, Straka (2022) predict significant job growth in artificial intelligence, robotics, machine learning, and other related fields. Industry 5.0 is expected to create more jobs that offer greater freedom, design thinking, and creativity (Alojaiman, 2023) shifting human labor towards more cognitive tasks (Chandel, Sharma, 2023).

The importance of soft skills, such as critical thinking and creativity, is growing as we move towards Industry 5.0 (Suciu, Plesea, Petre, Simion, Mituca, Dumitrescu, Bocaneala, Moroianu, Nasulea, 2023). There is an urgent need to train employees in handling new technologies (Hofmann, Sternberg, Chen, Pflaum, Prockl, 2019). Currently, many employees, including managers, lack the competence to work with artificial intelligence (Mourtzis, Angelopoulos, Panopoulos, 2022, Suciu, Plesea, Petre, Simion, Mituca, Dumitrescu, Bocaneala, Moroianu, Nasulea, 2023). Investing in employee training and lifelong learning is crucial (Saniuk, Grabowska, Straka, 2022). Companies should foster positive attitudes and collaboration (Hicking, Wenger, Abbas, Benning, Bremer, Clemens, 2020) and regard employees as essential assets (Patil, Thakir, Gandhi, Savale, Sayyed, 2022). Training, unlearning, and learning are vital competencies for adapting to the changing environment (Alojaiman, 2023). Furthermore, employees should be educated on principles of resource conservation and environmental protection (Ramachandran, Nagarjuna, Akram, Bhalani, Raju, Ponnusamy, 2023, Verma, Bhattacharya, Madhani, Trivedi, Bhushan, Tanwar, Sharma, Bokoro, Sharma, 2022). Universities must also ensure the integration of future-critical skills into their curricula (Banholzer, 2022). The tasks for employees will change significantly in Industry 5.0, focusing more on cognitive work. This transition requires both technical training and the

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promotion of soft skills. Companies must invest in the continuous development of their employees, while educational institutions need to ensure that graduates possess the necessary skills for the labor market. These investments will better prepare the workforce for the demands of the future.

LEVERAGING INTERDISCIPLINARY SYNERGIES

By combining and sharing their respective expertise and resources, organizations and institutions can *leverage interdisciplinary synergies* to achieve common objectives. This collaborative approach enables the integration of diverse perspectives and capabilities, fostering innovation and enhancing the effectiveness of collective efforts towards shared goals.

Interdisciplinary synergies are crucial for the advancement of Industry 5.0, as they enable the integration of diverse fields such as engineering, life sciences, and social sciences, fostering reciprocal learning and the optimization of strengths while minimizing weaknesses (Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang, 2022). These synergies not only promote collaboration among various disciplines and stakeholders but also catalyze the development of innovative solutions to complex challenges that exceed the capabilities of any individual field. By amalgamating knowledge, skills, and resources across multiple domains, novel avenues for achieving a sustainable and equitable future are unveiled.

DEPLOYMENT OF ENABLING TECHNOLOGIES

The transition to Industry 5.0 can be effectively facilitated by the *deployment of enabling technologies*, coupled with the application of advanced methodologies to optimize processes and develop innovative production techniques. This strategic approach not only enhances operational efficiency but also fosters the creation of cutting-edge solutions, thereby driving the evolution towards Industry 5.0.

Key enablers and drivers of Industry 5.0 are primarily advanced technologies. Distinguishing between technologies associated with Industry 4.0 and those characteristics of Industry 5.0 can be challenging. These include artificial intelligence, Big Data, the Internet of Everything, blockchain, and digital twins (Mourtzis, Angelopoulos, Panopoulos, 2022). While many of these technologies are common to both Industry 4.0 and Industry 5.0, the focus has shifted in the latter. In Industry 5.0, the emphasis is on technologies that facilitate work for employees, ensuring that technology serves human needs, thus supporting rather than replacing human workers (Zizic, Mladineo, Gjeldum, Celent, 2022). Consequently, Industry 5.0 prioritizes human-machine collaboration (Joglekar, Kadam, Dharmadhikari, 2023).

Developing capabilities that enable organizations to derive insights from data and make rapid decisions is crucial for enhancing organizational agility (Schuh, Anderl, Dumitrescu, Krüger, Hompel, 2020). Technologies that streamline and expedite decision-making processes, such as the Internet of Things (IoT) and Big Data analytics, are particularly noteworthy. Edge computing, for instance, is a significant enabler of real-time decision-making (Bajic, Suzic, Moraca, Stefanović, Jovicic, Rikalovic, 2023). IoT

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systems facilitate communication between humans and machines (Chander, Pal, De, Buyya, 2022), and inter-system communication supports mass customization (Rajumesh, 2024). Moreover, Green IoT offers a potential solution to mitigate the high energy consumption associated with traditional IoT systems (Fraga-Lamas, Lopes, Fernández-Caramés, 2021). However, the technology that garners the most attention in Industry 5.0 research is collaborative robots (Jafari, Azarian, Yu, 2022).

Humans and machines have distinct strengths and limitations. Humans excel in flexibility, adaptability, and empathy, while robots can perform repetitive tasks, allowing humans to focus on creativity and innovation (Aheleroff, Huang, Xu, Zhong, 2022, Maddikunta, Pham, B, Deepa, Dev, Gadekallu, Ruby, Liyanage, 2022). The deployment of collaborative robots can enhance employee well-being (Longo, Padovano, Umbrello, 2020). Enhancing human-robot collaboration maximizes the strengths of both, improving industrial production efficiency (Ordieres-Meré, Gutierrez, Villalba-Díez, 2023). This collaboration is particularly relevant during unforeseen events, such as the COVID-19 pandemic (Jafari, Azarian, Yu, 2022). Moreover, when robots and humans share work, the fear of job loss diminishes, and mass personalization becomes achievable (Aheleroff, Huang, Xu, Zhong, 2022). To facilitate interaction between humans and machines, cyber-physical systems (CPS) are indispensable (Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang, 2022). CPS technology, which was significant in Industry 4.0, forms the foundation for advanced concepts such as human-cyber-physical systems and cyber-physical-social systems, essential components of Industry 5.0 (Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang, 2022).

Enabling technologies are pivotal in the transition to Industry 5.0. These technologies optimize processes, foster innovation, and enhance human-machine collaboration. Collaborative robots perform repetitive tasks, allowing humans to engage in more complex activities. The implementation of CPS is crucial for effective human-machine interaction. Overall, *enabling technologies* enhance efficiency, flexibility, and sustainability in industrial production, thereby addressing contemporary challenges.

IMPLEMENTING ENABLING TECHNOLOGIES

To support and guide the advancements and applications of Industry 5.0 initiatives, it is imperative to establish comprehensive policies and regulatory frameworks. This involves the formulation of robust legal structures, standards, and guidelines to ensure the safe and responsible deployment of emerging technologies and innovative business models. By developing and *implementing* these regulatory frameworks, policymakers can align the deployment of Industry 5.0 technologies with ethical standards, promote sustainability, and mitigate potential risks, thereby creating a secure and conducive environment for technological advancement.

The adoption of new technologies and concepts necessitates the establishment of robust regulations and frameworks (Maddikunta, Pham, B, Deepa, Dev, Gadekallu, Ruby, Liyanage, 2022, Nahavandi, 2019). The synergy between humans and machines engenders numerous ethical and moral questions that must be meticulously addressed (Suciu, Plesea, Petre, Simion, Mituca, Dumitrescu, Bocaneala, Moroianu,

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Nasulea, 2023). The implementation of ethical behavior in software systems is particularly challenging, given machines' lack of empathy and their consequent inability to inherently recognize ethical behavior. Therefore, comprehensive regulations and binding standards based on ethical guidelines are imperative to ensure ethical conduct (Prasant, Sain, Al-Absi, Kumar, 2021).

Furthermore, the extensive data collection inherent in modern production processes introduces significant risks related to data security compliance and privacy (Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang, 2022). These concerns necessitate thorough discussion not only within the industrial sector but also within the context of legislative frameworks (Trstenjak, Hegedić, Tošanović, Opetuk, Đukić, Cajner, 2023).

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5. DESCRIPTION OF EXISTING FRAMEWORKS

A comprehensive analysis was undertaken to identify and evaluate existing frameworks relevant to the concepts and phenomena associated with Industry 5.0. This chapter seeks to establish a robust and coherent foundation for comprehending the multifaceted impacts of Industry 5.0 on sustainability, resilience, and human centricity. In pursuit of this objective, the frameworks were systematically categorized into academic and non-academic domains, facilitating a nuanced understanding of their respective contributions to the discourse on Industry 5.0.

5.1.1. Examination Academic Area

This subsection undertakes a rigorous examination of academic frameworks, which have been systematically categorized into three distinct domains: Excerpts of Relevant Academic Industry 4.0 Frameworks, Academic Industry 4.0 & Industry 5.0 Frameworks, and Academic Industry 5.0 Frameworks. A total of 14 frameworks have been identified within this scope, as summarized in Table 2. The following sections offer a concise overview of these frameworks, highlighting their key components and contributions. For an in-depth analysis, detailed profiles of each framework are provided.

Table 2 Overview of Identified Academic Frameworks (own depiction)

Source	Brief Description
Excerpt of Relevant Academic Industry 4.0 Frameworks	
Hicking, Wenger, Abbas, Benning, Bremer, Clemens (2020)	Development of the Aachen Digital Architecture Management (ADAM) framework focusing on guiding organizations through the digital transformation process while complying with the principles of Industry 4.0
Hofmann, Sternberg, Chen, Pflaum, Prockl (2019)	Description of the intersection of supply chain management and Industry 4.0 and development of an agenda of future supply chain management 4.0 research topics
Peças, John, Ribeiro, Baptista, Pinto, Dias, Henriques, Estrela, Pilastri, Cunha (2023)	Introduction of a holistic framework for data-driven sustainability assessment for a continuous improvement culture
Schuh, Anderl, Dumitrescu, Krüger, Hompel (2020)	Introduction of the acatech Industrie 4.0 Maturity Index, which is a methodological approach to measure the maturity of companies in their digital transformation journey towards industry 4.0
Academic Industry 4.0 & Industry 5.0 Frameworks	
Aheleroff, Huang, Xu, Zhong (2022)	Analysis of the evolution from Industry 4.0 to Industry 5.0 and proposal of a holistic framework for the development of future

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	products and business models complemented by Industry 5.0 components
Martín-Gómez, Agote-Garrido, Lama-Ruiz (2024)	Introduction of a framework to promote sustainable manufacturing practices aligned with the Industry 5.0 values by integrating Industry 4.0 technologies with Industry 5.0 values
Zizic, Mladineo, Gjeldum, Celent (2022)	Discussion of the transition from Industry 4.0 to Industry 5.0, providing a comprehensive analysis of the key enablers for Industry 4.0 and Industry 5.0
Academic Industry 5.0 Frameworks	
Adel (2022b)	Exploration of the concept of Industry 5.0 and discussion of opportunities, limitations and future research prospects of Industry 5.0 with a focus on technologies
Ghobakhloo, Iranmanesh, Mubarak, Mubarik, Rejeb, Nilashi (2022)	Introduction of a reference model consisting of four layers and offering a holistic overview of Industry 5.0 as a socio-technological phenomenon
Ghobakhloo, Iranmanesh, Tseng, Grybauskas, Stefanini, Amran (2023)	Conduction of a content-centric review of relevant literature and synthesis of evidence to develop an architectural design for Industry 5.0, which offers a holistic overview of Industry 5.0
Iqbal, Lee, Ren (2022)	Discussion of the transition from Industry 4.0 to Industry 5.0 and elaboration of the role that Industry 5.0 plays in achieving the UN's 17 SDGs
Ivanov (2023)	Exploration of the concept of Industry 5.0 and derivation of an Industry 5.0 framework contextualized through the lens of the viable supply chain model, the reconfigurable supply chain, and business ecosystems
Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang (2022)	Presentation of the transition framework "Industry 4.1" between Industry 4.0 and Industry 5.0 and development of a comprehensive tri-dimension architecture framework for implementing Industry 5.0
Rajumesh (2024)	Bibliometric analysis to identify emerging research areas and key topics in Industry 5.0 and provision of a clustered roadmap for future studies and development initiatives

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EXCERPT OF RELEVANT ACADEMIC INDUSTRY 4.0 FRAMEWORKS

The following section focuses on the "Excerpt of Relevant Academic Industry 4.0 Frameworks." This part provides a detailed exploration of selected frameworks that have significantly contributed to the foundational understanding of Industry 4.0. These frameworks serve as a critical reference point for assessing the evolution towards Industry 5.0 and its implications.

Hicking et al. 2020: Aachen Digital Architecture Management (ADAM): Your Guide to the Digitally Connected Enterprise)

ADAM framework offers a comprehensive guide for organizations navigating the complexities of digital transformation, particularly within the Industry 4.0 paradigm. Central to the framework is the emphasis on the formulation of a well-defined digitalization strategy, coupled with the implementation of a robust digital architecture (Hicking, Wenger, Abbas, Benning, Bremer, Clemens, 2020, p. 6) that aligns technology with business objectives and customer needs (Hicking, Wenger, Abbas, Benning, Bremer, Clemens, 2020, p. 30). ADAM integrates both digital infrastructure and business development perspectives, addressing the multifaceted nature of digital transformation by dividing digital infrastructure into four distinct design levels and business development into four corresponding development levels (Hicking, Wenger, Abbas, Benning, Bremer, Clemens, 2020, p. 6). This structure facilitates a holistic approach that effectively balances technological innovation with customer-centricity (Hicking, Wenger, Abbas, Benning, Bremer, Clemens, 2020, p. 30).

The framework's alignment with the core principles of Industry 4.0—such as interconnected systems, data-driven decision-making, and the seamless integration of digital technologies (Hicking, Wenger, Abbas, Benning, Bremer, Clemens, 2020, p. 5)—further underscores its relevance. However, the implementation of ADAM may necessitate significant organizational changes and investments, particularly for companies burdened by legacy systems (Hicking, Wenger, Abbas, Benning, Bremer, Clemens, 2020, pp. 6–7). The inherent interconnectedness of systems within the framework introduces heightened cybersecurity risks, a critical challenge that ADAM duly acknowledges and addresses (Hicking, Wenger, Abbas, Benning, Bremer, Clemens, 2020, p. 16).

Positioned as a sustainability-oriented framework, ADAM emphasizes economic scalability and adaptability (Hicking, Wenger, Abbas, Benning, Bremer, Clemens, 2020, p. 4), recognizing the pivotal role of corporate culture in ensuring long-term success (Hicking, Wenger, Abbas, Benning, Bremer, Clemens, 2020, p. 30). It also advocates for a human-centric approach, identifying employees as essential contributors to the transformation process (Hicking, Wenger, Abbas, Benning, Bremer, Clemens, 2020, p. 9) and underscoring the importance of their continuous education and collaboration (Hicking, Wenger, Abbas, Benning, Bremer, Clemens, 2020, p. 11). Furthermore, ADAM highlights the necessity of resilience, advocating for rapid prototyping (Hicking, Wenger, Abbas, Benning, Bremer, Clemens, 2020, p. 29) and the implementation of stringent

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information security measures to effectively counter the evolving landscape of cyber threats (Hicking, Wenger, Abbas, Benning, Bremer, Clemens, 2020, p. 16).

This refined articulation strengthens the logical coherence of the argument, clearly linking the framework's features to its broader implications for organizations engaging in digital transformation within the context of Industry 4.0. A detailed profile of the ADAM framework can be found in Figure 5.

Hicking et al. 2020: Aachen Digital Architecture Management (ADAM): Your Guide to the Digitally Connected Enterprise

General information & Background

- The paper presents the Aachen Digital Architecture Management (ADAM) framework, which focuses on guiding organizations through the digital transformation process by defining a digitalization strategy and implementing a digital architecture (p. 6)
- The framework integrates digital infrastructure and business development perspectives to create a holistic approach to digital transformation (p. 6)
- The paper addresses the increasing importance of digitally driven innovation and interconnectedness in companies, especially in the context of Industry 4.0 (p. 6)
- The complexity of digital transformation initiatives necessitates a structured approach like ADAM to align technology, business objectives, and customer needs (p. 30)
- ADAM considers two areas, digital infrastructure, which is subdivided into four design levels, and business development, which is subdivided into four development levels (p. 6)

Advantages & Disadvantages

- The ADAM framework aligns with the principles of Industry 4.0 by emphasizing the integration of digital technologies, data-driven decision-making, and interconnected systems (p. 5)
- ADAM offers a holistic approach to digital transformation by integrating digital infrastructure, business development, and customer-centricity (p. 30)
- With ADAM, the needs of internal and external customers are always at the center of activities (p. 30)
- This holistic view enables organizations to address the complexities of Industry 4.0 initiatives by considering technological advancements, business objectives, and customer needs in a coordinated manner (p. 30)
- Implementing the ADAM framework may require significant organizational changes and investments in technology, which can be challenging for some companies (pp. 6-7)
- The complexity of aligning digital architecture with business objectives and customer requirements may pose implementation challenges, especially for organizations with legacy systems (pp. 6-7)
- The interconnected nature of Industry 4.0 systems and the reliance on digital technologies introduce cybersecurity risks that need to be carefully managed (p. 16)

Sustainability

- The paper positions ADAM as a sustainability-oriented framework that focuses on economic scalability, needs-based adaptation, and future-proof robustness of solution components in digital transformation (p. 4)
- Corporate culture plays an important role for achieving sustainable corporate success (p. 11)

Human centricity

- Employees are not exclusively perceived as a resource, but as key players in the digital transformation process taking place within the fields of action (p. 9)
- Not only must companies provide employees with continuing education opportunities, but also foster positive attitudes and a spirit of collaboration (p. 11)

Resilience

- Modifications could be developed quickly and tested in the form of prototypes and gates are useful in achieving acceptance of deliverables and provided the necessary structure for the project (p. 29)
- ADAM addresses the importance of information security as a cross-cutting topic, emphasizing the need for robust measures to ensure the confidentiality, availability, and integrity of data in the face of evolving cyber threats (p. 16)

Figure 5 Detailed Framework evaluation Hicking, Wenger, Abbas, Benning, Bremer, Clemens, 2020 (own depiction)

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Hofmann et al. 2019: Supply chain management and Industry 4.0: conducting research in the digital age

Hofmann, Sternberg, Chen, Pflaum, Prockl (2019) investigate the intersection of Supply Chain Management (SCM) and Industry 4.0, with a particular focus on the digital and autonomous integration of processes both within and between organizations. Industry 4.0 is characterized by automation, interconnectivity, transparency, and a customer-centric approach, which collectively enable more proactive decision-making within supply chains. The paper seeks to identify research opportunities in the domain of SCM 4.0 and to lay a groundwork for future studies, underscoring the necessity for organizations to rethink their business models and the evolving roles of supply chain participants in a digitally transformed environment. A central theme is the empowerment of supply chain workers and managers, highlighting the critical need for them to acquire new competencies relevant to the digital age. This focus is particularly important as supply chains evolve into complex ecosystems that encompass not only traditional supply chain actors but also technology providers and intermediaries. The paper underscores the growing significance of these ecosystems and the need for a more integrated and collaborative approach in managing supply chains (Hofmann, Sternberg, Chen, Pflaum, Prockl, 2019, pp. 945–949).

While the paper provides valuable insights into the potential of Industry 4.0 for SCM and identifies key research opportunities, it also acknowledges the current paucity of comprehensive studies in this field (Hofmann, Sternberg, Chen, Pflaum, Prockl, 2019, p. 945). Additionally, although the paper touches on the emerging research related to the transition from Industry 4.0 to Industry 5.0, it falls short of offering practical guidance on how organizations can effectively navigate this shift (Hofmann, Sternberg, Chen, Pflaum, Prockl, 2019, p. 951). This highlights an important gap in the literature and suggests a need for future research to focus on actionable strategies for implementing Industry 5.0 principles in SCM. A detailed profile of the framework discussed in the paper of Hofmann, Sternberg, Chen, Pflaum, Prockl (2019) is provided in Figure 6.

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Hofmann et al. 2019: Supply chain management and Industry 4.0: conducting research in the digital age

General information & Background

- Focus on the intersection of supply chain management (SCM) and Industry 4.0, which refers to the trend of automation and data exchange in manufacturing technologies and processes (p. 945)
- SCM 4.0 is characterized by the digital and autonomous linkages within and between companies, with a focus on customer-centricity, interconnectivity, automation, transparency, and proactive decision-making (p. 946)
- The paper aims to explore the research opportunities associated with SCM 4.0 and lay down a foundation for future research in this emerging field (p. 945)
- The digital transformation in supply chains is driving organizations to rethink their business models and roles within their supply chains (p. 951)
- The paper emphasizes the importance of empowering supply chain workers and managers with the right skills in the digital age (p. 949)
- It highlights the shift towards supply chain ecosystems and the role of technology providers and intermediaries (p. 946)

Advantages & Disadvantages

- Provides insights into the promises and impacts of Industry 4.0 on supply chain management (p. 945)
- Identifies key characteristics and research opportunities associated with SCM 4.0 (pp. 945-946)
- Highlights the importance of empowering supply chain workers and managers in the digital age (p. 949)
- Research on the impacts of Industry 4.0 on SCM is still scarce, indicating a lack of comprehensive understanding in this area (p. 945)
- While the paper identifies research opportunities, it may not provide practical guidance on how organizations can effectively transition from Industry 4.0 to Industry 5.0 (p. 951)

Sustainability

- *The paper does not directly address sustainability in the context of supply chain management and Industry 4.0*

Human centricity

- The paper emphasizes the importance of empowering supply chain workers and managers in the digital age (p. 949)

Resilience

- *The paper does not explicitly discuss resilience in the context of supply chain management and Industry 4.0*

Figure 6 Detailed Framework evaluation Hofmann, Sternberg, Chen, Pflaum, Prockl, 2019 (own depiction)

Peças et al. 2023: Holistic Framework to Data-Driven Sustainability Assessment

Peças, John, Ribeiro, Baptista, Pinto, Dias, Henriques, Estrela, Pilastri, Cunha (2023) introduce a holistic framework for data-driven sustainability assessment (Peças, John, Ribeiro, Baptista, Pinto, Dias, Henriques, Estrela, Pilastri, Cunha, 2023, p. 13), meticulously structured into five key steps: identifying the scope of the assessment, defining relevant metrics and indicators, establishing data collection procedures, validating the data, and fostering a culture of continuous improvement (Peças, John, Ribeiro, Baptista, Pinto, Dias, Henriques, Estrela, Pilastri, Cunha, 2023, pp. 17–18). This framework is explicitly designed to address the increasing emphasis on sustainable practices within manufacturing and industry (Peças, John, Ribeiro, Baptista, Pinto, Dias, Henriques, Estrela, Pilastri, Cunha, 2023, p. 1), offering a systematic and universally applicable approach that can be employed across diverse industrial sectors (Peças, John, Ribeiro,

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Baptista, Pinto, Dias, Henriques, Estrela, Pilastri, Cunha, 2023, p. 18). By harnessing digital capabilities and data-driven methodologies, the framework aims to enable companies to effectively and efficiently assess their sustainability performance (Peças, John, Ribeiro, Baptista, Pinto, Dias, Henriques, Estrela, Pilastri, Cunha, 2023, p. 1).

However, despite its comprehensive design, the framework may pose challenges for organizations that lack prior experience in sustainability assessment or data-driven methodologies. The implementation of this framework demands significant resources for data collection, validation, and analysis, which could be particularly burdensome for smaller organizations. Additionally, companies accustomed to traditional sustainability assessment methods might face resistance in transitioning to this data-driven approach, along with the associated cultural shift toward continuous improvement. Moreover, while the structured nature of the framework provides a clear and methodical pathway, it may also constrain flexibility, making it more difficult to adapt to specific organizational contexts or industry-specific requirements (Peças, John, Ribeiro, Baptista, Pinto, Dias, Henriques, Estrela, Pilastri, Cunha, 2023, p. 18).

The paper underscores the pivotal role that sustainability assessment methodologies play in enhancing sustainability performance within industrial operations (Peças, John, Ribeiro, Baptista, Pinto, Dias, Henriques, Estrela, Pilastri, Cunha, 2023, p. 1). It highlights the importance of data-driven approaches in promoting measurable and sustainable business practices (Peças, John, Ribeiro, Baptista, Pinto, Dias, Henriques, Estrela, Pilastri, Cunha, 2023, p. 4), supporting informed decision-making, and fostering a culture of continuous improvement (Peças, John, Ribeiro, Baptista, Pinto, Dias, Henriques, Estrela, Pilastri, Cunha, 2023, p. 1). The subsequent Figure 7 provides a detailed breakdown of the framework, elucidating its components and their interrelations.

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Peças et al. 2023: Holistic Framework to Data-Driven Sustainability Assessment

General information & Background

- Paper introduces a holistic framework for data-driven sustainability assessment (p. 12)
- The framework is structured into five key steps (pp. 17-18):
  1. Identifying the Scope of the Assessment
  2. Defining Relevant Metrics and Indicators
  3. Establishing Data Collection Procedures
  4. Data Validation
  5. Adopting a Continuous Improvement Culture
- Background is the increasing importance of sustainable practices in manufacturing and industry (p. 1)
- The framework provides a systematic and universal framework for sustainability assessment that can be applied across various industrial sectors, irrespective of their operational areas (p. 18)
- Framework is tailored to help companies assess their sustainability performance effectively and easily by leveraging digital capabilities, data-driven concepts, and continuous improvement strategies (p. 1)

Advantages & Disadvantages

- Considering economic, environmental, and social dimensions based on the triple bottom line concept (p. 1)
- Can be applied across various industrial sectors, irrespective of their operational areas (p. 18)
- By integrating data-driven approaches and digital capabilities, the framework enables organizations to make informed decisions based on validated data (p. 18)
- The framework promotes a culture of continuous improvement in sustainability assessment and action implementation, aligning with the principles of lean thinking and fostering opportunities for industrial symbiosis and circular economy actions (p. 18)
- The framework may be complex to implement for organizations without prior experience in sustainability assessment or data-driven approaches, requiring dedicated resources and expertise (p. 18)
- Implementing the framework may require significant resources in terms of data collection, validation, and analysis, which could be challenging for smaller organizations with limited capabilities (p. 18)
- Organizations accustomed to traditional sustainability assessment methods may face resistance in adopting a data-driven approach and fostering a culture of continuous improvement (p. 18)
- The framework's structured approach may limit flexibility in adapting to specific organizational needs or industry requirements, potentially constraining its applicability in certain contexts (p. 18)

Sustainability

- Importance of Sustainability Assessment Methodologies:
  The paper underscores the critical necessity of sustainability assessment methodologies for evaluating and improving sustainability performance in industrial operations (p. 1)
- Role of Data-Driven Approaches:
  Data-driven approaches are highlighted as essential for guiding measurable and sustainable business practices, emphasizing the importance of collecting and utilizing data to make informed decisions in achieving sustainability goals (p. 4)
- Integration of Data-Driven Concepts with Sustainability Assessment:
  The integration of data-driven concepts with sustainability assessment approaches is crucial for fostering agile sustainable development and continuous improvement in sustainable practices across organizations (p. 1)

Human centricity

- The concept of Human centricity is not directly addressed in the paper

Resilience

- The concept of resilience is not directly addressed in the paper

Figure 7 Detailed Framework evaluation Peças, John, Ribeiro, Baptista, Pinto, Dias, Henriques, Estrela, Pilastri, Cunha, 2023 (own depiction)

Schuh et al. 2020: Industrie 4.0 Maturity Index: Managing the Digital Transformation of Companies

The study presents the acatech Industrie 4.0 Maturity Index, a methodological tool crafted to measure and guide companies through their digital transformation toward Industry 4.0 (Schuh, Anderl, Dumitrescu, Krüger, Hompel, 2020, p. 15). The index is organized around key development stages: computerization, connectivity, visibility,

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transparency, predictive capacity, and adaptability (Schuh, Anderl, Dumitrescu, Krüger, Hompel, 2020, p. 17). By addressing both the challenges and opportunities of Industry 4.0, the framework emphasizes critical capabilities such as digital readiness, structured communication, self-learning information processing, and dynamic collaboration within value networks (Schuh, Anderl, Dumitrescu, Krüger, Hompel, 2020, p. 23). This Maturity Index provides a systematic approach for companies to assess their digital maturity and chart a course for implementing Industry 4.0 technologies, potentially setting the stage for a future transition to Industry 5.0 (Schuh, Anderl, Dumitrescu, Krüger, Hompel, 2020, p. 3). Through its application, companies can sharpen their competitive edge in the digital landscape, derive actionable insights for transformation, and adopt best practices as they advance (Schuh, Anderl, Dumitrescu, Krüger, Hompel, 2020, pp. 47–53). Nevertheless, the study also highlights certain challenges, including the necessity for organizational changes that extend beyond mere technological advancements, and potential gaps in the framework's ability to fully accommodate the emerging paradigms of Industry 5.0 (Schuh, Anderl, Dumitrescu, Krüger, Hompel, 2020, p. 31).

Furthermore, the study underscores the importance of embedding sustainability into digital transformation efforts, advocating for the development of competencies like resilience, responsiveness, and adaptability. It argues that solutions aligned with a circular economy are essential for tackling global issues such as climate change and resource scarcity (Schuh, Anderl, Dumitrescu, Krüger, Hompel, 2020, p. 5). Additionally, it emphasizes the need for companies to cultivate the ability to make rapid decisions, enhance agility (Schuh, Anderl, Dumitrescu, Krüger, Hompel, 2020, p. 7), and build resilience, enabling them to effectively navigate the complexities of the digital landscape and respond to disruptions (Schuh, Anderl, Dumitrescu, Krüger, Hompel, 2020, p. 5). The following Figure 8 offers a detailed breakdown of the Maturity Index framework, illuminating its components and their interrelations.

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Schuh et al. 2020: Industrie 4.0 Maturity Index: Managing the Digital Transformation of Companies

General information & Background

- The study introduces the acatech Industrie 4.0 Maturity Index, which is a methodological approach to measure the maturity of companies in their digital transformation journey towards industry 4.0 (p. 15)
- The index is designed based on value-based development stages, including computerisation, connectivity, visibility, transparency, predictive capacity, and adaptability (p. 17)
- The research was conducted by a team of experts in collaboration with acatech, the German National Academy of Science and Engineering, to address the challenges and opportunities of Industrie 4.0 (p. 10)
- The study discusses various capabilities required for businesses in the context of Industrie 4.0, such as digital capability, structured communication, self-learning information processing, information system integration, organic internal organization, dynamic collaboration within the value network, willingness to change, and social collaboration (p. 23)

Advantages & Disadvantages

- The study provides a structured framework for companies to assess their digital maturity and develop a roadmap for implementing Industrie 4.0 technologies. This approach can serve as a foundation for transitioning to Industry 5.0, enabling companies to build on their existing digital capabilities. (p. 4)
- By leveraging the insights and recommendations from the Industrie 4.0 Maturity Index, companies can enhance their competitiveness in the evolving digital landscape. This positions them well to adapt to the advancements and requirements of Industry 5.0. (p. 3)
- The study offers valuable knowledge and best practices for digital transformation, which can be applied and adapted as companies progress towards Industry 5.0. This knowledge transfer can facilitate a smoother transition and help companies stay ahead in the digital transformation journey. (pp. 47-53)
- Industry 5.0 is expected to bring about new technologies and paradigms that may not be fully captured in the current Industrie 4.0 Maturity Index. Companies relying solely on the existing framework may face challenges in adapting to the rapid technological changes associated with Industry 5.0.
- Transitioning from Industry 4.0 to Industry 5.0 requires not only technological advancements but also significant organizational changes. The Industrie 4.0 Maturity Index may not fully address the organizational aspects needed for Industry 5.0, leading to potential gaps in the transformation process. (p. 31)
- Companies that have heavily invested in Industry 4.0 initiatives based on the Maturity Index may face challenges in reallocating resources and restructuring their strategies to align with the requirements of Industry 5.0. This transition may require additional investments and adjustments to existing plans. (pp. 15-16)

Sustainability

- The study emphasizes the importance of sustainability in the context of digital transformation, highlighting the need for companies to develop competencies such as resilience, responsiveness, and adaptability to remain competitive (p. 5)
- It suggests that solutions compatible with a circular economy are essential for addressing challenges such as climate change and resource scarcity (p. 5)

Human centricity

- The study underscores the importance of developing specific capabilities that enable companies to generate knowledge from data, facilitate rapid decision-making, and promote agility throughout the organization (p. 7)

Resilience

- The study suggests that companies need to cultivate resilience as a core competency to navigate the evolving digital landscape and respond effectively to disruptions (p. 5)
- The structured approach provided by the Industrie 4.0 Maturity Index can help companies build resilience by identifying areas for improvement and developing strategies to address challenges in the digital transformation process (p. 54)

Figure 8 Detailed Framework evaluation Schuh, Anderl, Dumitrescu, Krüger, Hompel, 2020 (own depiction)

INDUSTRY 4.0 TOWARDS INDUSTRY 5.0 FRAMEWORKS

The forthcoming section explores the frameworks that guide the transition from Industry 4.0 to Industry 5.0. This segment offers a comprehensive examination of key methodologies that bridge these two industrial paradigms. These frameworks are crucial for understanding the evolution of industrial practices, providing insights into

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how the foundational concepts of Industry 4.0 are being redefined to address the demands and opportunities of the next stage. Through this analysis, these frameworks serve as essential tools for navigating the shift towards a more advanced, human-centric, and sustainable industrial landscape.

Aheleroff et al. 2022: Toward sustainability and resilience with Industry 4.0 and Industry 5.0

Aheleroff, Huang, Xu, Zhong (2022) examine the transition from Industry 4.0 to Industry 5.0, advocating for a more human-centric, sustainable, and resilient industrial approach (Aheleroff, Huang, Xu, Zhong, 2022, p. 3). The paper presents a conceptual model and framework for Industry 5.0, focusing on sustainability through mass personalization (Aheleroff, Huang, Xu, Zhong, 2022, p. 3) and balancing technological progress with social and environmental responsibility (Aheleroff, Huang, Xu, Zhong, 2022, p. 7). While Industry 4.0's role in enhancing production efficiency is acknowledged, Industry 5.0 is seen as essential for sustainable development, addressing environmental challenges, and shifting from shareholder to stakeholder value (Aheleroff, Huang, Xu, Zhong, 2022, p. 17).

The framework offers a comprehensive structure for developing products and business models aligned with the United Nations Sustainable Development Goals (SDGs) (Aheleroff, Huang, Xu, Zhong, 2022, p. 12). However, challenges include the lack of specific implementation guidelines, the framework's generality, and potential difficulties in global adoption due to varying technological readiness and economic disparities (Aheleroff, Huang, Xu, Zhong, 2022, p. 11). Sustainability remains a central theme, with strong advocacy for eco-friendly practices and social responsibility (Aheleroff, Huang, Xu, Zhong, 2022, pp. 17–18). Governance structures aligned with global sustainability goals are emphasized (Aheleroff, Huang, Xu, Zhong, 2022, p. 8), along with the importance of human centricity through "Human Capital 5.0," which integrates human creativity with technology to promote personalized products and services (Aheleroff, Huang, Xu, Zhong, 2022, pp. 10–12).

The paper also highlights the need for resilience, particularly in response to economic challenges like the COVID-19 pandemic, suggesting that both technological innovation and human involvement are key to achieving resilience and sustainability in Industry 5.0 (Aheleroff, Huang, Xu, Zhong, 2022, p. 18). The following Figure 9 provides a detailed breakdown of the proposed framework, illustrating its components and interconnections.

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Aheleroff et al. 2022: Toward sustainability and resilience with Industry 4.0 and Industry 5.0

General information & Background

- The paper delves into the evolution from Industry 4.0 to Industry 5.0, highlighting the need for a more human-centric, sustainable, and resilient industry (p. 3)
- It proposes a conceptual model for the transition to Industry 5.0 and a framework for achieving sustainability through mass personalization (p. 3)
- The research emphasizes the role of Industry 4.0 technologies in enhancing production efficiency and the significance of Industry 5.0 in leading to sustainable development (p. 7)
- The paper discusses the emergence of Industry 5.0 as a response to the environmental threats posed by automation and digitization advancements, aiming for a more sustainable and human-centric approach (p. 7)
- It discusses the need to address the global challenge of transitioning towards sustainability and resilience in the manufacturing industry, moving from a focus on shareholder value to stakeholder value (p. 17)
- Current trends make the world shift towards Industry 5.0, which aims to address environmental concerns, social inequality, and overuse of natural resources through a more value-driven and human-centric approach (p. 3)

Advantages & Disadvantages

- The proposed Reference Architecture Model for Industry 5.0 gives businesses a holistic framework for developing future products and business models using a three-dimensional map in a structured manner complemented by the Industry 5.0 components (p. 12)
- The framework can be mapped with the United Nations Sustainable Development Goals (SDGs) and compromises crucial aspects of Industry 5.0 describing all essential elements and providing a common understanding of what Industry 5.0 requires, the function of each component and the interfaces (p. 12)
- The paper highlights the shift from technology-driven (I4.0) strategies to a value-driven human-centric (I5.0) approach which ensures that Industry 5.0 initiatives prioritize long-term benefits for all stakeholders (p. 13)
- The paper introduces a conceptual model and framework for Industry 5.0, but lacks specific implementation guidelines for organizations transitioning from Industry 4.0 to Industry 5.0, suggesting that clearer guidance on practical steps and best practices could enhance the applicability of the research findings (p. 11)
- The framework is very general and not specific enough to derive specific benefits for implementation in companies (p. 11)
- The framework may encounter challenges in global adoption due to varying levels of technological readiness, economic disparities, and regulatory environments, emphasizing the crucial need to address these challenges effectively for the successful implementation of Industry 5.0 initiatives worldwide (p. 11)

Sustainability

- The paper emphasizes the importance of sustainability in addressing global environmental challenges and promotes eco-friendly practices (p. 17)
- It highlights the need for social responsibility in Industry 5.0 initiatives, aiming to balance economic growth with social well-being and equity (pp. 17-18)
- The role of governance structures in Industry 5.0 that are in line with global sustainability goals such as the SDGs is discussed (p. 8)

Human centricity

- Human Capital 5.0 brings the unique creativity of the human being to a production model, where the focus lies on humans using machines and enabling technologies (p. 10)
- The paper promotes customer-centric strategies under Industry 5.0, aiming to deliver personalized products and services that meet the diverse needs and preferences of customers (pp. 11-12)

Resilience

- The paper underscores the need for addressing economic challenges and quick recovery with resilience in the wake of the COVID pandemic (p. 18)
- Both technologies and humans are crucial to accomplishing resilience for meeting mass personalization, which could address individuals' requirements and provide a sense of ownership with loyalty to products, resulting in higher sustainability and reducing various waste, including physical, digital, social, and process (p. 18)

Figure 9 Detailed Framework evaluation Aheleroff, Huang, Xu, Zhong, 2022 (own depiction)

Martín-Gómez et al. 2024: A Framework for Sustainable Manufacturing: Integrating Industry 4.0 Technologies with Industry 5.0 Values

Martín-Gómez, Agote-Garrido, Lama-Ruiz (2024) propose a framework that integrates Industry 4.0 technologies with Industry 5.0 values to support sustainable manufacturing. This framework aims to guide the development of manufacturing systems that prioritize sustainability, human centricity, and resilience. It highlights the

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seamless integration of advanced technologies, machinery, and human expertise throughout the system life cycle, addressing challenges related to resource scarcity and minimizing environmental and societal impacts (Martín-Gómez, Agote-Garrido, Lama-Ruiz, 2024, p. 1).

The framework takes a holistic approach, considering the economic, social, and environmental dimensions of sustainability. It introduces a methodology for industries and academia to incorporate emerging technologies while aligning with Industry 5.0 values (Martín-Gómez, Agote-Garrido, Lama-Ruiz, 2024, p. 2). However, the early stage of Industry 5.0 presents challenges in the framework's applicability, and the authors call for empirical studies to validate and refine the proposed concepts (Martín-Gómez, Agote-Garrido, Lama-Ruiz, 2024, p. 14). The shift from Industry 4.0 to Industry 5.0 may also require significant organizational and operational changes, as the focus moves from a technology-centric approach to one centered on sustainability and ethics (Martín-Gómez, Agote-Garrido, Lama-Ruiz, 2024, p. 8).

Sustainability is a key focus, with an emphasis on balancing social, environmental, and economic goals. Human centricity is promoted by prioritizing well-being, autonomy, privacy, and security for all involved in the manufacturing process. The framework also underscores the importance of resilience, ensuring that industrial systems can adapt and maintain continuity in the face of challenges. The paper suggests that integrating Industry 5.0 values with Industry 4.0 technologies can lead to more sustainable, inclusive, and resilient manufacturing systems (Martín-Gómez, Agote-Garrido, Lama-Ruiz, 2024, pp. 1–8)The following Figure 10 provides a detailed breakdown of the framework, illustrating its components and their interconnections.

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Martín-Gómez et al. 2024: A Framework for Sustainable Manufacturing: Integrating Industry 4.0 Technologies with Industry 5.0 Values

General information & Background

- The paper explores the impact of Industry 4.0 technologies on achieving sustainable manufacturing (p. 1)
- It proposes a theoretical framework for designing sustainable manufacturing systems guided by the Industry 5.0 values sustainability, Human centricity, and resilience (p. 1)
- The framework enables the seamless integration of enabling technologies, machinery, and human expertise throughout the system life cycle (p. 1)
- The limitations imposed by resource scarcity and the need to mitigate adverse environmental and societal impacts have increased the urgency for sustainable manufacturing systems (p. 1)
- The digital divide among vulnerable workers is exacerbated by the rapid development and implementation of new technologies (p. 1)
- Industry 4.0 technologies offer potential to enhance the competitiveness of manufacturing systems, but their impact on sustainable manufacturing is uncertain (p. 1)

Advantages & Disadvantages

- By integrating Industry 4.0 technologies with Industry 5.0 values, the framework aims to promote sustainable manufacturing practices that prioritize humanity, the environment, and process continuity (p. 8)
- The framework considers the economic, social, and environmental dimensions of sustainability, providing a holistic view of how emerging technologies can align with the core values of Industry 5.0 (p. 2)
- It introduces a novel approach to guide the incorporation of technologies and values into manufacturing systems, offering a theoretical framework for industries and academics to select and apply technologies in line with Industry 5.0 values (p. 2)
- One limitation of the framework is the early stage of Industry 5.0, which may impact the applicability and relevance of the proposed approach as the concept evolves (p. 14)
- The framework would benefit from empirical studies to validate and refine its theoretical concepts, suggesting a need for further research and practical application in real industrial contexts (p. 14)
- Transitioning from Industry 4.0 to Industry 5.0 involves a shift in focus from technology-driven productivity to values-centered sustainability, which may require significant organizational and operational changes (p. 8)
- The impact of Industry 4.0 technologies on achieving sustainable manufacturing in the context of Industry 5.0 remains uncertain, highlighting the need for ongoing evaluation and adjustment of the framework (p. 1)

Sustainability

- The paper emphasizes the importance of sustainability in manufacturing, focusing on balancing social, environmental, and economic dimensions (triple bottom line) (p. 1)
- Sustainability is considered a key strategic objective for manufacturing companies, with approaches like Circular Economy seen as viable for improving environmental impact while maintaining profitability (p. 1)

Human centricity

- Industry 5.0 values include Human centricity, emphasizing the well-being of all individuals involved in the industrial context (p. 8)
- Values such as autonomy, privacy, and security are considered important within the human-centric approach (p. 8)
- The paper suggests that the integration of new technologies guided by Industry 5.0 values can help bridge the technological divide among vulnerable workers, promoting inclusivity and empowerment (p. 1)

Resilience

- Resilience is a core value of Industry 5.0, focusing on the industrial system's ability to positively adapt to changes and face adversities (p. 8)
- The resilient approach allows the system to become robust and ensure system continuity (p.1, p. 8)

Figure 10 Detailed Framework evaluation Martín-Gómez, Agote-Garrido, Lama-Ruiz, 2024 (own depiction)

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Zizic et al. 2022: From Industry 4.0 towards Industry 5.0: A Review and Analysis of Paradigm Shift for the People, Organization and Technology – Focus section: 3. Review of Key Enablers

Zizic, Mladineo, Gjeldum, Celent (2022) investigate the evolution from Industry 4.0 to Industry 5.0, focusing on the integration of human-centric values, sustainable practices, and resilient systems within industrial frameworks. The paper emphasizes the necessity of rethinking the relationship between humans and technology, advocating for organizational models that prioritize long-term value creation and ethical considerations. It critiques Industry 4.0 for its insufficient focus on human and ethical dimensions, urging a shift towards Industry 5.0 to better incorporate these critical aspects. The analysis offers detailed insights into the driving forces behind both Industry 4.0 and 5.0, examining their broader implications across various sectors (Zizic, Mladineo, Gjeldum, Celent, 2022, p. 6). However, the absence of a specific framework in the paper may limit the practical application of Industry 5.0 principles (Zizic, Mladineo, Gjeldum, Celent, 2022, p. 11). Moreover, the lack of concrete guidance on integrating human-centric practices within diverse organizational contexts could challenge the effective adoption of these concepts (Zizic, Mladineo, Gjeldum, Celent, 2022, p. 13).

The discussion also addresses the importance of developing sustainable business models that incorporate environmental and social criteria into technology selection (Zizic, Mladineo, Gjeldum, Celent, 2022, pp. 11–13). Additionally, the enhancement of human-machine collaboration, particularly through technologies such as networked sensors and AI, is explored as a means of achieving greater human centricity (Zizic, Mladineo, Gjeldum, Celent, 2022, p. 9). Resilience is underscored as essential for managing disruptions, with a focus on enhancing information visibility and strategic human resource management to strengthen adaptability and robustness in industrial settings (Zizic, Mladineo, Gjeldum, Celent, 2022, pp. 11–12). For a more comprehensive understanding, the following Figure 11 provides a detailed breakdown of the proposed approach, illustrating the components and their interconnections.

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Zizic et al. 2022: From Industry 4.0 towards Industry 5.0: A Review and Analysis of Paradigm Shift for the People, Organization and Technology – Focus section: 3. Review of Key Enablers

General information & Background

- The focus section discusses the transition from Industry 4.0 to Industry 5.0, focusing on key enablers such as Human centricity, sustainability, and resilience (p. 6)
- It highlights the importance of understanding the interplay between humans and technology, as well as the need for appropriate organizational models and long-term value creation (p. 6)
- The focus section also explores the impact of new technologies on sustainability and resilience, including the development of sustainable business models and the integration of technologies to improve organizational performance (p. 10)
- The focus section addresses the limitations and criticisms of Industry 4.0, particularly regarding the lack of human perspective and ethical considerations (p. 6)
- Current trends drive the development of the focus section by indicating a growing awareness of the importance of human-centric approaches and ethical considerations in technological advancements (p. 6)
- The drivers of Industry 4.0 and Industry 5.0 necessitate the exploration of Human centricity, sustainability, and resilience to ensure the successful implementation and societal impact of these industrial paradigms (p. 6, p. 12)

Advantages & Disadvantages

- The results of the focus section provide a comprehensive analysis of the key enablers for Industry 4.0 and Industry 5.0, particularly in relation to people, organization, and technology (p. 6)
- The analysis of the practical context of Industry 4.0 and Industry 5.0 provides valuable insights for developing a framework that is independent of sector and levels in companies and society, as it considers the broader implications of these paradigms on various aspects of the industrial landscape (p. 6)
- In the focus section, the core lies in the presentation of the enablers, sustainability, Human centricity and resilience, so that there is no provided framework (p. 13)
- Limited integration of Human centricity, sustainability, and resilience into a cohesive framework may hinder the comprehensive implementation of Industry 5.0 principles (p. 11)
- Insufficient guidance on practical strategies for implementing human-centric practices across diverse industrial sectors and organizational levels may impede the effective adoption of Industry 5.0 principles (p. 13)

Sustainability

- The focus section emphasizes sustainability in Industry 4.0 and 5.0, advocating for sustainable business models using smart data and technology integration (p. 10)
- It highlights technology's environmental impacts and stresses integrating environmental and social criteria into technology selection to promote greener practices (pp. 10-11)
- The section addresses technology's ethical dimensions, emphasizing ethical considerations for Industry 5.0's sustainability and societal impact (p. 11)

Human centricity

- Operator 4.0 seeks to foster trust and interaction between humans and machines, envisioning proactive, participative factory workers (p. 6)
- The focus section underscores understanding the dynamics between humans and technology in Industry 4.0, stressing technology's role to complement rather than replace human work (p. 7)
- The section highlights the development of technology aligned with human needs, focusing on networked sensors, digital twins, virtual training, and AI to enhance human-machine collaboration (p. 9)

Resilience

- The section emphasizes the importance of resilience in Industry 4.0 and Industry 5.0, highlighting the need for organizational resilience to withstand disruptions and manage vulnerabilities (p. 11)
- It discusses the multidisciplinary nature of organizational resilience, underscoring the role of strategic human resource management in developing requisite knowledge, skills, and abilities to navigate challenging situations (p. 11)
- The focus section addresses the role of technology in enhancing organizational resilience, emphasizing the need for information visibility, integration, and smart platforms (p. 12)

Figure 11 Detailed Framework evaluation Zizic, Mladineo, Gjeldum, Celent (2022) (own depiction)

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INDUSTRY 5.0 FRAMEWORKS

This section provides an in-depth analysis of key frameworks that are shaping and advancing the principles of Industry 5.0. These frameworks are crucial for understanding how Industry 5.0 distinguishes itself from its predecessor by prioritizing human-centric values, sustainability, and resilience. Through a careful exploration, this section illustrates how these frameworks are guiding the future of industrial practices, offering essential strategies for implementing the core principles of Industry 5.0 and addressing the complexities of the evolving industrial landscape.

Adel (2022a) Future of industry 5.0 in society: human-centric solutions, challenges and prospective research areas

The paper by Adel (2022a) explores the opportunities, limitations, and future research directions of Industry 5.0, the next phase in the industrial revolution. It highlights the shift from Industry 4.0, dominated by technology, to Industry 5.0, where the focus is on synergistic collaboration between humans and machines. The study analyzes Industry 5.0's applications across various sectors, including healthcare, supply chain management, and manufacturing, and identifies key technologies such as big data analytics, the Internet of Things, collaborative robots, Blockchain, digital twins, and emerging 6G systems (Adel, 2022a, p. 1). Industry 5.0 promises increased productivity, enhanced customer satisfaction, and economic growth through the seamless integration of human and machine capabilities (Adel, 2022a, p. 1). However, the paper acknowledges significant challenges, particularly in human-robot collaboration on assembly lines, but falls short of providing in-depth solutions for these challenges during the transition from Industry 4.0 to Industry 5.0. The discussion on challenges remains somewhat superficial, lacking a thorough analysis of the complexities involved (Adel, 2022a, p. 9).

On sustainability, the paper suggests that Industry 5.0 can drive sustainable manufacturing by using technologies like artificial intelligence to enhance personalization, reduce waste, and optimize resource efficiency. It advocates for iterative processes focused on repurposing, recycling, and asset recovery to maintain sustainability in manufacturing. Central to the discussion is the concept of human centricity, where collaboration between humans and machines is key to innovation and progress (Adel, 2022a, pp. 5–6). The accompanying Figure 12 provides a detailed breakdown of the framework, illustrating its components and their interconnections.

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Adel 2022: Future of industry 5.0 in society: human-centric solutions, challenges and prospective research areas

General information & Background

- The paper discusses the opportunities, limitations, and future research prospects of Industry 5.0, which is considered the next phase of industrial revolution (p. 1)
- It explores the concept of Industry 5.0, its applications in various sectors such as healthcare, supply chain, and manufacturing, and the advanced technologies involved (p. 1)
- Challenges and issues related to the collaboration between humans and robots in the assembly line are highlighted (p. 1)
- Goal is to analyze the potential applications of Industry 5.0 and provide insights into the future direction of research in this field (p. 1)
- Industry 4.0 has been implemented for the past decade, but it has limitations (p. 1)
- Industry 5.0 is seen as a paradigm shift that emphasizes collaboration between humans and machines, rather than solely relying on technology (p. 1)
- It discusses the definitions and features of Industry 5.0, as well as the advanced technologies required for this industrial revolution (p. 1)
- Discussed technologies are big data analytics, Internet of Things, collaborative robots, Blockchain, digital twins and future 6G systems (p. 1)

Advantages & Disadvantages

- Industry 5.0 offers opportunities for increased business productivity, customer satisfaction, and economic growth by emphasizing collaboration between humans and machines (p. 1)
- The paper highlights the potential applications of Industry 5.0 in sectors such as healthcare, supply chain, and manufacturing, which can lead to personalized products and improved efficiency (pp. 5-7)
- It discusses advanced technologies like big data analytics, Internet of Things, and Blockchain, which are crucial for the successful implementation of Industry 5.0 (pp. 7-9)
- The study addresses the challenges of Industry 5.0 (p. 9)
- The paper does not provide a comprehensive analysis of the limitations faced in implementing Industry 5.0. The challenges mentioned are merely general things that are important for Industry 5.0 (p. 9)
- It does not offer specific recommendations or solutions for overcoming the challenges in the transformation from Industry 4.0 to Industry 5.0 (p. 9)

Sustainability

- The paper mentions that sustainable manufacturers can utilize advanced technologies like artificial intelligence to boost personalization, minimize waste, and optimize resource productivity (p. 5)
- It also suggests that for maintaining the sustainability of the manufacturing process, iterative procedures that repurpose, recycle, and recover assets need to be improved (p. 5)

Human centricity

- The paper emphasizes the concept of Human centricity in Industry 5.0, which focuses on collaboration between humans and machines for progress and innovation (p. 1, pp. 5-6)
- It acknowledges the challenges and issues related to the collaboration between humans and robots in the assembly line, indicating the importance of considering human factors in the implementation of Industry 5.0 (p. 1)

Resilience

- *The concept of resilience is not directly addressed in the paper*

Figure 12 Detailed Framework evaluation Adel, 2022a (own depiction)

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Ghobakhloo, Iranmanesh, Mubarak, Mubarik, Rejeb, Nilashi (2022): Identifying industry 5.0 contributions to sustainable development: A strategy roadmap for delivering sustainability values – Focus section: 2.2. Industry 5.0 reference model

Ghobakhloo, Iranmanesh, Mubarak, Mubarik, Rejeb, Nilashi (2022) present a pivotal examination of Industry 5.0, introducing a reference model designed to guide the integration of sustainability into modern industrial practices. Recognizing the growing complexity at the intersection of technology and society, the authors propose a comprehensive framework that encapsulates the multifaceted demands of Industry 5.0. This model, structured into four interconnected layers—enabling technologies, emerging technologies, smart components, and value objectives—offers a strategic roadmap for transitioning from the technology-driven focus of Industry 4.0 to a more balanced approach that emphasizes human centricity, resilience, and sustainability.

The framework is lauded for its adaptability across various sectors and organizational levels, ensuring broad applicability in diverse industrial contexts. By aligning technological advancements with core sociocultural values—such as human dignity, equality, privacy, and autonomy—the model aims to enhance societal well-being while also fostering economic productivity. However, the framework's complexity may present challenges in implementation, as it could hinder effective understanding and integration. Additionally, while designed for adaptability, there is a potential risk of overspecialization in certain industries, which might limit its broader application (Ghobakhloo, Iranmanesh, Mubarak, Mubarik, Rejeb, Nilashi, 2022, pp. 718–719).

Sustainability is a central focus of the framework, with a strong emphasis on balancing economic productivity with socio-environmental responsibilities. Industry 5.0 is depicted as a crucial driver for preserving ecological integrity, promoting principles of the circular economy, carbon neutrality, renewable energy integration, and resource efficiency. The paper also highlights the human-centric approach of Industry 5.0, emphasizing the role of adaptive robots, cognitive CPS, and smart wearables in enhancing workforce productivity and well-being. Resilience is another critical aspect of the model, with the integration of dynamic simulation, big data analytics, and the Internet of Everything (IoE) aimed at strengthening supply chain adaptability and responsiveness. The incorporation of blockchain and smart materials further supports operational agility and the development of new business models, underscoring the importance of resilience in the evolving landscape of Industry 5.0 (Ghobakhloo, Iranmanesh, Mubarak, Mubarik, Rejeb, Nilashi, 2022, pp. 718–719). The subsequent Figure 13 provides a detailed breakdown of the framework, illustrating its components and the interconnections between them.

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Ghobakhloo et al. 2022: Identifying industry 5.0 contributions to sustainable development: A strategy roadmap for delivering sustainability values – Focus section: 2.2. Industry 5.0 reference model

General information & Background

- The focus section discusses the development and presentation of a reference model for the understudied topic of Industry 5.0 (p. 718)
- This reference model offers a holistic overview of Industry 5.0 as a socio-technological phenomenon, describing the technological constituents, principles, components, and core value objectives (p. 718)
- The model consists of four layers compromising enabling technologies, emerging technologies, smart components and value (p. 719)
- The ambiguity and complexity surrounding Industry 5.0 is mentioned as the motivation for developing the reference model (p. 718)
- Industry 4.0 and emerging technological trends drive the need for Industry 5.0, which focuses on Human centricity, resilience and sustainability (p. 718)

Advantages & Disadvantages

- The focus section provides a comprehensive understanding of Industry 5.0 by developing a reference model encompassing technological constituents, principles, components, and core value objectives, facilitating a thorough examination of the phenomenon (p. 718)
- The developed framework's adaptability across sectors and organizational levels ensures flexibility for its application in diverse industrial settings, accommodating various industries and organizational structures (p. 719)
- Alignment of the framework with sociocultural values such as human dignity, equality, privacy, and autonomy ensures that technological advancements are steered towards promoting fundamental sociocultural values, enhancing societal well-being (p. 718)
- The comprehensive nature of the framework may lead to its complexity, potentially making it challenging to understand and implement effectively due to its intricate layers and components (p. 718)
- While aiming to be adaptable, there's a risk of overspecialization in certain industries or organizational levels, limiting the framework's applicability to broader contexts and potentially overlooking crucial aspects in different sectors (p. 719)
- As a comprehensive framework, the layers, which appear to be separate from each other, should have greater interconnectivity with each other in order to represent a holistic approach (p. 719)

Sustainability

- The focus section emphasizes sustainability across economic, environmental, and social aspects, promoting a balanced approach towards economic productivity and socio-environmental sustainability (p. 719)
- Industry 5.0 aims to preserve Earth's ecological and resource integrity by promoting the circular economy, carbon neutrality, renewable integration, and resource efficiency (p. 719)

Human centricity

- The focus section prioritizes a human-centric approach by integrating adaptive robots, cognitive cyberphysical systems, and human interaction technologies to address core human worker needs while enhancing industrial productivity (p. 718)
- Smart wearables are highlighted as crucial for improving the information capacity, intelligence, stability, and productivity of the human workforce in industrial settings (p. 719)

Resilience

- The focus section underscores resilience through dynamic simulation, big data analytics, and the internet of everything (IoE) to enhance supply chain adaptability and responsiveness (p. 719)
- Integration of dynamic simulation, blockchain, and smart materials supports operational agility and new business models, fostering resilience in Industry 5.0 (p. 719)

Figure 13 Detailed Framework evaluation Ghobakhloo, Iranmanesh, Mubarak, Mubarik, Rejeb, Nilashi (2022) (own depiction)

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Ghobakhloo, Iranmanesh, Tseng, Grybauskas, Stefanini, Amran (2023): Behind the definition of Industry 5.0: a systematic review of technologies, principles, components, and values

Ghobakhloo, Iranmanesh, Tseng, Grybauskas, Stefanini, Amran (2023) offer a comprehensive exploration of Industry 5.0 through the development of an architectural framework that integrates technological components, design principles, and core values. Positioned as an evolution of Industry 4.0, this framework emphasizes the integration of societal and ecological considerations into digital industrial transformation (Ghobakhloo, Iranmanesh, Tseng, Grybauskas, Stefanini, Amran, 2023, pp. 9–10). The study underscores the importance of stakeholder engagement and robust technology governance in advancing Industry 5.0, aiming to overcome the limitations of its predecessor by aligning industrial practices with sustainable development goals and broader socio-environmental responsibilities (Ghobakhloo, Iranmanesh, Tseng, Grybauskas, Stefanini, Amran, 2023, 1;12).

While the framework provides a structured approach to understanding Industry 5.0, it also acknowledges potential challenges in implementation. The complexity of integrating diverse technologies and principles may pose significant obstacles, particularly for organizations with limited resources or expertise (Ghobakhloo, Iranmanesh, Tseng, Grybauskas, Stefanini, Amran, 2023, p. 10). Additionally, the framework's adaptability across different sectors and organizational levels could be constrained by structural differences and resistance to change, potentially limiting its scalability (Ghobakhloo, Iranmanesh, Tseng, Grybauskas, Stefanini, Amran, 2023, p. 12). Although the framework offers a broad overview, certain areas may require further depth, indicating the need for validation and refinement in practical applications (Ghobakhloo, Iranmanesh, Tseng, Grybauskas, Stefanini, Amran, 2023, p. 9).

Sustainability is a key focus, with the framework advocating for circular economy principles, innovation, and the use of renewable resources to mitigate environmental impact. Industry 5.0 is portrayed as a crucial response to global challenges like shortened product life cycles and the need for improved recyclability. The framework also prioritizes human centricity, emphasizing workforce reskilling, technology tailored to human needs, and enhanced industrial safety. Additionally, it addresses social resilience, particularly in response to the COVID-19 pandemic, by supporting the digitalization of healthcare and the advancement of public health under the Healthcare 5.0 initiative (Ghobakhloo, Iranmanesh, Tseng, Grybauskas, Stefanini, Amran, 2023, pp. 10–11). The following Figure 14 offers a detailed breakdown of this framework, illustrating its components and their interconnections.

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Ghobakhloo et al. 2023: Behind the definition of Industry 5.0: a systematic review of technologies, principles, components, and values

General information & Background

- To address the knowledge gaps resulting from the limited understanding of the technological components, design principles and intended values of Industry 5.0, the study conducts a content-centric review of relevant literature and synthesizes evidence to develop an architectural design for Industry 5.0 (p. 1)
- The architectural design of Industry 5.0 is depicted as a logical continuation of the existing digital industrial transformation, addressing the shortcomings of Industry 4.0 and emphasizing societal and ecological values (p. 9)
- The framework highlights the importance of stakeholder involvement and technology governance in driving the transition towards Industry 5.0 (p. 1, p. 12)
- Current trends in digital industrial transformation, driven by Industry 4.0, have highlighted the need to explore the potential of Industry 5.0 in addressing societal and ecological challenges (p. 1)
- The architectural design of Industry 5.0 provides a structured approach to understanding the technological advancements, design principles, components, and values associated with this emerging industrial paradigm (p. 9)
- The archetype developed in this study offers insights into the potential of digital industrial transformation to achieve sustainable development goals and address the socio-environmental concerns of Industry 4.0 (p. 12)

Advantages & Disadvantages

- The framework offers a **holistic overview of Industry 5.0, encompassing its technological constituents, design principles, components, and values**, facilitating a deep understanding of the key elements propelling the transformation towards Industry 5.0 (pp. 9-10)
- The framework emphasizes the significance of stakeholder involvement and collaboration in governing technological advancements within Industry 5.0, fostering a supportive ecosystem for innovation and progress through an inclusive approach (p. 12)
- The paper's results offer strategic guidance for policymakers, industrialists, and managers on leveraging Industry 5.0 principles for sustainable development and societal impact, shaping effective strategies for embracing the changes it brings (p. 1, p. 12)
- The detailed nature of the architectural design may pose implementation challenges for organizations transitioning to Industry 5.0, as integrating various technologies and principles could demand significant resources and expertise (p. 10)
- Implementing the framework across diverse sectors, company levels, and society may encounter resistance or adaptation difficulties due to varying organizational structures and capabilities, potentially posing a challenge to ensuring its universal applicability and scalability (p. 12)
- While the framework developed in the paper seems holistic, it lacks sufficient depth in various specific areas, rendering it superficial in appearance (p. 10)
- While the paper offers a theoretical framework for Industry 5.0, the practical application of the proposed architectural design may require further validation and refinement in real-world settings (p. 9)

Sustainability

- The paper stresses Industry 5.0's focus on environmental sustainability, promoting circularity, innovation, and renewables to prevent degradation (p. 10)
- Industry 5.0 tackles global sustainability challenges like shortened product life cycles, recyclability, and rebound effects (pp. 10-11)

Human centricity

- Industry 5.0 prioritizes Human centricity through workforce re/up-skilling, tailoring technology to human needs, and enhancing industrial safety (p. 11)
- At the socio-political level, it promotes social protection to enhance social welfare via minimizing labor disruptions and preventing workforce polarization (p. 11)

Resilience

- Drawing on the adverse socio-economic effects of the COVID-19 pandemic, the socio-centricity of Industry 5.0 involves enhancing social resilience using technology and data sources to prevent or manage crises (p. 11)
- The social resilience goal of Industry 5.0 also involves digitalizing the healthcare systems under Healthcare 5.0 agenda and strengthening public health (p. 11)

Figure 14 Detailed Framework evaluation Ghobakhloo, Iranmanesh, Tseng, Grybauskas, Stefanini, Amran, 2023 (own depiction)

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Iqbal, Lee, Ren (7 Dec. 2022-10 Dec. 2022): Industry 5.0: From Manufacturing Industry to Sustainable Society – Focus on sections V. and VI. to consider SDGs in the context of Industry 5.0

The framework discussed by Iqbal, Lee, Ren (7 Dec. 2022-10 Dec. 2022) provides an in-depth analysis of the transition from Industry 4.0 to Industry 5.0, emphasizing a shift from a production-centric model to one with a broader societal focus. This evolution prioritizes sustainability, human centricity, and resilience, positioning Industry 5.0 as a framework that aligns technological advancements with societal well-being. A key element is the role of AI and advanced technologies in addressing global challenges, such as the COVID-19 pandemic, while promoting a circular economy. This transition from a linear to a circular economic model underscores a strong commitment to sustainable practices within the manufacturing sector, with a focus on environmental stewardship. The framework also addresses potential drawbacks of rapid Industry 5.0 advancements, including job displacement and increased socio-economic disparities if workforce development is neglected. Concerns about digital divides, data privacy ethics, and the need for robust regulation are also highlighted as critical issues that must be managed to effectively govern emerging technologies (Iqbal, Lee, Ren, 7 Dec. 2022-10 Dec. 2022, pp. 1418–1420).

Sustainability is a cornerstone of Industry 5.0, advocating for a balanced approach that addresses both economic and environmental challenges. The framework emphasizes the importance of a human-centric approach, focusing on continuous worker training and the enhancement of healthcare through AI to build resilience against global threats. While Industry 5.0 promises a more inclusive and sustainable future, vigilant monitoring, strong governance, and international collaboration are essential to fully realize its potential (Iqbal, Lee, Ren, 7 Dec. 2022-10 Dec. 2022, pp. 1418–1419). Figure 15 delves into the intricacies of the framework, offering a comprehensive illustration of its components and the ways in which they interrelate.

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Iqbal et al. 2022: Industry 5.0: From Manufacturing Industry to Sustainable Society – Focus on sections V. and VI. to consider SDGs in the context of Industry 5.0

General information & Background

- The focus sections discuss the transition from Industry 4.0 to Industry 5.0, highlighting a broader societal focus, as opposed to Industry 4.0's emphasis on cost reduction and production efficiency. (p. 1419)
- The sections delve into the role of technology, especially AI, in addressing challenges such as the COVID-19 pandemic and advancing healthcare (p. 1419)
- They explore the promotion of circular economy principles in Industry 5.0, emphasizing a shift from a linear economy to towards a circular economy and sustainable practices in manufacturing (p. 1418)
- The focus sections serve to understand the evolving landscape of industry and technology, particularly in light of advancements from Industry 4.0 to Industry 5.0 (p. 1419)
- It addresses current trends, such as the COVID-19 pandemic, which accelerates the adoption of Industry 4.0 technologies, further contributing to the advancement of Industry 5.0 (p. 1419)
- Industry 4.0 and Industry 5.0 are drivers for the development of the focus sections, as they represent significant shifts in technology and industry paradigms (p. 1418)

Advantages & Disadvantages

- Integration of the Sustainable Development Goals (SDGs) into the Industry 5.0 framework provides a holistic approach to societal and environmental challenges, which aims to promote sustainability across sectors and levels of society (p. 1419)
- Emphasis on technology, particularly AI, in addressing societal issues such as healthcare and pandemic management, aligning with the aim to leverage innovation for societal well-being (p. 1419)
- The shift towards circular economy principles in Industry 5.0 promotes resource efficiency and environmental sustainability, with the objective of fostering sustainable production and consumption (p. 1419)
- The focus on technology and automation in Industry 5.0 may lead to concerns about job displacement and widening socio-economic disparities if not accompanied by adequate measures for upskilling and workforce development (p. 1418)
- While the integration of SDGs into the Industry 5.0 framework is commendable, the practical implementation and measurement of progress towards these goals may pose challenges, requiring robust monitoring and evaluation mechanisms (p. 1419)
- The rapid pace of technological advancement in Industry 5.0 may exacerbate digital divides and raise ethical concerns related to data privacy, security, and algorithmic bias, necessitating careful regulation and governance frameworks (p. 1420)

Sustainability

- The sections emphasize the importance of sustainability in the transition to Industry 5.0 (p. 1418)
- The promotion of a circular economy and eco-system-oriented innovation policies for a healthy future is highlighted, indicating a commitment to environmental sustainability (p. 1419)
- There is a need to address economic and environmental issues while leveraging innovative technologies, showcasing a balanced approach to sustainability (p. 1418)

Human centricity

- The focus sections advocate for a human-centric approach in Industry 5.0, stressing the importance of equal attention to employees and customers (p. 1418)
- They discuss the importance of human labor in manufacturing industries, highlighting the need for constant training and enrichment of workers (p. 1419)
- There is recognition of the role of technology, particularly AI, in improving people's lives and enhancing healthcare services for customers (pp. 1418-1419)

Resilience

- The role of technology, especially AI, enhances resilience against challenges such as natural disasters, hazards or the COVID-19 pandemic through early detection and response mechanisms (p. 1419)
- There is recognition of the potential of Industry 5.0 to foster resilience and inclusivity through collaboration across borders, leading to a more sustainable and safer global future (p. 1419)

Figure 15 Detailed Framework evaluation Iqbal, Lee, Ren (7 Dec. 2022-10 Dec. 2022) (own depiction)

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Ivanov 2023: The Industry 5.0 framework: viability-based integration of the resilience, sustainability, and human centricity perspectives

The framework presented by Ivanov (2023) for Industry 5.0 integrates resilience, sustainability, and human centricity into the design and management of operations and supply chains (Ivanov, 2023, p. 1683). Building on existing literature, it situates these principles within viable supply chain models, reconfigurable supply chains, and broader business ecosystems. While recognizing the technological advancements of Industry 4.0, the framework enhances these technologies by embedding them within a structure focused on resilience, sustainability, and human centricity (Ivanov, 2023, p. 1690).

Operating on three levels—societal, network, and plant—the framework addresses key aspects of Industry 5.0. It emphasizes sustainable resource use, energy-efficient manufacturing, and the development of inclusive, human-centric workplaces that foster collaboration between humans and AI. Resilience is also highlighted, with a focus on interconnected networks and adaptable supply chains to ensure continuous service even during disruptions (Ivanov, 2023, pp. 1688–1689).

Challenges are acknowledged, particularly the complexity of implementing a multi-dimensional framework, which may complicate decision-making (Ivanov, 2023, p. 1688). The rapid transition to Industry 5.0, following closely after Industry 4.0, also raises concerns about integration and practicality, especially for companies still adapting to the previous industrial paradigm. Despite these challenges, the framework offers a holistic approach to aligning technological, organizational, and societal goals within the Industry 5.0 landscape (Ivanov, 2023, p. 1690). *Figure 16* provides a detailed breakdown of the framework, illustrating its components and their interconnections.

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Ivanov 2023: The Industry 5.0 framework: viability-based integration of the resilience, sustainability, and Human centricity perspectives

General information & Background

- The paper explores the concept of Industry 5.0, which combines organizational principles and technologies to design and manage operations and supply chains as resilient, sustainable, and human-centric systems (p. 1683)
- Based on an analysis of the existing literature on supply chain and operations resilience, sustainability, and Human centricity, a framework of Industry 5.0 is derived and contextualized through the lens of the viable supply chain model, the reconfigurable supply chain, and business ecosystems (p. 1692)
- While the technological aspects of Industry 5.0 have gained research attention, there is a need for a comprehensive understanding of Industry 5.0 across management, organization, and technology perspectives (p. 1684)
- The current trends in Industry 5.0 emphasize the importance of resilience, sustainability, and Human centricity in operations and supply chain management, driving the need for a framework that integrates these perspectives (p. 1683)

Advantages & Disadvantages

- Industry 5.0 is described on three levels in the developed framework: society level, network level and plant level (p. 1688)
- The paper provides a comprehensive framework for Industry 5.0, integrating resilience, sustainability, and Human centricity perspectives, which can guide organizations in aligning their operations and supply chains with these principles (p. 1692)
- **The consideration of technologies from Industry 4.0 offers added value when considered from the resilience, sustainability, and human-centric perspectives (p. 1690)**
- **The paper emphasizes that Industry 5.0 does not replace Industry 4.0, that, but rather supplements and extends it (p. 1690)**
- Many companies just started implementing Industry 4.0, and the appearance of Industry 5.0 just 10 years after the contextualisation of Industry 4.0 may create questions (p. 1690)
- The proposed framework for Industry 5.0 is of limited general utility as it is viewed through the lens of the viable supply chain model, the reconfigurable supply chain, and human-centric ecosystems (p. 1683)
- The multi-dimensional nature of the framework, encompassing technological, organizational, and societal aspects, may introduce complexity in implementation, requiring organizations to navigate diverse considerations and trade-offs, potentially leading to challenges in prioritization and decision-making (p. 1688)

Sustainability

- Sustainable utilization of Earth's resources and energy is essential in designing and operating these interconnected networks and ecosystems (p. 1688)
- Supply chain sustainability through reconfigurable supply chains (pp. 1688-1689)
- Energy-efficient manufacturing and logistics are developed to enhance sustainability at plant level (p. 1689)

Human centricity

- The approach integrates ecosystems like food, agriculture, communication, energy, education, healthcare, and leisure (p. 1688)
- Cyber-physical supply chains through digital supply chains (pp. 1688-1689)
- Human-centric approach to create inclusive workplaces and promote collaboration between human and artificial intelligence (p. 1689)
- Health protection protocols and layouts are developed in response to the COVID pandemic (p. 1689)

Resilience

- Industry 5.0 focuses on creating interconnected networks to ensure continuous provision of goods and services during disruptions (p. 1688)
- Supply chain resilience through reconfigurable supply chains (pp. 1688-1689)
- Measures like facility fortification are taken to increase the resilience of individual facilities within networks (p. 1689)

Figure 16 Detailed Framework evaluation Ivanov (2023) (own depiction)

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Leng et al. 2022: Industry 5.0: Prospect and retrospect

Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang (2022) present a comprehensive framework for Industry 5.0, focusing on its evolution from Industry 4.0 and defining its core characteristics. Unlike Industry 4.0, which primarily centers on technological innovation, Industry 5.0 introduces a tri-dimensional architecture emphasizing human centricity, sustainability, and resilience to foster a more inclusive and sustainable socio-economic system (Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang, 2022, p. 283). The framework integrates the technological advancements of Industry 4.0 with the societal focus of Society 5.0, described as "Industry 4.1" during the transition. This approach highlights the importance of addressing human and societal needs, positioning human centricity as vital for sustainable industrial growth (Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang, 2022, p. 283). The proposed architecture includes technical, reality, and application dimensions, offering a detailed guide for implementing Industry 5.0. However, the framework's complexity may pose challenges, particularly for organizations with limited resources, due to the significant investment and careful management required (Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang, 2022, p. 286).

Sustainability is central to the framework, advocating for a balanced integration of economic, environmental, and social goals. The human-centric focus aims to enhance both industrial performance and worker well-being, supported by intelligent systems that enable advanced human-machine interactions. Resilience is also emphasized as crucial, ensuring the ability to recover swiftly from disruptions such as geopolitical shifts or pandemics, not only at the enterprise level but across entire industrial ecosystems. While the framework is theoretically robust, translating it into actionable strategies remains challenging, particularly for SMEs, due to the resource-intensive nature of the transition from Industry 4.0 to Industry 5.0 (Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang, 2022, pp. 283–284). The subsequent Figure 17 offers a detailed breakdown of the framework, illustrating its components and their interconnections.

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Leng et al. 2022: Industry 5.0: Prospect and retrospect

General information & Background

- The paper published in the Journal of Manufacturing Systems offers a comprehensive examination of Industry 5.0 (p. 279)
- The paper reviews the evolution of Industry 5.0 and the three leading characteristics: Human centricity, sustainability, and resiliency (p. 279)
- A tri-dimensional system architecture for implementing Industry 5.0 is proposed and key enablers, potential applications, and challenges of Industry 5.0 are discussed (p. 279)
- Unlike the technological innovation of Industry 4.0, Society 5.0, envisioned as a sustainable, inclusive socio-economic system, leads far beyond Industry 4.0 (p. 282)
- The paper describes the transformation towards industry 5.0 as follows: In the evolution toward Industry 5.0, Industry 4.0 lays the technical foundation, and Society 5.0 focuses the societal needs, while Operator 5.0 emphasis on the human aspect (p. 283)

Advantages & Disadvantages

- The integration of Industry 4.0 and Society 5.0 concepts into a unified system, referred to as "Industry 4.1" provides a framework for the transition to Industry 5.0, emphasizing the importance of human-centric thinking and societal foundations (p. 283)
- **Industry 4.0 lays the technical foundation of industry 5.0 (p. 283)**
- The paper provides a comprehensive overview of the evolution and key concepts of Industry 5.0, offering valuable insights into the transition from Industry 4.0 to Industry 5.0 in the form of an implementation path (pp. 282-283)
- The tri-dimension architecture considers the technical dimension, reality dimension, and application dimension, providing a comprehensive framework for implementing Industry 5.0 (p. 286)
- The integration of multiple dimensions and enabling technologies may introduce complexity into the implementation process, requiring careful planning and management to ensure seamless execution (p. 286)
- Implementing the tri-dimension architecture may require significant resources in terms of technology adoption, training, and infrastructure development, which could pose challenges for organizations with limited resources (p. 286)
- While the architecture provides a theoretical framework, it may lack specific practical guidance on how organizations can effectively translate the model into actionable strategies and initiatives for Industry 5.0 implementation (p. 286)
- The transition from Industry 4.0 to Industry 5.0 is a time-consuming and resource-intensive transformation process, which can be a problem for SMEs (p. 283)

Sustainability

- The paper emphasizes the importance of sustainability in Industry 5.0, considering economic, environmental, and social pillars (p. 284)
- The paper stands for a balanced solution in sustainability, highlighting the shift towards Human centricity and societal needs in Industry 5.0 (p. 284)
- Sustainable implementation is to better achieve the global construction of Industry 5.0 with more quantity, faster speed, better quality, and cost savings (p. 284)

Human centricity

- Emphasizing human-centric approaches and societal needs, the paper aligns with the vision of a super-smart society in Industry 5.0, which is crucial for sustainable development and inclusivity (pp. 282-283)
- Integrating Human centricity in industrial systems enhances performance and well-being (p. 284)
- Human centricity necessitates intelligent robots understanding human-machine interactions in diverse environments (p. 284)

Resilience

- Resiliency in Industry 5.0 entails quick recovery from major disruptions like geopolitical shifts or natural disasters, including COVID-19 (p. 284)
- Industry 5.0 emphasizes resilience not only at the enterprise level but also across entire industrial chains and regional systems (p. 284)
- Achieving a high level of resiliency is a recognized essential ability of Industry 5.0 (p. 284)

Figure 17 Detailed Framework evaluation Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang (2022) (own depiction)

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Rajumesh (2024): Promoting sustainable and human-centric industry 5.0: a thematic analysis of emerging research topics and opportunities

The study presents a detailed bibliometric analysis of the evolving landscape of Industry 5.0 research, focusing on growth trends, publishing patterns, and key themes. It reveals a significant rise in publications and citations, with China, the USA, and India leading in contributions (Rajumesh, 2024, p. 111). Through co-occurrence and bibliographic coupling analyses, the research identifies limited collaboration among authors and emphasizes critical themes, such as the impact of digital transformation on society and industry, with a strong emphasis on sustainability, human-centric design, and ethical innovation (Rajumesh, 2024, p. 119).

The analysis underscores the integration of advanced technologies to promote sustainable and ethical innovation within Industry 5.0, particularly in areas like human-machine interaction, democracy, and ecological considerations. By mapping emerging research areas, the study provides a strategic roadmap for future exploration, aiding researchers, policymakers, and practitioners in navigating the complexities of Industry 5.0. However, it also highlights a gap in collaborative efforts among scholars, which may hinder the exchange of diverse perspectives essential for advancing the field. Additionally, the reliance on data from the Scopus database could limit the comprehensiveness of the findings, potentially missing recent developments from other sources (Rajumesh, 2024, p. 111).

The study emphasizes Industry 5.0's potential to exceed Industry 4.0 in promoting sustainable development by advocating for human-centered smart environments that prioritize well-being and performance. It calls for resilient manufacturing systems designed around human needs, stressing that a holistic approach to digital transformation—integrating both technological and societal factors—is essential for fostering sustainability and resilience (Rajumesh, 2024, p. 119). While the study provides valuable insights, it also acknowledges the ongoing need for research to address the dynamic challenges in transitioning from Industry 4.0 to Industry 5.0 (Rajumesh, 2024, pp. 121–123). The following Figure 18 further illustrates the concept, offering a visual representation of the framework's key components and their interrelationships.

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Rajumesh 2024: Promoting sustainable and human-centric industry 5.0: a thematic analysis of emerging research topics and opportunities

General information & Background.

- The study aims to explore the growth trend, top publishing countries, co-authorship patterns, and author keywords in the field of Industry 5.0 through a bibliometric analysis (p. 111)
- Revealed a significant increase in publications and citations related to Industry 5.0, with China, the USA, and India leading research efforts (p. 111)
- Identified limited collaboration among authors and highlighted key research themes through co-occurrence and bibliographic coupling analyses (p. 111)
- Explored the influence of digital transformation on society and industry, emphasizing sustainability, human-centric design, and innovation within Industry 5.0 (p. 119)
- Addressed the integration of advanced technologies for sustainable and ethical innovation, focusing on human-machine interaction, democracy, and ecology (p. 121)
- The research employs bibliometric analysis as a valuable tool to identify research trends, knowledge gaps, and influential publications in the field of Industry 5.0, providing insights for researchers, policymakers, and practitioners (p. 113)

Advantages & Disadvantages

- The bibliometric analysis helps in identifying emerging research areas and key themes in Industry 5.0, providing a roadmap for future studies and development initiatives (p. 113)
- The analysis of co-authorship patterns sheds light on collaboration among scholars from different regions and fields, facilitating knowledge exchange and interdisciplinary research in Industry 5.0 (p. 121)
- The findings enhance the knowledge of professionals and academia in Industry 5.0, enabling them to efficiently manage and sustainably develop the sector (p. 111)
- The analysis indicates limited collaboration among authors in the field of Industry 5.0, which may hinder the exchange of diverse perspectives and innovative ideas crucial for the advancement of the sector (p. 111)
- The study solely relies on data from the Scopus database at a specific time, which may limit the comprehensiveness of the analysis and overlook recent developments or insights from other databases (p. 111)
- While the study provides valuable insights, there is a need for continued exploration and research to address evolving trends, gaps, and challenges in the transformation from Industry 4.0 to Industry 5.0 (pp. 121-123)

Sustainability

- The paper discusses how Industry 5.0 surpasses Industry 4.0 in promoting sustainable development goals, presenting various functions that contribute to sustainability (p. 119)
- Authors stress the significance of human-centered smart environments for well-being and performance, advocating for transparent and trustworthy technologies that create a rewarding work environment based on practical needs (p. 119)

Human centricity

- The paper underscores the significance of human-centric design and innovation in the context of Industry 5.0, advocating for a holistic approach that considers both technological and societal factors (p. 119)
- It supports the transition towards an industry that is sustainable, human-centric, and resilient within the framework of Industry 5.0, highlighting the importance of designing systems that cater to human needs and well-being (p. 119)

Resilience

- The paper advocates for resilient industries and societies within the framework of Industry 5.0, focusing on creating manufacturing systems that are both resilient and centered around human needs (p. 119)
- It highlights the importance of enhancing resilience and sustainability by embracing the principles of Industry 5.0, emphasizing the need for a comprehensive approach to digital transformation that considers both technology and societal factors (p. 119)

Figure 18 Detailed Framework evaluation Rajumesh, 2024 (own depiction)

5.1.2. Examination non-academic Area

In this section, the focus shifts from academic explorations to non-academic frameworks, providing a critical examination of how Industry 5.0 is being conceptualized and implemented outside the academic realm. While academic literature often delves deeply into theoretical underpinnings and comprehensive models, non-academic frameworks tend to be more pragmatic, driven by industry needs and real-world applications. This analysis aims to evaluate these frameworks'

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contributions to the discourse on Industry 5.0, identifying both their strengths and limitations in addressing the complex, multifaceted nature of this emerging industrial paradigm. Through this examination, we seek to understand how non-academic perspectives complement or diverge from academic approaches, offering a broader view of the current landscape and the practical implications of Industry 5.0. A total of 6 frameworks have been identified within this scope, as summarized in Table 3. The following sections offer a concise overview of these frameworks, highlighting their perspectives and key learnings. A detailed figure of each framework is provided for an in-depth analysis.

Table 3 Overview of Identified Non-Academic Frameworks (own depiction)

Source	Brief Description
Deuring (2023)	Discussion of the transition from Industry 4.0 to Industry 5.0, highlighting the enhanced collaboration between humans and technology, particularly AI, in industrial processes while emphasizing the goals of Industry 5.0
German Federal Ministry for Economic Affairs and Climate Action (2023)	Introduction of Manufacturing-X, a framework aiming to revolutionize industrial production by enabling collaborative and scalable data use across sectors while emphasizing common standards, interoperable data exchange, and a focus on economic and ecological impact
Henkel (2024)	Discussion of Industry 4.0, highlighting how digitalization is changing production and logistics processes at Henkel, emphasizing the focus on technology, sustainability, upskilling and strategic alignment
McKinsey & Company (2022)	Exploration of Industry 4.0, the Fourth Industrial Revolution, emphasizing its disruptive technologies, workforce upskilling, sustainability opportunities, and economic impact
SAP (2024)	Discussion on the transition from Industry 4.0 to Industry 5.0, with an emphasis on human-machine collaboration, sustainability, resilience and the potential for personalized industrial automation
Stockwell (2017)	Introduction of Industry 4.0, highlighting its key components: instrumented, interconnected, inclusive and intelligent, and discussing how they drive innovation at all stages of manufacturing, as well as highlighting the potential economic benefits of Industry 4.0

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Deuring (2023) – Industry 5.0: What added value does the extension of the Industry 4.0 concept offer?

Deuring's (2023) exploration of Industry 5.0, exemplified by *Vernaio*'s integration of AI, offers key insights into the PROSPECTS 5.0 initiative, particularly concerning the transformative impact of AI on industrial processes, as illustrated in Figure 19. The transition from Industry 4.0 to Industry 5.0 centers on a human-centric approach, where the synergy between humans and technology takes precedence. This shift aims to prioritize human needs, reduce environmental impacts, and enhance resilience against disruptions. AI is crucial in this evolution, providing real-time insights and optimizing production processes. Vernaio's Process Booster exemplifies this by significantly improving operational efficiency, root cause analysis, and key performance indicators, such as overall equipment effectiveness (OEE), downtime, and scrap. This AI-driven focus highlights Industry 5.0's potential to achieve greater operational robustness and sustainability. Following this, the perspective, input, and key learnings derived from these advancements will be further explored, providing a comprehensive understanding of the transformative potential within Industry 5.0 (Deuring, 2023).

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Deuring 2023 – Industry 5.0: What added value does the extension of the Industry 4.0 concept offer?

Perspective & Input

Perspective:

- Vernaio is an AI IoT solutions provider headquartered in Munich, Germany. Their industrial AI helps companies optimize production processes, in particular avoiding production disruptions before they occur.
- Their perspective, as presented in the article, aligns with the transition from Industry 4.0 to Industry 5.0, emphasizing the importance of AI integration to optimize collaboration between humans and technology.

Input:

- The article discusses the transition from Industry 4.0 to Industry 5.0, emphasizing the enhanced collaboration between humans and technology, particularly AI, in industrial processes.
- It highlights the goals of Industry 5.0, such as prioritizing human interests, sustainability, and resilience against disruptions, and showcases Vernaio's AI solution, "Process Booster," as an example of Industry 5.0 implementation.

Learnings for PROSPECTS 5.0

- **Human-Centric Approach:** Industry 5.0 prioritizes human interests and needs, aiming to optimize collaboration between humans and technology in industrial processes.
- **Sustainability Focus:** The transition to Industry 5.0 underscores the importance of reducing negative environmental impacts and increasing resource efficiency within businesses.
- **Resilience Against Disruptions:** Industry 5.0 seeks to enhance the resilience of industrial operations, enabling robustness against crises and disruptions through proactive measures.
- **AI Integration:** Advanced AI plays a pivotal role in Industry 5.0 by facilitating collaboration between humans and technology, offering real-time insights, and optimizing manufacturing processes.
- **Operational Improvements:** The application of AI in Industry 5.0 leads to significant enhancements in operational efficiency, root cause analysis, risk management, and optimization of key performance indicators (KPIs) such as OEE, downtime, and scrap.

Figure 19 Detailed Framework evaluation Deuring (2023) (own depiction)

German Federal Ministry for Economic Affairs and Climate Action Industrie 4.0 2024 – Architecture and technological base: Make Data Work

The *Manufacturing-X framework*, introduced by the German Federal Ministry for Economic Affairs and Climate Action (2023), plays a pivotal role in revolutionizing industrial production through collaborative and scalable data utilization. It emphasizes the need for a unified, sovereign infrastructure with common standards to ensure resilient, sustainable, and competitive manufacturing. A key takeaway for PROSPECTS 5.0 is the critical importance of establishing interoperable data exchange systems and standardizing technical infrastructure to promote cross-sector collaboration. The

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Manufacturing-X framework addresses both economic and ecological impacts, focusing on use cases that deliver tangible benefits while preserving data sovereignty. Essential technological components — such as identity and trust, visibility and access, service and sharing, and agreements—are vital to achieving these goals and facilitating tailored, cross-industry solutions (German Federal Ministry for Economic Affairs and Climate Action, 2023). The analysis results are shown in Figure 20.

German Federal Ministry for Economic Affairs and Climate Action | Plattform Industrie 4.0 2024 – Architecture & technological base: Make Data Work

Perspective & Input

Perspective:
- The Plattform Industrie 4.0 of the German Federal Ministry for Economic Affairs and Climate Action is shaping the digital transformation in production.
- With Manufacturing-X, the platform is contributing to the digitalization of supply chains in industry.
- The article highlights the need for a common sovereign infrastructure, common standards, and interoperable data exchange to achieve resilience, sustainability, and competitiveness in the manufacturing industry.

Input:
- The article introduces Manufacturing-X, a framework aiming to revolutionize industrial production by enabling collaborative and scalable data use across sectors.
- It emphasizes common standards, interoperable data exchange, and a focus on economic and ecological impact, facilitated by four core technological elements.

Learnings for PROSPECTS 5.0

- **Manufacturing-X Framework:** The Manufacturing-X initiative promotes collaborative and scalable data usage across industries through a common sovereign infrastructure.
- **Strategic Objectives:** It focuses on establishing a resilient, sustainable, and competitive industry by addressing cross-sector use cases with economic and ecological impact.
- **Common Standards and Infrastructure:** Common standards and a trustworthy technical infrastructure are essential for ensuring interoperability and sovereignty in data exchange.
- **Focus on Economic and Ecological Use Cases:** Manufacturing-X prioritizes use cases that offer clear economic and ecological benefits across supply chains, considering the interests of all partners.
- **Interoperable Data Exchange:** Interoperable data exchange and sovereignty of all value chain partners are central, facilitated by core technological elements like identity & trust, visibility & access, service & sharing, and agreements.
- **Collaborative Development:** The Manufacturing-X community collaboratively develops a common technological basis that can be applied across industries to enable customized solutions.

Figure 20 Detailed Framework evaluation German Federal Ministry for Economic Affairs and Climate Action Industrie 4.0 2024 (own depiction)

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Henkel (2024) – Industry 4.0: How digitalization transforms production and logistics

Henkel a global leader in consumer goods and industrial solutions, is at the forefront of digital transformation within the manufacturing sector. Their engagement with Industry 4.0 provides valuable insights, particularly in the realm of digital transformation, as illustrated in Figure 21. A key takeaway is the crucial role of digitalization as the foundation for future industrial advancements, enhancing connectivity, data flow, and automation across production and logistics. The integration of advanced technologies such as automation, sensorics, and artificial intelligence is identified as essential for boosting operational efficiency, product quality, and sustainability. Henkel's emphasis on sustainability highlights the importance of using digitalization to reduce environmental impact through optimized resource consumption and waste minimization. Additionally, the focus on workforce adaptability underscores the necessity of continuous learning and upskilling to prepare employees for the dynamic challenges of the digital age. Strategically aligning these elements with Industry 4.0 principles positions organizations to maintain competitiveness and successfully navigate the evolving industrial landscape (Henkel, 2024). The analysis results are shown in Figure 21.

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Henkel 2024 – Industry 4.0: How digitalization transforms production and logistics

Perspective & Input

Perspective:
- Henkel is a German multinational chemical and consumer goods company operating in the manufacturing industry, particularly in sectors like consumer goods, adhesives, and beauty care.
- Their perspective on Industry 4.0 is proactive and forward-thinking, viewing digitalization to revolutionize their production and logistics processes.

Input:
- The article discusses Industry 4.0, highlighting how digitalization is transforming production and logistics processes at Henkel.
- It emphasizes the use of automation, sensorics, data analytics, and sustainability measures to enhance efficiency and connectivity across the value chain, while also addressing changes in job roles and the company's commitment to upskilling its workforce.

Learnings for PROSPECTS 5.0

- **Importance of Digitalization:** The foundation for the next industrial age rests in digitalization, enabling connectivity, data exchange, and automation across production and logistics processes.
- **Technological Integration:** Integration of technologies like automation, sensorics, data analytics, and artificial intelligence enhances efficiency, quality, and sustainability in manufacturing and logistics.
- **Sustainability Focus:** Digitalization and automation play crucial roles in reducing environmental impact, such as minimizing paper usage, optimizing resource consumption, and reducing waste throughout the production and logistics chain.
- **Adaptability and Upskilling:** Recognizing the evolving nature of job roles in the digital era, prioritizing continuous learning and upskilling programs empowers employees with the necessary skills to thrive in Industry 4.0.
- **Strategic Alignment:** Aligning company strategies with Industry 4.0 principles, from planning and production to product delivery, ensures competitiveness and future-readiness in the evolving industrial landscape.

Figure 21 Detailed Framework evaluation Henkel (2024) (own depiction)

McKinsey & Company (2022)– What are Industry 4.0, the Fourth Industrial Revolution, and 4IR?

The exploration of Industry 4.0 of McKinsey & Company (2022) highlights the transformative potential of disruptive technologies such as artificial intelligence, robotics, and additive manufacturing in revolutionizing manufacturing processes. Harnessing these advancements requires a strong focus on workforce development, with upskilling and reskilling being essential to ensure employees are prepared to meet the evolving demands of the industry. *The Global Lighthouse Network*, co-founded by McKinsey & Company, serves as a valuable benchmark, showcasing successful large-

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scale implementations of Industry 4.0 that can guide other organizations. Adopting an agile approach, characterized by rapid iterations and continuous learning, is vital for fostering innovation and refining digital strategies. Additionally, Industry 4.0's role in enhancing sustainability is emphasized through data-driven improvements in resource efficiency, waste reduction, and emissions control. The significant economic impact of Industry 4.0 further underscores the importance of timely adoption to maintain competitiveness and achieve positive financial outcomes McKinsey & Company (2022). The following Figure 22 provides a visual representation of these concepts, illustrating the key elements and their interconnections.

McKinsey & Company 2022 – What are Industry 4.0, the Fourth Industrial Revolution, and 4IR?

Perspective & Input

Perspective:

- McKinsey & Company is an American multinational strategy and management consulting firm that offers professional services to corporations, governments, and other organizations.
- In this article, they discuss theMcKinsey & Company 2022 – What are Industry 4.0, the Fourth Industrial Revolution, and 4IR? implications and opportunities of Industry 4.0, emphasizing its transformative potential for manufacturing companies.
- Their perspective underscores the importance of leveraging disruptive technologies, upskilling the workforce, and embracing sustainability to drive successful digital transformations and economic growth within the manufacturing sector.

Input:

- The article explores Industry 4.0, the Fourth Industrial Revolution, emphasizing its disruptive technologies, workforce implications, sustainability opportunities, and economic impact.
- It highlights the importance of upskilling, showcases successful implementations through the Global Lighthouse Network, and underscores the need for workforce engagement in driving successful digital transformations in manufacturing.

Learnings for PROSPECTS 5.0

- **Disruptive Technologies:** Industry 4.0 introduces disruptive technologies like artificial intelligence, robotics, and additive manufacturing, revolutionizing manufacturing processes.
- **Workforce Upskilling:** Successful adoption of Industry 4.0 requires upskilling and reskilling the workforce to adapt to evolving job requirements and fill skill gaps.
- **Global Lighthouse Network:** The Global Lighthouse Network identifies organizations leading the 4IR transformation, offering insights and benchmarks for successful implementation of 4IR technologies at scale.
- **Agile Approach:** Adopting an agile approach, incorporating quick iterations and continuous learning, is crucial for driving innovation and refining digital transformation strategies.
- **Sustainability Opportunities:** Industry 4.0 technologies offer opportunities for sustainability by enabling data-informed actions, improving performance indicators, and reducing consumption, waste, and emissions.
- **Economic Impact:** Industry 4.0 is expected to have a significant economic impact, with front-runners experiencing positive cash flow changes, emphasizing the importance of timely adoption and adaptation to remain competitive.

Figure 22 Detailed Framework evaluation McKinsey & Company (2022) (own depiction)

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SAP (2024) – Industry 5.0: Adding the human edge to industry 4.0

To fully grasp the transformative potential of PROSPECTS 5.0, it is essential to consider SAP (2024) vision for Industry 5.0, which builds upon the legacy of Industry 4.0 by seamlessly merging human creativity with cutting-edge technology. This vision highlights the importance of human-machine collaboration, where the synergy between human innovation and machine precision becomes the driving force behind new levels of operational excellence and innovation. Industry 5.0 further underscores the importance of sustainability and resilience, recognizing them as critical for long-term success, especially amid global challenges like climate change and pandemics. A notable feature is personalized automation, where collaborative robots (cobots) work alongside humans to enable large-scale customization, ensuring swift and agile responses to customer demands. Additionally, cultivating a workplace that values and engages human talent is vital for attracting and retaining skilled employees, which in turn boosts satisfaction and productivity. The consolidated figure in SAP's framework illustrates how embracing Industry 5.0 principles can deliver a competitive edge by aligning with sustainability goals, enhancing operational resilience, and driving superior economic outcomes SAP (2024). The results are shown in Figure 23.

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SAP 2024 – Industry 5.0: Adding the human edge to Industry 4.0

Perspective & Input

Perspective:
- SAP is a software provider that has a process- and technology-driven perspective on the transformation path towards Industry 5.0.
- In terms of the transformation from industry 4.0 towards industry 5.0 SAP's supply chain management portfolio provides solutions for Industry 4.0 capabilities across a company's ecosystem by combining digital manufacturing in factories and plants with business process execution across the supply chain.

Input:
- The article discusses the transition from Industry 4.0 to Industry 5.0, highlighting the integration of human creativity with technological advancements in manufacturing.
- It emphasizes collaboration between humans and machines, sustainability, resilience, and the potential for personalized industrial automation.

Learnings for PROSPECTS 5.0

- **Human-Machine Collaboration:** Industry 5.0 emphasizes collaboration between humans and machines, leveraging the strengths of both to drive innovation and efficiency in manufacturing processes.
- **Sustainability and Resilience:** Prioritizing sustainability and resilience in industrial practices is crucial for long-term success, especially in light of challenges like climate impacts and pandemics.
- **Personalized Automation:** Integration of collaborative robots (cobots) with human workers enables personalized industrial automation, facilitating customization of goods at scale while ensuring real-time responsiveness to customer needs.
- **Talent Engagement:** Providing a progressive working environment that values human creativity, and contribution can enhance talent attraction, retention, and overall employee satisfaction.
- **Competitive Advantage:** Adopting Industry 5.0 principles and technologies can enhance competitiveness by meeting sustainability expectations, improving operational resilience, and promoting economic performance.

Figure 23 Detailed Framework evaluation SAP (2024) (own depiction)

Stockwell 2017 – A framework for Industry 4.0

The framework of Stockwell (2017) for Industry 4.0 provides vital insights into the foundational elements and their broader implications, offering a sophisticated lens through which to understand the dynamics of the fourth industrial revolution. The framework identifies four pivotal components—instrumented, interconnected, inclusive, and intelligent—that collectively propel the transformative power of Industry 4.0. At the core of these elements is the integration and analysis of vast datasets, which facilitate informed decision-making and drive innovation across industries.

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Interconnectivity, particularly through cloud computing and IoT, is highlighted as essential, with industry standards playing a critical role in ensuring seamless communication and interoperability across diverse systems. Furthermore, the framework underscores the importance of collaboration and strategic partnerships, noting that cross-industry cooperation not only enhances responsiveness to consumer demands but also fuels revenue growth (Stockwell, 2017).

In addition, Stockwell (2017) emphasizes the profound impact of technological advancements—such as artificial intelligence, machine learning, and cloud computing—on manufacturing processes. These technologies enable innovations like predictive maintenance and data-driven design, which are reshaping the manufacturing landscape. However, the framework also acknowledges that while Industry 4.0 offers substantial economic advantages, it introduces significant disruptions. This necessitates adaptive strategies and the implementation of robust cybersecurity measures to protect against emerging risks in this rapidly evolving technological environment, as consolidated in Figure 24.

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Stockwell (2024) IBM 2017 – A framework for Industry 4.0

Perspective & Input

Perspective:
- IBM operates in the technology and IT services industry.
- Their perspective on Industry 4.0 is grounded in leveraging advanced technologies, such as data analytics, cloud computing, and artificial intelligence, to drive innovation and efficiency across various sectors.
- They advocate for collaboration, standardization, and adoption of Industry 4.0 principles to unlock its potential benefits for businesses and economies globally.

Input:
- The article introduces Industry 4.0 as the fourth industrial revolution, emphasizing its key components: instrumented, interconnected, inclusive, and intelligent.
- It discusses how these components drive innovation across manufacturing stages and highlights the potential economic benefits of Industry 4.0, projected to contribute $15 trillion to global GDP by 2020.

Learnings for PROSPECTS 5.0

- **Key Components of Industry 4.0:** The framework highlights four essential elements - instrumented, interconnected, inclusive, and intelligent - driving the fourth industrial revolution.
- **Data Integration and Analysis:** Industry 4.0 emphasizes leve-raging vast data for informed decision-making and innovation.
- **Interconnectivity and Standards:** Seamless communication via cloud computing and IoT frameworks is crucial, with industry standards ensuring interoperability.
- **Collaboration and Partnerships:** Industry 4.0 thrives on collaborations across industries, enabling effective consumer response and revenue growth.
- **Technological Advancements:** Leveraging AI, machine learning, and cloud computing is essential for intelligent decision-making.
- **Impact on Manufacturing Stages:** Industry 4.0 transforms designing, making, and using stages through predictive maintenance, data-driven design, and enhanced human-computer interaction.
- **Economic Benefits and Disruptions:** While promising growth, Industry 4.0 brings disruptions, requiring adaptation and robust cybersecurity measures.

Figure 24 Detailed Framework evaluation Stockwell (2017) (own depiction)

5.1.3. Gaps and Opportunities in Industry 5.0 Framework Development

The comprehensive analysis of existing frameworks reveals a significant diversity in approaches to understanding and implementing Industry 5.0. Yet, a truly holistic framework that encapsulates the entire scope of Industry 5.0 remains conspicuously absent. Among the academic contributions, the work of Ghobakhloo, Iranmanesh, Tseng, Grybauskas, Stefanini, Amran (2023) is particularly noteworthy for its breadth and depth, presenting an architectural design that meticulously integrates the technological, societal, and environmental dimensions of Industry 5.0. This framework is distinguished by its rigorous content-centric review, which synthesizes a vast body of

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literature to offer a nuanced and all-encompassing perspective on Industry 5.0. Similarly, the framework proposed by Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang (2022) is lauded for its sophisticated elaboration of the transition from Industry 4.0 to Industry 5.0, offering a tri-dimensional architecture that adeptly balances human centricity, sustainability, and resilience. Despite these substantial contributions, no single framework has yet emerged that fully encapsulates the overarching vision of Industry 5.0, highlighting a critical gap in the academic discourse.

In the non-academic sphere, the frameworks identified underscore the importance of Industry 5.0 within the industrial context, yet they too fall short of providing a comprehensive perspective. These frameworks, while emphasizing key aspects such as technological innovation and human centricity, lack an integrative approach that fully addresses the complex and multifaceted nature of Industry 5.0. This shortcoming suggests a broader challenge across both academic and non-academic frameworks: while they offer valuable insights and detailed methodologies, there remains an unmet need for a unified, all-encompassing framework capable of guiding the full realization of Industry 5.0's transformative potential.

Based on varying understandings, the current definition by the European Commission (2024) identifies Industry 5.0 through three core strategic objectives: Human centricity, sustainability, and resilience. These competencies necessitate the development of comprehensive policies and regulatory structures to support and guide advancements and applications of Industry 5.0 initiatives. It is imperative to establish robust legal frameworks, standards, and guidelines that ensure the safe and responsible deployment of new technologies and business models.

The transformation towards Industry 5.0 is driven by several key triggers. Acute crises, such as the COVID-19 pandemic, have highlighted the fragility of global supply chains, underscoring the urgent need for innovative solutions to enhance resilience. These crises necessitate immediate changes and emphasize the critical importance of focusing on employee needs and roles within organizations (Zizic, Mladineo, Gjeldum, Celent, 2022, Sarfraz, Sarfraz, Iftikar, Akhund, 2021, European Comission, 2021). Market changes, including shifts in consumer behavior and competitive dynamics, compel businesses to adopt adaptive strategies. The increasing demand for personalized products requires companies to invest in advanced technologies that enable cost-effective personalization (Aheleroff, Huang, Xu, Zhong, 2022, Costa, Amorim, Reis, Melão, 2023). Furthermore, attracting and retaining skilled employees is crucial due to the increasing complexity of job roles and rapid technological advancements. Companies must offer attractive incentives, prioritize employee well-being, and address the skills gap to meet the demands of the modern workplace (Lu, Zheng, Chand, Xia, Liu, Xu, Wang, Qin, Bao, 2022, Alves, Lima, Gaspar, 2023, Trstenjak, Hegedić, Tošanović, Opetuk, Đukić, Cajner, 2023).

Political volatility and crises, such as geopolitical tensions and protectionist ideologies, pose significant threats to global value chains and employee security. Organizations must cultivate adaptability, resilience, and strategic planning to navigate these challenges effectively (Simion, Avasilcai, Alexa, European Comission, 2021, Leng, Sha,

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Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang, 2022). Additionally, transgressing planetary boundaries poses severe risks to humanity and the Earth system. Industry must adopt sustainable practices to mitigate environmental impact, driven by consumer demand for eco-friendly products and regulatory pressures (Richardson, Steffen, Lucht, Bendtsen, Cornell, Donges, Drüke, Fetzer, Bala, Bloh, Feulner, Fiedler, Gerten, Gleeson, Hofmann, Huiskamp, Kummu, Mohan, Nogués-Bravo, Petri, Porkka, Rahmstorf, Schaphoff, Thonicke, Tobian, Virkki, Wang-Erlandsson, Weber, Rockström, 2023, Costa, Amorim, Reis, Melão, 2023). Ethical challenges and social responsibilities in Industry 5.0 involve compliance with legal standards and proactive engagement in socially beneficial practices. Companies must prioritize corporate social responsibility, ethical research, and transparency to promote social good and environmental sustainability (Pang, Lee, Murshed, 2023, Ghobakhloo, Iranmanesh, Mubarak, Mubarik, Rejeb, Nilashi, 2022).

To achieve the transformation to Industry 5.0, companies require well-defined strategies and tools. Integrating Industry 5.0 objectives within corporate strategies is crucial. This involves developing agile business models, enhancing resilience, and promoting human-centric and sustainable practices (Trstenjak, Hegedić, Tošanović, Opetuk, Đukić, Cajner, 2023, Ivanov, 2023). Companies must redesign existing models and create new ones to support this evolution (Möller, Vakilzadian, Haas, 2022). Meeting the demands of a rapidly evolving workforce necessitates continuous employee development. Upskilling involves enhancing technical, leadership, and communication skills, while enablement focuses on providing necessary tools and a supportive work environment (Hofmann, Sternberg, Chen, Pflaum, Prockl, 2019, Saniuk, Grabowska, Straka, 2022).

Leveraging interdisciplinary synergies is essential for achieving Industry 5.0 objectives. Combining expertise from various fields fosters innovation and enhances collective efforts towards shared goals. Collaboration among companies, academic institutions, and government bodies is fundamental to the success of Industry 5.0 (Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang, 2022, Longo, Padovano, Umbrello, 2020, De Giovanni, 2023). Advanced technologies, such as artificial intelligence, Big Data, IoT, blockchain, and digital twins, are key enablers of Industry 5.0. These technologies optimize processes, enhance human-machine collaboration, and improve decision-making (Mourtzis, Angelopoulos, Panopoulos, 2022, Schuh, Anderl, Dumitrescu, Krüger, Hompel, 2020, Bajic, Suzic, Moraca, Stefanović, Jovicic, Rikalovic, 2023). Collaborative robots, in particular, enhance employee well-being and productivity (Jafari, Azarian, Yu, 2022).

Establishing comprehensive policies and regulatory frameworks is essential for the safe and responsible deployment of emerging technologies. This includes creating legal structures, standards, and guidelines that ensure ethical conduct and data security (Prasant, Sain, Al-Absi, Kumar, 2021, Trstenjak, Hegedić, Tošanović, Opetuk, Đukić, Cajner, 2023, Ghobakhloo, Iranmanesh, Tseng, Grybauskas, Stefanini, Amran, 2023). By focusing on these triggers and enablers, organizations can effectively navigate the transformation towards Industry 5.0, ensuring sustainable, resilient, and human-centric

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industrial practices. The detailed breakdown of the identified literature, underscoring the analysis presented, is provided in Chapter 7.1.2.

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6. DELPHI SURVEY

6.1. Methodological Approach of the Delphi Study

Given the identified gaps and limitations in both academic and non-academic frameworks for Industry 5.0, it becomes evident that a more comprehensive and integrative approach is necessary to fully capture the multifaceted nature of this emerging paradigm. To address this need, conducting a Delphi Study emerges as a valuable method. This approach will allow us to gather expert insights and build a more nuanced understanding of Industry 5.0 by engaging with use-case partners from across Europe. Through this collaborative effort, the Delphi Study will facilitate the synthesis of diverse perspectives, leading to the development of a more robust and holistic framework that better reflects the practical realities and future potentials of Industry 5.0.

The structured Delphi method aims to systematically collect and synthesize a broad spectrum of opinions and information from a carefully selected panel of use-case-providers. The holistic goal of this method is to formulate a comprehensive and consolidated statement that accurately reflects the collective expertise of the participants. The process typically begins with a detailed description, concretization, and operationalization of the problem to be addressed, which is followed by the careful formulation of specific objectives that guide the entire study (Häder, 2021, pp. 206–209). This initial phase is crucial for establishing a solid foundation for the subsequent steps. Once the objectives are clearly defined, a standardized questionnaire is developed as the primary survey instrument, ensuring consistency and reliability in data collection. Following this, a panel of experts, particularly use-case-providers who possess relevant experience and knowledge, is selected and recruited to participate in the study (Häder, 2021, pp. 206–209).

During the initial round of the survey, the expert panel provides responses that are then anonymized, compiled, and shared with all participants. This step is intended to promote transparency and encourage participants to engage in a reflection on the diverse perspectives offered by their peers before proceeding to the second round of the survey. The survey is then repeated with the same panel, thereby enabling the refinement of the collected data and facilitation of a consensus among the experts (Häder, 2021, pp. 206–209). The final phase of the Delphi method involves a thorough evaluation and documentation of the survey data, as well as the conclusions drawn from the analysis. This ensures that the findings are robust and clearly articulated.

The survey rounds within the Delphi method are structured into two main stages, with an interim analysis stage situated between them. In the first stage, experts respond to open-ended questions, which are formulated to elicit a comprehensive range of ideas and insights. This stage is essential for capturing the initial diversity of perspectives from the expert panel. Following this, the organizers conduct an interim analysis, during which they analyze the responses from the first survey round in order to develop hypotheses that will guide the focus of the subsequent survey rounds (Häder, 2021, pp. 209–211). In the second stage, known as the consensus-building phase, experts are

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asked to address these hypotheses through closed questions. This phase is designed to consolidate and refine the insights gathered during the first round, gradually building towards a robust and well-supported consensus among the expert panel. The iterative nature of this process, characterized by continuous refinement and consensus-building, ultimately leads to a comprehensive and validated outcome, which is then documented as the key result of the study (Häder, 2021, pp. 209–211). This process is visually summarized in Figure 25.

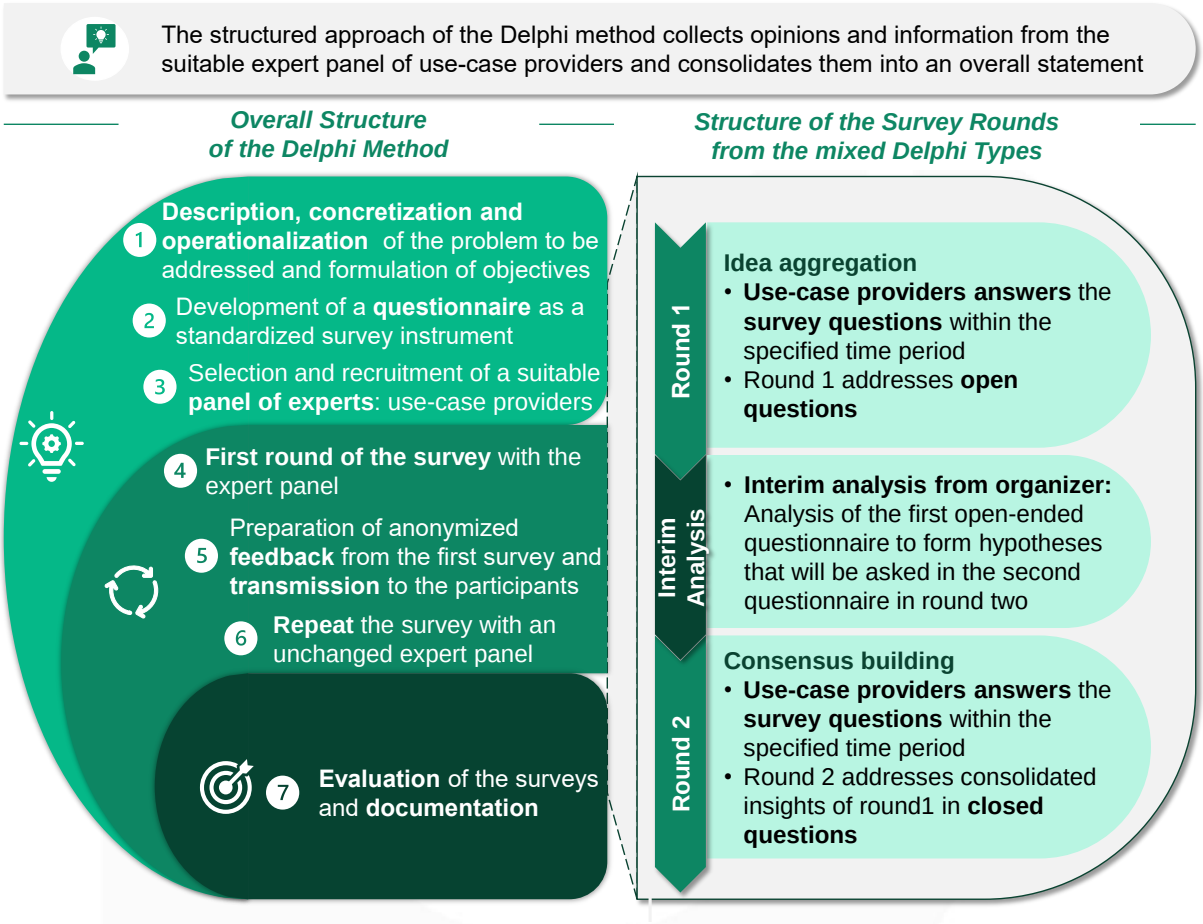

Figure 25 Overall Structure of the Delphi Method according to Häder (2021, pp. 206–211) (own depiction)

The Delphi Study was meticulously designed to obtain comprehensive insights from use-case-providers through a series of targeted questionnaires administered via Microsoft Office Forms. To ensure the study's cross-sectoral and international relevance, 14 different organizations (PROSPECTS5.0 use-cases) were selected from a diverse range of industries and countries. These companies collectively formed the cohort of the study. However, to better elucidate the disparities in responses across various sectors, all participants were classified into distinct groups based on their respective modes of production or service. These categorizations were established by compiling detailed information on the services or products offered by each organization, followed by an analysis to cluster the firms. As a result, three sectors have been identified: Consumer Goods, Life Sciences and Heavy Industry. The Consumer Goods sector comprised four participating companies, the Life Sciences sector

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included five companies, and an equal number of five companies were surveyed in the Heavy Industry domain, as shown in Figure 26. Within the consumer goods group, the participating organizations span a diverse spectrum, ranging from the production of safety footwear and hair colors to the manufacture of firefighter protective clothing and jewelry. In the Life Sciences sector, participants operate in a broad array of fields, including healthcare production, laboratory and scientific equipment manufacturing, IT-services, energy storage solutions, as well as consulting with a focus on digital transformation and sustainability. Companies focusing on precision engineering, friction stir welding, manufacturing of marine or automotive components and the production of lifting systems can be classified together in the heavy industry sector. To ensure the inclusion of diverse perspectives across these sectors, participation from all use-case-providers was mandatory in both survey rounds.

Figure 26 Industry-Specific Insights from 14 Companies: A Delphi Method Approach (own depiction)

The study focused on four key thematic areas, each addressing critical aspects of Industry 5.0. These areas encompassed the objectives and vision of Industry 5.0, the driving forces behind its transition, the enabling technologies and collaborative efforts necessary for its realization, and the integration of sustainability, human centricity, and resilience within this emerging industrial paradigm, as shown in detail in the following Table 4.

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Table 4 Structure and content of Delphi Study (own depiction)

Topic Area	***Specific questions to be answered by use-case-providers***
Objectives and target image of Industry 5.0	
Purpose	What should be the primary objectives of Industry 5.0 for companies, besides aspects of profit generation?
Economic Growth	How can Industry 5.0 contribute to the long-term economic growth and competitiveness of European industries?
Triggers of Industry 5.0	
Primary Triggers	What are the primary technological, economic, ecological, and social triggers driving the transition to Industry 5.0?
Global Trends and Challenges	What roles do global trends and challenges (e.g., climate change, digital transformation) play in accelerating Industry 5.0?
Enablers of Industry 5.0	
Key Technologies	What are the key technologies and innovations that will enable the transition to Industry 5.0 in your opinion?
Collaboration	How can collaboration between industry, government, and academia facilitate the development and implementation of Industry 5.0?
Enablers of Industry 5.0	
Integration of Practices	How can European industries integrate sustainable practices into their operations during the transition to Industry 5.0?
Sustainability Mission	What specific sustainability goals are most important for your company to achieve in the next five years?
Redefining Roles	How should Industry 5.0 redefine the role of humans within the industrial environment?
Impact on Jobs and Skills:	What are the potential impacts of Industry 5.0 on job roles, skills, and workforce development?
Disruption Preparedness:	How can Industry 5.0 help industries better prepare for and respond to disruptions (e.g., economic, environmental, technological)?
Business Continuity	In what ways can Industry 5.0 technologies support business continuity and adaptability?

The questionnaires were designed to elicit expert opinions on the strategic goals of Industry 5.0, emphasizing not only profit generation but also broader economic and societal impacts. Additionally, the study aimed to identify the primary technological, economic, ecological, and social catalysts propelling the shift towards Industry 5.0, as well as the global trends and challenges shaping this transformation. The survey further

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explored the essential technologies and innovations that will enable Industry 5.0, as well as the critical role of collaboration between industry, government, and academia in facilitating this transition. Moreover, the study addressed the integration of sustainable practices, the redefinition of human roles within industrial environments, and the preparedness for and response to disruptions as important topics.

Through this structured approach, the Delphi Study sought to provide a nuanced understanding of the various factors influencing the development and implementation of Industry 5.0. The insights gained are intended to inform strategies that will foster long-term economic growth, sustainability, and resilience within European industries.

6.2. Conduction and Analysis of the Delphi Study

The survey process was meticulously structured into two distinct survey rounds, encompassing both the planned and executed activities. The first round of data collection was initially scheduled for the period from June 17 to July 7, 2024, and was conducted accordingly. The second round, planned for July 15 to July 28, 2024, also proceeded as intended within the specified timeframe.

The surveys were carried out across various perspectives, targeting different industrial sectors: Consumer Goods, Life Sciences, and Heavy Industry. Within each round, the collected responses underwent thorough analysis, followed by revisions and a subsequent survey aimed at further refining the outcomes.

The perspectives were categorized by industry sectors, with specific companies participating in each:

- Consumer Goods: Cameleo, Eco Coatings, Smarald, AMF
- Life Sciences: B. Braun, Efesto, Knowit, Octave, ELMI
- Heavy Industry: Stirtec, GTW Bearings, Zeuko, Teknorot, Trygons

Each sector was subjected to both survey rounds, with tailored feedback and revisions, ultimately culminating in the final analysis to be completed in August 2024. The process is shown in Figure 27.

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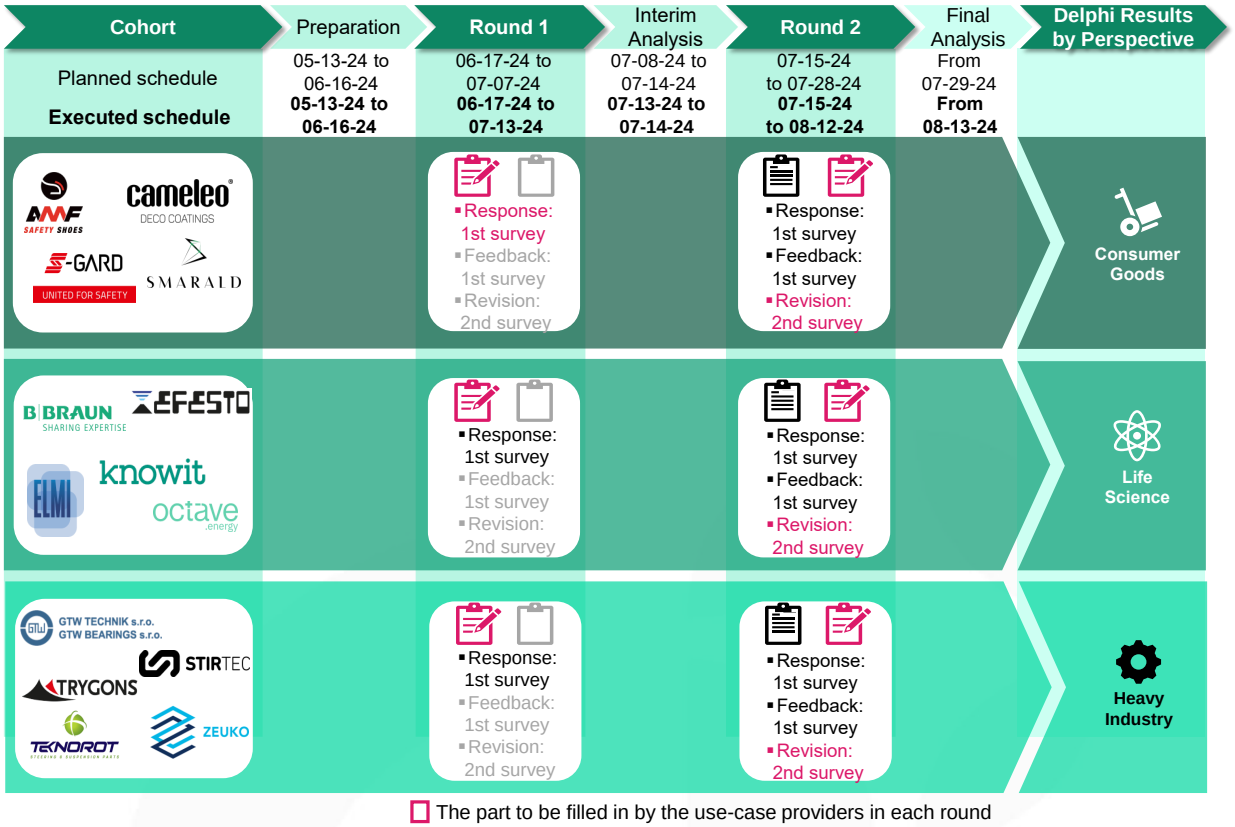

Figure 27 The participating companies provide industry-specific perspectives in two rounds using the Delphi Method (own depiction)

In the initial round of the Delphi Study, the collected responses were systematically organized and recorded in a Microsoft Excel spreadsheet, where each of the 12 columns corresponded to a specific inquiry. These inquiries were thoughtfully grouped according to thematic areas derived from the primary research domains highlighted in the systematic literature review. The data were then meticulously categorized based on the individual responses and the respective respondents. Furthermore, the frequency of each response was calculated and documented as numerical values, facilitating a detailed and comprehensive analysis of the response patterns.

These thematic areas included critical research domains such as the objectives and target image of Industry 5.0, key elements like sustainability, human centricity, and resilience, as well as the triggers and enablers of Industry 5.0. Specific questions under these domains aimed to explore the purpose and economic growth potential of Industry 5.0, integration of sustainable practices, redefinition of roles within industrial environments, impact on job roles, and the role of key technologies and collaborations in driving this industrial transition.

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Research area	*Open questions to be answered by use-case providers*
Objectives and target image of Industry 5.0	**Purpose**: What should be the primary objectives of Industry 5.0 for companies, besides aspects of profit generation? **Economic Growth**: How can Industry 5.0 contribute to the long-term economic growth and competitiveness of European industries?
Key element: Sustainability, Human-Centricity, Resilience	**Integration of Practices:** How can European industries integrate sustainable practices into their operations during the transition to Industry 5.0? **Sustainability Mission:** What specific sustainability goals are most important for your company to achieve in the next five years? **Redefining Roles:** How should Industry 5.0 redefine the role of humans within the industrial environment? **Impact on Jobs and Skills:** What are the potential impacts of Industry 5.0 on job roles, skills, and workforce development? **Disruption Preparedness:** How can Industry 5.0 help industries better prepare for and respond to disruptions (e.g., economic, environmental, technological)? **Business Continuity:** In what ways can Industry 5.0 technologies support business continuity and adaptability?
Triggers of Industry 5.0	**Primary Triggers:** What are the primary technological, economic, ecological, and social triggers driving the transition to Industry 5.0? **Global Trends and Challenges:** What role do global trends and challenges (e.g., climate change, digital transformation) play in accelerating Industry 5.0?
Enablers of Industry 5.0	**Key Technologies:** What are the key technologies and innovations that will enable the transition to Industry 5.0 in your opinion? **Collaboration:** How can collaboration between industry, government, and academia facilitate the development and implementation of Industry 5.0?

Figure 28 Overview of Questions in the First Round of the Delphi Study (own depiction)

The evaluation of the responses from the 14 participating companies was conducted meticulously on a question-by-question basis, ensuring that each inquiry received a tailored and focused analysis. The questions, as illustrated in the accompanying Figure 28, were systematically categorized into distinct research areas, including the objectives and target image of Industry 5.0, key elements such as sustainability, human centricity, and resilience, as well as the triggers and enablers of Industry 5.0. This structured approach facilitated a comprehensive analysis of each company's responses to these open-ended questions.

From this detailed examination, hypotheses were derived and formulated into clear, statement-based propositions. These initial hypotheses, grounded in the responses from the first round, are slated for rigorous testing in the second round of the Delphi Study. In this phase, they will be presented to the participating companies for validation and further refinement. This iterative process is designed to progressively refine the collective insights of the industry, ensuring that the final conclusions are robust and

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representative of the broader industrial perspective. By systematically building on the insights gathered in the first round, the study aims to achieve a nuanced understanding of the industry's vision for Industry 5.0, while addressing the specific challenges and opportunities identified by the participants.

In the second round of the Delphi Study, the hypotheses derived from the first round were consolidated and evaluated using a 5-point Likert scale. Unlike typical surveys, where respondents can opt out of answering questions if they feel unqualified, this study did not permit skipping questions. A preliminary competence check was deemed unnecessary, as the participants were carefully selected for their expertise prior to the study, ensuring that all respondents were well-equipped to provide informed answers. Additionally, the survey allowed participants to offer comments and pose questions at the end, aligning with best practices recommended in similar studies. Figure 29 presents the hypotheses that were evaluated during the Delphi study, categorized into key research areas. Each hypothesis is associated with a specific aspect of Industry 5.0, and the outcomes reflect the consensus reached by the expert panel during the study.

Following the second round, the Likert scale responses were analyzed with the primary objective of establishing hypotheses regarding Industry 5.0 that could be accepted by expert consensus—a common goal in Delphi surveys (Fink, Kosecoff, Chassin, Brook, 1984, Häder, 2021, Häder, 2009). Two distinct methods were employed for data analysis, which will be detailed in the subsequent section. The first method utilized descriptive statistics to set specific criteria for hypothesis acceptance. To be considered accepted by the experts, a hypothesis needed to meet two conditions: first, the median of the Likert scale responses had to exceed 3 (on a scale where 1 represents "strongly disagree" and 5 represents "strongly agree"); second, the interquartile range (IQR) needed to be less than 1. These criteria were established to ensure that the hypotheses reflected a strong and consistent agreement among the participants. While there is no universally accepted standard for evaluating Delphi surveys (Gracht, 2012), the use of median values is considered robust by Trevelyan, Robinson (2015), with Gracht (2012) specifically recommending the median to mitigate the impact of outliers.

In addition to the descriptive statistical analysis, the results were visually represented through charts. The incorporation of visualizations alongside descriptive analysis enhances the clarity and interpretability of the findings, as recommended by Gracht (2012). This combined approach ensures a comprehensive and accessible presentation of the study's results, facilitating a deeper understanding of the industry's collective perspectives on Industry 5.0.

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Research area	*Identified Industry position (Accepted hypothesis)*
Objectives and target image of Industry 5.0	**Purpose**: • Industry 5.0 initiatives that prioritize both technological advancement and human-centric innovation will increase adoption rates of the concept and foster a positive perception of the concept. • Resilient business models that support talent development are essential for achieving long-term success in Industry 5.0 initiatives. • The implementation of sustainable practices, including the use of renewable energy sources and optimized waste management, is crucial for Industry 5.0 success. **Economic Growth**: • Industry 5.0 strategies that integrate innovative technologies with emphasizing energy efficiency will increase economic growth and enhance competitiveness in European industries within the next decade. • The integration of AI in Industry 5.0 will optimize production processes and facilitate the development of customer-specific products within the next decade. • Efforts in upskilling employees and fostering human-robot collaboration in Industry 5.0 will increase industry resilience.
Key element: Sustainability Human centricity Resilience	**Integration of Practices:** • The integration of sustainable practices, including energy-efficient technologies and circular economy principles, is essential for European industries to achieve long-term environmental and economic benefits within Industry 5.0. **Sustainability Mission:** • Developing digital skills among employees will position companies better for sustainability success. **Redefining Roles:** • Industry 5.0 initiatives that fail to leverage human creativity, decision-making, and problem-solving abilities will stagnate, whereas prioritizing these aspects will redefine the role of humans in industrial innovation and drive significant advancements. **Impact on Jobs and Skills:** • Prioritizing skills diversification through strong collaboration between industry and educational institutions will result in a workforce well-equipped for Industry 5.0. • Ignoring the development of soft skills will leave the workforce unprepared for the challenges and opportunities of Industry 5.0. **Disruption Preparedness:** • Prioritizing process standardization will significantly enhance Industry 5.0's preparedness while improving process efficiency. **Business Continuity:** • Integrating autonomous systems is crucial for Industry 5.0 to effectively respond to dynamic market conditions. • Failing to foster visibility in leadership roles will undermine employee engagement, whereas promoting these elements will significantly enhance the strategic contribution of human skills.
Triggers of Industry 5.0	**Primary Triggers:** • Technological advancements such as AI, robotics, and IoT are crucial drivers in facilitating operational efficiency in Industry 5.0. **Global Trends and Challenges:** • A holistic approach that addresses global challenges, incorporating Human centricity at the forefront of innovation, is essential for Industry 5.0 to successfully evolve and adapt.
Enablers of Industry 5.0	**Key Technologies:** • Additive manufacturing is a key technology that revolutionizes production processes in Industry 5.0, increasing production flexibility. • The integration of IoT is crucial for the seamless connectivity and real-time data exchange in Industry 5.0, enhancing operational visibility. • Industry 5.0 initiatives that fail to leverage advanced data analytics will be left behind, as these technologies will propel adopters to a significant boost in innovation and operational excellence. **Collaboration:** • The integration AI is not just beneficial but absolutely essential for accelerating the adoption and effectiveness of Industry 5.0 in practice • Proactive government policies will be the catalyst for transforming and successfully implementing Industry 5.0 technologies.

Figure 29 Overview of Delphi Study Round 2 hypothesis (own depiction)

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6.3. Results of the Delphi Study

In the analysis of the Delphi Study, an intricate methodological approach was employed to explore the perspectives of Industry 5.0, focusing specifically on the overarching groups identified as (1) Objectives and Target Image of Industry 5.0, (2) Key Elements: Sustainability, Human centricity, Resilience, (3) Triggers of Industry 5.0 and (4) Enablers of Industry 5.0. Additionally, the study investigated the triggers and enablers of Industry 5.0, as identified through an extensive literature review. The initial phase of the study involved the formulation and dissemination of open-ended questions to participating enterprises, aimed at eliciting detailed insights into the significance and prioritization of these aspects from the industry's perspective.

The responses gathered during the first round were meticulously analyzed to identify patterns and correlations between different companies' viewpoints. This analysis provided a granular understanding of how various enterprises perceive and prioritize the objectives, key elements, and enabling factors of Industry 5.0. The data from this round allowed for the identification of thematic clusters and company-specific emphasis on certain aspects of Industry 5.0, thereby laying the groundwork for the formulation of targeted hypotheses.

Building on this initial analysis, a set of hypotheses was derived for the second round of the study. These hypotheses were crafted to test and refine the initial insights, thereby allowing for a more nuanced understanding of the industry's collective vision and priorities concerning Industry 5.0. In the second round, these hypotheses were presented to the participating companies in a closed-question format, enabling a structured and quantifiable validation process. The closed-question approach was essential to distill the broader, qualitative insights from the first round into specific, testable assertions that could be systematically evaluated.

The primary aim of this methodological progression was to not only assess but also to substantiate the industry's perspective on the future trajectory of Industry 5.0, particularly in relation to the crucial elements of sustainability, human centricity, and resilience. The iterative nature of the Delphi method, moving from open-ended exploration to hypothesis testing, ensured that the study captured both the diversity of thought within the industry and the consensus on key strategic objectives. The results from the first and second round of hypothesis testing provided critical insights into the priorities and strategic orientations of different companies and sectors regarding Industry 5.0. These findings are pivotal for understanding how industry leaders envisage the future landscape of Industry 5.0 and offer a robust foundation for developing actionable strategies and policies aimed at fostering sustainability, human-centric approaches, and resilience in the industrial sector. The described findings are visualized in detail in the Appendix, with detailed analysis of the accepted hypotheses for each cohort and overall results, consolidated in the following Table 5 and detailed in the Appendix.

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Table 5 Hypothesis status Round 2 Delphi study (own depiction)

	Hypothesis	*Median*	*Interquartile Range (IQR)*	*Status*
Purpose	Industry 5.0 initiatives that prioritize both technological advancement and human-centric innovation will increase adoption rates of the concept and foster a positive perception of the concept.	4	1	**Accepted**
	Resilient business models that support talent development are essential for achieving long-term success in Industry 5.0 initiatives.	4	1	**Accepted**
	The implementation of sustainable practices, including the use of renewable energy sources and optimized waste management, is crucial for Industry 5.0 success.	5	1	**Accepted**
Economic Growth	Industry 5.0 strategies that integrate innovative technologies with emphasizing energy efficiency will increase economic growth and enhance competitiveness in European industries within the next decade.	4	0,75	**Accepted**
	The integration of AI in Industry 5.0 will optimize production processes and facilitate the development of customer-specific products within the next decade.	4,5	1	**Accepted**
	Efforts in upskilling employees and fostering human-robot collaboration in Industry 5.0 will increase industry resilience.	4	0,75	**Accepted**
Integration of Practices	The integration of sustainable practices, including energy-efficient technologies and circular economy principles, is essential for European industries to achieve long-term environmental and economic benefits within Industry 5.0.	4	1	**Accepted**
	European industries that fail to adopt energy-efficient technologies and embrace circular economy principles within Industry 5.0 will fall behind.	4	1,75	**Rejected**
Sustainability Mission	Optimizing raw material utilization will significantly boost companies' success in sustainability.	4	1,5	**Rejected**
	Developing digital skills among employees will position companies better for sustainability success.	5	1	**Accepted**

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Redefining Roles	Industry 5.0 initiatives that fail to leverage human creativity, decision-making, and problem-solving abilities will stagnate, whereas prioritizing these aspects will redefine the role of humans in industrial innovation and drive significant advancements.	4	0,75	**Accepted**
	Without a strong emphasis on human-machine collaboration, Industry 5.0 will fall short of its potential.	4	1,75	**Rejected**
Impact on Jobs and Skills	Prioritizing skills diversification through strong collaboration between industry and educational institutions will result in a workforce well-equipped for Industry 5.0.	4,5	1	**Accepted**
	Ignoring the development of soft skills will leave the workforce unprepared for the challenges and opportunities of Industry 5.0.	4	0,75	**Accepted**
Disruption Preparedness	Fostering human-robot collaboration boosts Industry 5.0's ability to manage disruptions.	4	1,5	**Rejected**
	Prioritizing process standardization will significantly enhance Industry 5.0's preparedness while improving process efficiency.	4	1,5	**Rejected**
Business Continuity	Integrating autonomous systems is crucial for Industry 5.0 to effectively respond to dynamic market conditions.	4	0	**Accepted**
	Failing to foster visibility in leadership roles will undermine employee engagement, whereas promoting these elements will significantly enhance the strategic contribution of human skills.	4	0,75	**Accepted**
Primary Triggers	Technological advancements such as AI, robotics, and IoT are crucial drivers in facilitating operational efficiency in Industry 5.0.	5	1	**Accepted**
	Global competition is a significant economic factor influencing the transition to Industry 5.0.	4	1	**Accepted**
	The promotion of circular economy practices significantly influences the transition to Industry 5.0, enhancing sustainability.	4	2	**Rejected**
Global Trends and Challenges	A holistic approach that addresses global challenges, incorporating human centricity at the forefront of innovation, is essential for Industry 5.0 to successfully evolve and adapt.	4,5	1	**Accepted**
	Adoption of advanced automation techniques by companies is driven by customer demands.	4	1,75	**Rejected**

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	Digital transformation is not just a trend but a revolution that is radically accelerating the adoption of sustainable practices in Industry 5.0, making it an indispensable driver for achieving environmental goals and operational efficiency.	4	1	**Accepted**
Key Technologies	Additive manufacturing is a key technology that revolutionizes production processes in Industry 5.0, increasing production flexibility.	4	1	**Accepted**
	The integration of IoT is crucial for the seamless connectivity and real-time data exchange in Industry 5.0, enhancing operational visibility.	5	1	**Accepted**
	Industry 5.0 initiatives that fail to leverage advanced data analytics will be left behind, as these technologies will propel adopters to a significant boost in innovation and operational excellence.	5	1	**Accepted**
	The integration AI is not just beneficial but absolutely essential for accelerating the adoption and effectiveness of Industry 5.0 in practice.	4,5	1	**Accepted**
Collaboration	Effective collaboration between industry, government, and academia significantly enhances innovation, supporting the growth of Industry 5.0.	5	1	**Accepted**
	Practical industry-related education will be the linchpin in enhancing collaboration between industry, government, and academia.	4	1,75	**Rejected**
	Proactive government policies will be the catalyst for transforming and successfully implementing Industry 5.0 technologies.	4	0,75	**Accepted**
	The evolution of job roles and skills diversification brought by Industry 5.0 will mandate increased collaboration between industry and educational institutions.	4	1	**Accepted**

The results of the second round of the Delphi Study provide a comprehensive overview of the collective understanding and attitudes towards Industry 5.0 across diverse industrial sectors. The analysis of the hypotheses, evaluated by participants from the Consumer Goods, Life Sciences, and Heavy Industry cohorts, reveals both convergences and divergences in the perceived importance and feasibility of integrating technological advancements, human-centric innovation, and sustainability within the framework of Industry 5.0. In the following section, the results will be discussed starting with an overall analysis of the cohort followed by a detailed analysis of each cohort.

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Purpose:

The hypothesis asserting that Industry 5.0 initiatives should balance technological advancement with human-centric innovation is broadly accepted (Median = 4, IQR = 1), indicating consensus across industrial sectors that balancing these two factors will foster adoption. This underscores the importance of a synergistic approach, where human-centric innovation complements technological progress, thereby facilitating the broader integration of Industry 5.0 initiatives. Similarly, the hypothesis that resilient business models that support talent development are essential for long-term success in Industry 5.0 is widely accepted across all cohorts. This finding emphasizes the broad belief that human talent and development must be central to Industry 5.0, suggesting that the workforce's role will be pivotal in driving the transformation required for sustainable Industry 5.0 growth. The hypothesis concerning the adoption of sustainable practices, such as renewable energy, is viewed as important overall (Median = 5, IQR = 1). However, this hypothesis is rejected by the Consumer Goods sector, which exhibits considerable variability (IQR = 1.75). This rejection may be attributed to concerns about immediate cost implications or challenges in implementing these practices within this sector.

Economic Growth:

The hypothesis that innovative technologies combined with energy efficiency will drive economic growth is accepted (Median = 4, IQR = 0,75), though Consumer Goods rejects it (Median = 3.5, IQR = 1.25), potentially viewing energy efficiency as a long-term rather than short-term driver. In contrast, the Life Sciences and Heavy Industry sectors accept this hypothesis, likely due to the anticipated benefits of energy efficiency in industrial sectors where energy consumption is more pronounced and its financial impacts more immediate. The integration of AI into production processes is widely accepted across all sectors, with a shared recognition of its importance for enhancing customization and optimization (Median = 4.5 overall). This finding highlights the universal acknowledgement of AI as a key enabler of operational efficiency in Industry 5.0. Efforts to upskill employees and foster human-robot collaboration are also widely endorsed (Median = 4, IQR = 0,75), signifying a cross-sector recognition of the importance of workforce development for ensuring resilience within the Industry 5.0 paradigm.

Integration of Practices:

There is widespread agreement on the need for sustainable practices and the adoption of circular economy principles within Industry 5.0. Nevertheless, the Consumer Goods sector rejects this hypothesis (Median = 4, IQR = 2.25), likely due to concerns about the financial and practical challenges of implementation. In contrast, the Life Sciences and Heavy Industry sectors accept these practices, driven perhaps by stronger regulatory frameworks and heightened environmental pressures. The hypothesis that failure to adopt energy-efficient technologies will cause industries to fall behind is rejected overall (Median = 4, IQR = 1,75) and in Consumer Goods (Median = 3, IQR = 2.25), indicating variability in how immediate the threat of falling behind is perceived. However, Heavy Industry accepts this, likely due to its significant energy consumption and the growing importance of energy efficiency in reducing operational costs.

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Sustainability Mission:

The hypothesis that optimizing raw material utilization is essential for achieving sustainability is rejected overall (Median = 4, IQR = 1.5) and particularly by the Heavy Industry sector (Median = 3, IQR = 1), likely reflecting the challenges faced by large-scale industries in optimizing resource use. In contrast, the Consumer Goods and Life Sciences cohorts accept this hypothesis, with lower levels of variability. The development of digital skills is universally regarded as essential for supporting sustainability efforts, and this hypothesis is accepted across all cohorts (Median = 5, IQR = 1), reflecting the widespread belief that digital competencies are crucial to the realization of Industry 5.0's sustainability objectives.

Redefining Roles:

The hypothesis that failing to leverage human creativity and decision-making will stagnate the progression of Industry 5.0 is accepted overall (Median = 4, IQR = 0,75), but it is rejected by the Consumer Goods sector (Median = 4, IQR = 2). This may indicate the sector's reliance on automation, where human roles are perceived as secondary to technological advancements. The second hypothesis is rejected overall (Median = 4, IQR = 1.75), indicating that not all sectors see human-machine collaboration as a critical factor for Industry 5.0's success. This rejection suggests that there are other, more pressing priorities such as automation, sustainability, or technological development.

Impact on Jobs and Skills:

The emphasis on diversifying skills and collaborating with educational institutions is accepted across all cohorts (Median = 4.5, IQR = 1). This finding underscores the recognition of the need to prepare the workforce for the evolving demands of Industry 5.0, particularly as technological advancements transform industrial operations. The importance of developing soft skills—such as communication, problem-solving, and adaptability—is also widely accepted (Median = 4, IQR = 0.75), reflecting a shared understanding that as AI and automation continue to grow, these human skills will become increasingly critical for enabling effective collaboration and innovation within Industry 5.0 environments.

Disruption Preparedness:

The hypothesis that human-robot collaboration enhances disruption preparedness is rejected overall (Median = 4, IQR = 1.5), though it is strongly accepted by the Consumer Goods sector (Median = 5, IQR = 0,5). This divergence may be explained by the sector's focus on automation as a buffer against disruptions in production and logistics. The prioritization of process standardization as a means of enhancing Industry 5.0 preparedness is also rejected overall (Median = 4, IQR = 1.5), though it is accepted within the Consumer Goods and Heavy Industry sectors, where standardization may still be viewed as key to managing disruptions and improving efficiency.

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Business Continuity:

Autonomous systems are broadly accepted across all cohorts (Median = 4, IQR = 0) as essential for Industry 5.0, reflecting a shared understanding that such systems enhance operational flexibility and resilience by enabling industries to rapidly adapt to changing market demands and conditions. Leadership visibility is seen as critical overall (Accepted, Median = 4, IQR = 0.75), but it is rejected by the Consumer Goods sector (Median = 3.5, IQR = 1.5). This sectoral difference might reflect a stronger focus on automation and efficiency within Consumer Goods, while Life Sciences and Heavy Industry, with their more human-centric or large-scale operations, recognize the value of leadership visibility in aligning human skills with strategic goals.

Primary Triggers:

Technological advancements such as AI, robotics, and IoT are universally accepted as critical drivers of Industry 5.0 (Median = 5, IQR = 1). This consensus underscores the importance of these technologies in enhancing operational efficiency across sectors. However, the role of global competition as a key driver, while accepted overall, is rejected by the Consumer Goods sector (Median = 4.5, IQR = 1.25). This suggests that internal factors—such as cost control and supply chain efficiency — may be more pressing concerns for this sector than global competitive pressures. The promotion of circular economy practices is also rejected overall (Median = 4, IQR = 2), with only the Life Sciences cohort accepting (Median = 4, IQR = 1) this hypothesis, likely due to sector-specific regulatory and environmental considerations.

Global Trends and Challenges

The hypothesis that a holistic approach to addressing global challenges is essential for Industry 5.0 is widely accepted (Median = 4.5, IQR = 1), reflecting broad recognition of the importance of human-centric innovation. The hypothesis that customer demands will drive automation is rejected overall (Median = 4, IQR = 1.75), suggesting that automation is more internally driven by efficiency needs than by external pressures. The Life Sciences sector alone accepts this hypothesis (Median = 4, IQR = 1). Digital transformation is accepted as a key driver of both sustainability and operational efficiency, particularly in Life Sciences (Median = 5, IQR = 1), highlighting its significant role in enhancing productivity and environmental outcomes in highly regulated industries. The consumer goods cohort however rejected this hypothesis (Median = 3,5, IQR = 1,5).

Key Technologies:

There is broad acceptance of additive manufacturing as a key enabler of operational flexibility (Median = 4). However, the Heavy Industry sector remains skeptical (Rejected, Median = 3, IQR = 1), likely due to sector-specific challenges associated with large-scale manufacturing. The integration of IoT is universally accepted as crucial for seamless connectivity and real-time data exchange (Median = 5, IQR = 1), underscoring the technology's importance in enhancing operational visibility and decision-making across sectors. Advanced data analytics and AI are strongly accepted as accelerators of Industry 5.0, with little variability in responses (Median = 5, IQR = 1). This reflects

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widespread recognition of the critical role that data-driven decision-making and AI-driven automation will play in achieving the objectives of Industry 5.0.

Collaboration:

Effective collaboration between industry, government, and academia is widely seen as essential (Median = 5, IQR = 1), though Heavy Industry shows some skepticism (Rejected, Median = 5, IQR = 2), likely due to concerns about the practicalities of collaboration, such as misalignment of goals and the slow pace of governmental processes. The importance of industry-related education is rejected overall (Median = 4, IQR = 1.75), suggesting that industries may feel education systems are not yet fully aligned with Industry 5.0 needs, or that practical, hands-on experience within the industry may be more effective than formal education in developing the required skills. Government policies are mostly accepted as a catalyst for transforming and implementing Industry 5.0 technologies (Median = 4, IQR = 0,75), though Consumer Goods again shows skepticism (Rejected, Median = 3, IQR = 2.25), preferring market-driven solutions over government intervention.

Detailed analysis cohort 1

Consumer Goods within the Delphi Study reflects a nuanced understanding of Industry 5.0, demonstrating a mixture of acceptance and rejection across various hypotheses. This cohort exhibits a clear focus on technological and human-centric approaches, while showing some divergence on sustainability and economic aspects.

The hypothesis that "Industry 5.0 initiatives that prioritize both technological advancement and human-centric innovation will increase adoption rates of the concept and foster a positive perception of the concept" was rejected, with a median score of 4 and an IQR of 2. This indicates variability in opinions about the impact of integrating these elements on Industry 5.0 adoption. Similarly, the statement concerning the implementation of sustainable practices was rejected, despite a median score of 4.5 and an IQR of 1.75, suggesting a less consistent view on the importance of sustainability within this sector. On the other hand, significant acceptance was observed for the hypotheses regarding the role of AI in optimizing production processes, upskilling employees, and fostering human-robot collaboration, all of which were rated high median scores (5 and 4) and low IQRs (0.25 and 0.5). This reflects a consensus on the importance of these elements for enhancing resilience and operational efficiency. The emphasis on technological advancements, such as AI and additive manufacturing, with high acceptance rates, underscores the sector's focus on integrating advanced technologies to drive industry progress. Additionally, the hypothesis related to the integration of autonomous systems for business continuity was accepted with a median score of 4 and an IQR of 0.5, highlighting its perceived importance. Conversely, hypotheses about the promotion of circular economy practices and the impact of global competition were rejected, indicating less emphasis on these areas.

In general, the findings for Cohort 1 are as follows: Consumer Goods demonstrates a strong alignment with technological advancements and operational efficiency, while

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exhibiting more varied opinions on sustainability and economic growth strategies. These insights provide a clear understanding of the sector's priorities and potential areas for further exploration in the context of Industry 5.0.

Detailed analysis cohort 2

Life Sciences reveal a strong consensus on several key aspects of Industry 5.0, emphasizing a balanced integration of technological, sustainable, and human-centric factors. This cohort demonstrates a notable alignment in recognizing the importance of these elements for achieving success in Industry 5.0.

Most hypotheses within this cohort were accepted, indicating a robust agreement on the critical factors driving Industry 5.0. For instance, the hypothesis that "Industry 5.0 initiatives that prioritize both technological advancement and human-centric innovation will increase adoption rates of the concept and foster a positive perception of the concept" was rated a high median score of 5 and an IQR of 1, reflecting strong support for this integrative approach. Similarly, hypotheses emphasizing the importance of sustainable practices, energy efficiency, and the integration of AI were uniformly accepted, with median scores ranging from 4 to 5 and IQRs of 0 to 1. The acceptance of statements about upskilling employees and fostering human-robot collaboration, with medians of 5 and low IQRs, underscores the cohort's recognition of these factors as essential for enhancing resilience and operational effectiveness. The consistent acceptance across various areas, including sustainability missions and the role of advanced technologies, highlights a comprehensive endorsement of Industry 5.0 principles within the Life Sciences sector. Conversely, some hypotheses were rejected, such as the one on the impact of human-machine collaboration, which indicates a less unanimous view on its role. Similarly, the statement concerning practical industry-related education as a linchpin for enhancing collaboration was also rejected, with a lower median score and higher IQR.

In general, the findings for Cohort 2 are as follows: The cohort Life Sciences reflects a broad consensus on the importance of integrating technological advancements, sustainability, and human-centric approaches for the successful implementation of Industry 5.0. The high acceptance rates across most hypotheses suggest a strong alignment with the core principles of Industry 5.0, providing a clear indication of the sector's priorities and strategic outlook.

Detailed analysis cohort 3

The cohort Heavy Industry reflects a broad acceptance of the fundamental principles of Industry 5.0, with a particular emphasis on the integration of technological and human-centric elements. The data reveals a strong consensus on the necessity of both technological advancement and human-centric innovation for successful implementation.

In this cohort, hypotheses related to the prioritization of technological and human-centric innovation received high acceptance rates. For example, the hypothesis that

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"Industry 5.0 initiatives that prioritize both technological advancement and human-centric innovation will increase the adoption rates of the concept and foster a positive perception of the concept" was rated a median score of 4 and an IQR of 0, indicating unanimous support. Similarly, hypotheses regarding the implementation of sustainable practices, energy efficiency, and AI integration were consistently accepted, with medians ranging from 4 to 5 and low IQRs, underscoring their perceived importance in driving the success of Industry 5.0. Hypotheses about optimizing raw material utilization and developing digital skills among employees were also accepted, reinforcing the cohort's view on sustainability and skill development. However, there were some notable rejections. For instance, the hypothesis that "additive manufacturing is a key technology that revolutionizes production processes in Industry 5.0" was rated a median of 3 and was rejected, suggesting a more cautious or skeptical view on its impact compared to other technologies. Additionally, the hypothesis concerning effective collaboration between industry, government, and academia was rejected, with a high IQR of 2, indicating variability in opinions about the role of collaboration in enhancing innovation within Industry 5.0.

In general, the findings for Cohort 3 are as follows: This cohort shows a solid alignment with the core principles of Industry 5.0, particularly in valuing technological integration and human-centric approaches. Despite some areas of contention, the cohort's overall acceptance of the key hypotheses highlights a comprehensive understanding of the essential elements required for Industry 5.0's successful implementation in the heavy industry sector.

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7. CONSOLIDATED FINDINGS

7.1. Overview Research Findings

7.1.1. Implications of Event Executed in t1.1

On May 29, 2024, the inaugural Industry 5.0 Community of Interest (I5.C) event was hosted in Brussels, bringing together 34 representatives from diverse European entities. The event commenced with a morning session during which speakers from various European initiatives, together with a representative from the E4 unit of DG RTD engaged in a discussion of existing frameworks and methodologies pertinent to the Industry 5.0 paradigm. A subsequent panel discussion examined the relationship between Industry 5.0 and Industry 4.0. The afternoon session shifted focus to interactive discussions about the perception and implementation of Industry 5.0 pillars by companies and stakeholders across different sectors. Industry partners from Octave (Belgium) and Zeuko (Spain) shared their experiences with Industry 5.0 initiatives at various levels, including governance, organizational, and operational.

Participants engaged in a world café style discussion to evaluate and prioritize key performance indicators (KPIs) related to sustainability, resilience, and human centricity. While the sustainability and human centricity groups efficiently assigned priority levels to the KPIs, the resilience group engaged in in-depth discussions about the relevance and definition of the proposed KPIs before reaching a consensus. This highlights the novelty and varied interpretations of the Industry 5.0 paradigm, emphasizing the need for standardized KPIs.

The insights derived from these discussions will inform the internal analyses and contribute to the ongoing tasks (e.g. Task 1.2), ultimately shaping the Industry 5.0 framework. The outcomes from the event are integrated into this deliverable, providing a comprehensive overview of community trends and the status of Industry 5.0 initiatives.

7.1.2. Implications of Literature Research

Based on varying understandings, the current definition by the European Commission (25 Mar. 2024), identifies Industry 5.0 through three core strategic objectives: Human centricity, sustainability, and resilience. These objectives necessitate the development of comprehensive policies and regulatory structures to support and guide advancements and applications of Industry 5.0 initiatives. It is imperative to establish robust legal frameworks, standards, and guidelines that ensure the safe and responsible deployment of new technologies and business models.

The transformation towards Industry 5.0 is driven by several key triggers. Acute crises, such as the COVID-19 pandemic, have highlighted the fragility of global supply chains, underscoring the urgent need for innovative solutions to enhance resilience. These crises necessitate immediate changes and emphasize the critical importance of focusing on employee needs and roles within organizations (Zizic, Mladineo, Gjeldum, Celent, 2022, Sarfraz, Sarfraz, Iftikar, Akhund, 2021, European Comission, 2021). Market changes, including shifts in consumer behavior and competitive dynamics, compel businesses to adopt adaptive strategies. The increasing demand for personalized

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products requires companies to invest in advanced technologies that enable cost-effective personalization (Aheleroff, Huang, Xu, Zhong, 2022, Costa, Amorim, Reis, Melão, 2023). Furthermore, attracting and retaining skilled employees is crucial due to the increasing complexity of job roles and the rapid technological advancements. In order to meet the demands of the modern workplace, companies must offer attractive incentives, prioritize employee well-being, and address the skills gap to meet the demands of the modern workplace (Lu, Zheng, Chand, Xia, Liu, Xu, Wang, Qin, Bao, 2022, Alves, Lima, Gaspar, 2023, Trstenjak, Hegedić, Tošanović, Opetuk, Đukić, Cajner, 2023).

Political volatility and crises, such as geopolitical tensions and protectionist ideologies, pose significant threats to global value chains and employee security. Organizations must cultivate adaptability, resilience, and strategic planning to navigate these challenges effectively (Simion, Avasilcai, Alexa, European Comission, 2021, Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang, 2022). Additionally, transgressing planetary boundaries poses severe risks to humanity and the Earth system. Industry must adopt sustainable practices to mitigate environmental impact, driven by consumer demand for eco-friendly products and regulatory pressures (Richardson, Steffen, Lucht, Bendtsen, Cornell, Donges, Drüke, Fetzer, Bala, Bloh, Feulner, Fiedler, Gerten, Gleeson, Hofmann, Huiskamp, Kummu, Mohan, Nogués-Bravo, Petri, Porkka, Rahmstorf, Schaphoff, Thonicke, Tobian, Virkki, Wang-Erlandsson, Weber, Rockström, 2023, Costa, Amorim, Reis, Melão, 2023). Ethical challenges and social responsibilities in Industry 5.0 involve compliance with legal standards and proactive engagement in socially beneficial practices. Companies must prioritize corporate social responsibility, ethical research, and transparency to promote social good and environmental sustainability (Pang, Lee, Murshed, 2023, Ghobakhloo, Iranmanesh, Mubarak, Mubarik, Rejeb, Nilashi, 2022).

To achieve the transformation to Industry 5.0, companies require well-defined strategies and tools. Integrating Industry 5.0 objectives within corporate strategies is crucial. This involves developing agile business models, enhancing resilience, and promoting human-centric and sustainable practices (Trstenjak, Hegedić, Tošanović, Opetuk, Đukić, Cajner, 2023, Ivanov, 2023). Companies must redesign existing models and create new ones to support this evolution (Möller, Vakilzadian, Haas, 2022). Meeting the demands of a rapidly evolving workforce necessitates continuous employee development. Upskilling involves enhancing technical, leadership, and communication skills, whereas enablement focuses on providing necessary tools and a supportive work environment (Hofmann, Sternberg, Chen, Pflaum, Prockl, 2019, Saniuk, Grabowska, Straka, 2022).

Leveraging interdisciplinary synergies is essential for achieving Industry 5.0 objectives. Combining expertise from various fields fosters innovation and enhances collective efforts towards shared goals. Collaboration among companies, academic institutions, and government bodies is fundamental to the success of Industry 5.0 (Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang, 2022, Longo, Padovano, Umbrello, 2020, De Giovanni, 2023). Advanced technologies, such as artificial intelligence, Big Data, IoT, blockchain, and digital twins, are key enablers of Industry 5.0. These technologies

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optimize processes, enhance human-machine collaboration, and improve decision-making (Mourtzis, Angelopoulos, Panopoulos, 2022, Schuh, Anderl, Dumitrescu, Krüger, Hompel, 2020, Bajic, Suzic, Moraca, Stefanović, Jovicic, Rikalovic, 2023). Collaborative robots, in particular, enhance employee well-being and productivity (Jafari, Azarian, Yu, 2022).

Establishing comprehensive policies and regulatory frameworks is essential for the safe and responsible deployment of emerging technologies. This includes creating legal structures, standards, and guidelines that ensure ethical conduct and data security (Prasant, Sain, Al-Absi, Kumar, 2021, Trstenjak, Hegedić, Tošanović, Opetuk, Đukić, Cajner, 2023, Ghobakhloo, Iranmanesh, Tseng, Grybauskas, Stefanini, Amran, 2023). By focusing on these triggers and enablers, organizations can effectively navigate the transformation towards Industry 5.0, ensuring sustainable, resilient, and human-centric industrial practices. The Table in the appendix provides a detailed breakdown of the identified literature, underscoring the analysis presented.

The consolidated results from the literature and community event form the foundation for the subsequent investigation, structured around three pivotal components: Triggers, Strategic Objectives, and Enablers. This comprehensive overview highlights the interconnections between external influences, core goals, and facilitating factors essential for Industry 5.0. The following Figure 30 encapsulates the intricate interplay between these components, illustrating the multifaceted nature of Industry 5.0. It emphasizes the external influences that necessitate transformation (Triggers), the fundamental goals driving this evolution (Strategic Objectives), and the key facilitators that enable successful implementation (Enablers). This conceptual model offers a strategic roadmap.

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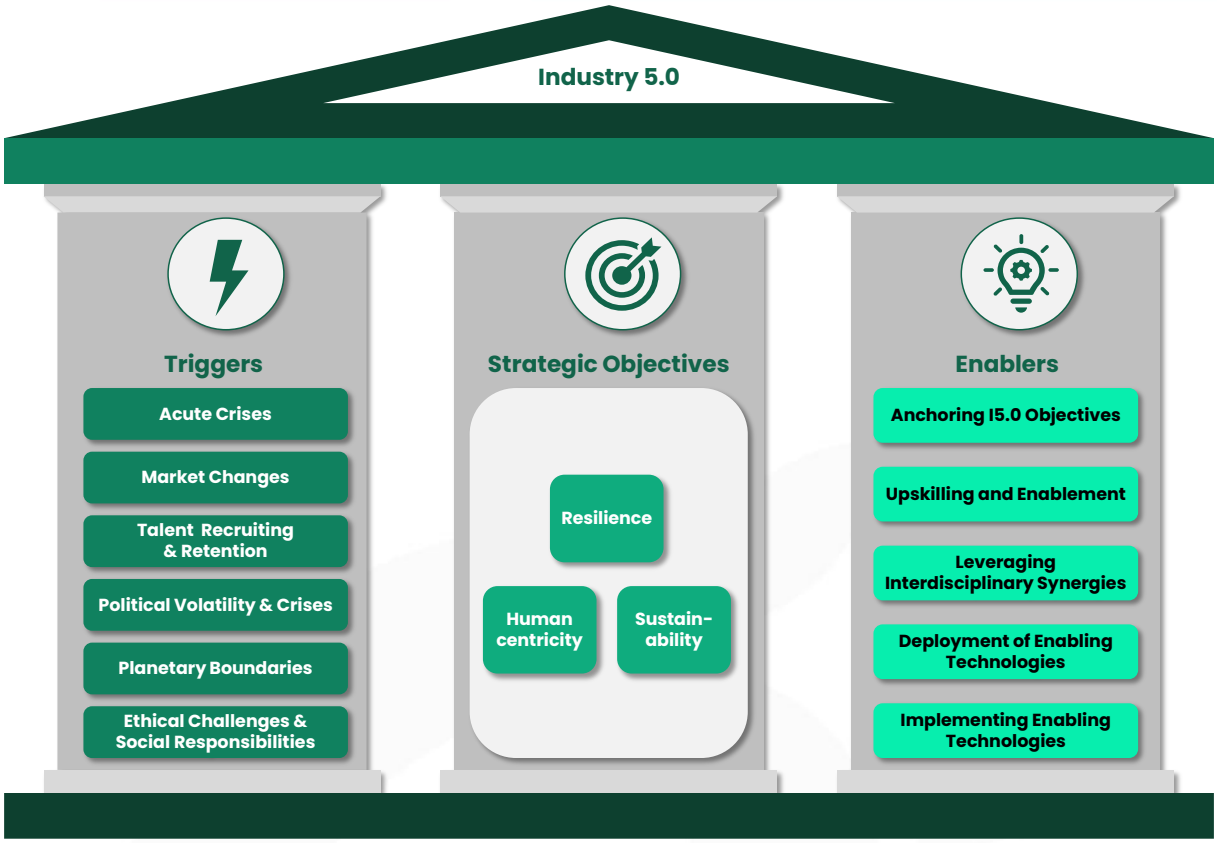

Figure 30 Industry 5.0: Interconnections Between Triggers, Strategic Objectives, and Enablers (own depiction)

The *Triggers* column identifies the critical external factors—including Acute Crises, Market Changes, Talent Recruiting & Retention, Political Volatility & Crises, Planetary Boundaries, and Ethical Challenges & Social Responsibilities — that prompt the need for adaptive and resilient industrial practices. These factors underscore the urgency and relevance of transitioning to Industry 5.0 in response to the dynamic and often unpredictable environmental, economic, and social challenges.

The *Strategic Objectives* column delineates the primary goals of Industry 5.0: Resilience, Human centricity, and Sustainability. These objectives represent the foundational pillars upon which Industry 5.0 is built, aiming to create an industrial ecosystem that is not only robust and adaptable but also one that prioritizes human welfare and environmental stewardship.

The *Enablers* column highlights the essential mechanisms and strategies required to achieve these objectives. This includes the integration of Industry 5.0 objectives into corporate strategies (Anchoring I5.0 Objectives), the continuous development and empowerment of the workforce (Upskilling and Enablement), the fostering of cross-disciplinary collaborations (Leveraging Interdisciplinary Synergies), the adoption of advanced technological solutions (Deployment of Enabling Technologies), and the establishment of supportive regulatory and ethical frameworks (Implementing Enabling Technologies).

All in all, the consolidated results encapsulate the comprehensive landscape of Industry 5.0, presenting a holistic overview of its driving forces, fundamental objectives, and

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essential enablers. These findings intricate dynamics and multifaceted interactions that are necessary for navigating the complexities inherent in contemporary industrial transformation.

7.1.3. Implications of the Delphi Study

The future of Industry 5.0 is centered around a dual focus on technological advancement and human-centric innovation. The industry recognizes that these elements are crucial for the widespread adoption and positive perception of Industry 5.0 initiatives. In order to achieve long-term success, businesses must develop resilient models that support continuous talent development. This focus on human resources is seen as essential for maintaining competitiveness in a rapidly evolving industrial landscape.

Sustainability plays a pivotal role in the vision of Industry 5.0. Implementing sustainable practices, such as the use of renewable energy and optimized waste management, is of importance for meeting the ambitious goals set forth by this new industrial paradigm. Additionally, economic growth within European industries is expected to be driven by the integration of innovative technologies, particularly those that enhance energy efficiency and leverage AI-driven processes. A key component of this vision is the upskilling of employees and fostering effective human-robot collaboration. This is seen as a critical strategy for increasing industrial resilience, ensuring that the workforce is prepared to adapt to new technological advancements.

Sustainability is not just an objective, but a fundamental element of Industry 5.0. The integration of energy-efficient technologies and circular economy principles is seen as crucial for long-term industrial benefits. Achieving these sustainability goals will require the development of digital skills among employees, which will enable companies to better capitalize on these advances. The role of humans in Industry 5.0 is undergoing a redefinition, with an emphasis on the harnessing of human creativity and problem-solving capabilities. This shift is critical to driving innovation and ensuring that human capital remains at the heart of industrial processes. Workforce preparedness is another critical element, with a strong emphasis on skills diversification and collaboration between industry and education. This partnership is essential to prepare the workforce for the challenges and opportunities presented by Industry 5.0. In addition, the standardization of processes is seen as essential to improve ´preparedness for disruption and operational efficiency.

The integration of autonomous systems is highlighted as a key strategy for ensuring business continuity in dynamic market conditions. These systems are expected to play an important role in maintaining operational stability and responding effectively to market changes.

Technological advances are identified as the main drivers of Industry 5.0. Developments in AI, robotics and the IoT are seen as critical to increasing efficiency and optimizing operational processes. These technologies are at the forefront of the industry's transition to a more advanced, connected industrial landscape. Global trends and challenges, such as climate change and the ongoing digital transformation, are also recognized as key triggers necessitating the transition to Industry 5.0. The industry

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recognizes the need for a comprehensive, human-centered approach to address these global challenges and ensure the successful evolution of Industry 5.0. Several key technologies are identified as critical enablers for Industry 5.0. Additive manufacturing is seen as revolutionary for production processes, offering increased flexibility and customization in manufacturing. The IoT is seen as essential for ensuring seamless connectivity and real-time data exchange, significantly improving operational transparency and efficiency. Advanced data analytics is also regarded as critical to driving innovation and achieving operational excellence. Collaboration between different stakeholders - including industry, government and academia - is considered as essential for the successful implementation of Industry 5.0. In particular, the integration of AI is seen as essential to accelerate the adoption of Industry 5.0 technologies. In addition, supportive government policies and regulatory frameworks are seen as critical enablers, creating an environment conducive to innovation and facilitating the widespread adoption of these new technologies. In conclusion, the transition to Industry 5.0 will be driven by a combination of technological advances, sustainability initiatives and human-centered strategies. Successful implementation of Industry 5.0 will require cross-sector collaboration, continuous talent development, and the integration of innovative technologies to ensure resilience, sustainability, and economic growth.

7.2. Industry 5.0 Insights

Industry 5.0 represents a profound evolution from the previous industrial paradigms, characterized by a shift towards human-centric, sustainable, and resilient industrial practices. The framework developed, as shown in Figure 31, is intended to empower stakeholders to effectively advance their Industry 5.0 implementation.

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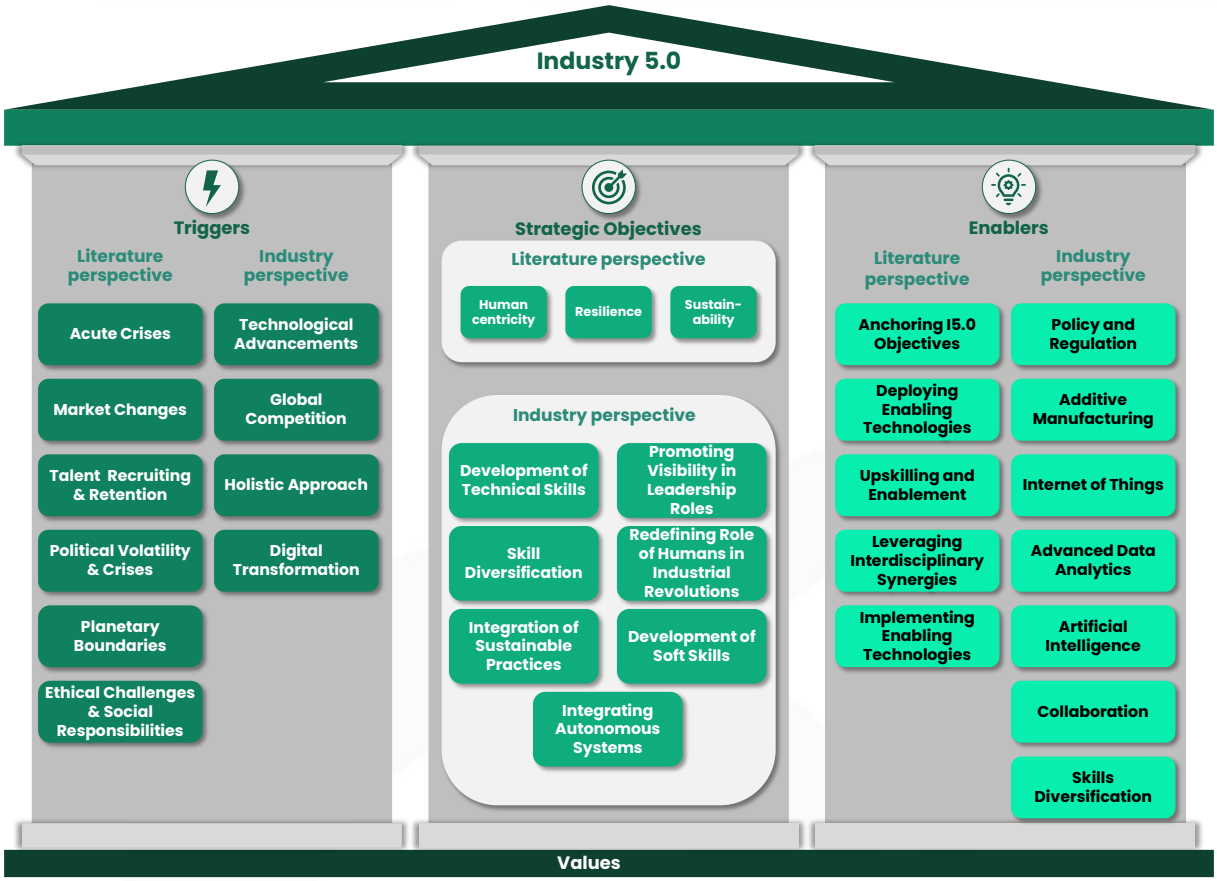

Figure 31 Identified focus areas from systematic literature review and industry perspective (own depiction)

The conceptual framework extends the existing literature by integrating an industry perspective, elucidating the complex dynamics and interrelations essential to the conceptualization and operationalization of Industry 5.0. It delineates core components—triggers, strategic objectives, and enablers—serving as the foundation for understanding the multifaceted nature of Industry 5.0, bridging the gap between theoretical discourse and practical implementation, and embedding them within a broader socio-economic and technological context. Underpinning these components is a foundational value layer that encompasses ethical, social, and economic principles that guide the evolution towards Industry 5.0, centered on sustainability, human centricity, and ethical responsibility. These are key to ensuring the positive societal impact of Industry 5.0.

The triggers identified include external factors necessitating industry adaptation, as well as internal drivers such as technological advancement, global competition, digital transformation, and holistic approaches. These elements are critical in propelling the transition to Industry 5.0. The rapid advancement of technologies like AI, IoT, and robotics forms the backbone of Industry 5.0, enhancing efficiency, productivity, and customization. Concurrently, global competition compels continuous innovation, while digital transformation serves as both a catalyst and an enabler for Industry 5.0. Industries are increasingly recognizing the importance of a holistic approach,

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balancing financial outcomes with environmental and social impacts, in line with the broader goals of Industry 5.0 - sustainability and human centricity.

Strategic objectives, drawn from the literature, emphasize enhancing resilience, promoting human centricity, and ensuring sustainability. From an industry perspective, these objectives translate into key drivers for Industry 5.0 adoption: upskilling the workforce to match technological advancements, fostering skill diversification to meet the demands of a dynamic industrial landscape, and embedding sustainability as a strategic priority. Furthermore, Industry 5.0 redefines the human role in industrial innovation, positioning humans as innovators and decision-makers, essential for cultivating a culture of continuous improvement. Efforts to promote diversity and inclusivity in leadership align with Industry 5.0's broader objectives of creating equitable industrial environments. Additionally, the integration of autonomous systems is a strategic objective to enhance efficiency, reduce human error, and boost productivity.

The enablers section identifies critical tools and strategies for achieving these objectives, including embedding Industry 5.0 principles into corporate strategies, continuous workforce skill enhancement, promoting interdisciplinary collaboration, adopting cutting-edge technologies, and establishing robust regulatory and ethical frameworks. From an industry standpoint, several key factors are essential for a successful transition to Industry 5.0: supportive regulatory frameworks, the adoption of additive manufacturing for greater production flexibility, the use of IoT for interconnected systems and real-time data exchange, and the deployment of advanced data analytics for driving innovation and maintaining competitiveness. AI plays a pivotal role in automation, predictive maintenance, and enhancing human-machine collaboration, solidifying competitive positioning in the global market. Collaboration across industries, academia, and government is crucial for fostering innovation and ensuring alignment with broader societal goals. Finally, ongoing skill diversification and upskilling are imperative for preparing the workforce to navigate the complexities of Industry 5.0, ensuring adaptability and competitiveness in a rapidly evolving industrial landscape.

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9. APPENDIX

Table 6 Results Delphi Study (own depiction)

			Overall		
			Median	**Interquartile Range (IQR)**	**Acceptance / Rejection of the Hypothesis**
Objectives and target image of Industry 5.0	**Purpose**	Industry 5.0 initiatives that prioritize both technological advancement and human-centric innovation will increase adoption rates of the concept and foster a positive perception of the concept.	4	1	**Accepted**
		Resilient business models that support talent development are essential for achieving long-term success in Industry 5.0 initiatives.	4	1	**Accepted**
		The implementation of sustainable practices, including the use of renewable energy sources and optimized waste management, is crucial for Industry 5.0 success.	5	1	**Accepted**
	Economic Growth	Industry 5.0 strategies that integrate innovative technologies with emphasizing energy efficiency will increase economic growth and enhance competitiveness in European industries within the next decade.	4	0,75	**Accepted**
		The integration of AI in Industry 5.0 will optimize production processes and facilitate the development of customer-specific products within the next decade.	4,5	1	**Accepted**
		Efforts in upskilling employees and fostering human-robot collaboration in Industry 5.0 will increase industry resilience.	4	0,75	**Accepted**
Key element: Sustainability, Human	**Integration of Practices**	The integration of sustainable practices, including energy-efficient technologies and circular economy principles, is essential for European industries to achieve long-term environmental and economic benefits within Industry 5.0.	4	1	**Accepted**

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		European industries that fail to adopt energy-efficient technologies and embrace circular economy principles within Industry 5.0 will fall behind.	4	1,75	**Rejected**
	Sustainability Mission	Optimizing raw material utilization will significantly boost companies' success in sustainability.	4	1,5	**Rejected**
		Developing digital skills among employees will position companies better for sustainability success.	5	1	**Accepted**
	Redefining Roles	Industry 5.0 initiatives that fail to leverage human creativity, decision-making, and problem-solving abilities will stagnate, whereas prioritizing these aspects will redefine the role of humans in industrial innovation and drive significant advancements.	4	0,75	**Accepted**
		Without a strong emphasis on human-machine collaboration, Industry 5.0 will fall short of its potential.	4	1,75	**Rejected**
	Impact on Jobs and Skills	Prioritizing skills diversification through strong collaboration between industry and educational institutions will result in a workforce well-equipped for Industry 5.0.	4,5	1	**Accepted**
		Ignoring the development of soft skills will leave the workforce unprepared for the challenges and opportunities of Industry 5.0.	4	0,75	**Accepted**
	Disruption Preparedness	Fostering human-robot collaboration boosts Industry 5.0's ability to manage disruptions.	4	1,5	**Rejected**
		Prioritizing process standardization will significantly enhance Industry 5.0's preparedness while improving process efficiency.	4	1,5	**Rejected**
	Business Continuity	Integrating autonomous systems is crucial for Industry 5.0 to effectively respond to dynamic market conditions.	4	0	**Accepted**
		Failing to foster visibility in leadership roles will undermine employee engagement, whereas promoting these elements will significantly enhance the strategic contribution of human skills.	4	0,75	**Accepted**

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Triggers of Industry 5.0	Primary Triggers	Technological advancements such as AI, robotics, and IoT are crucial drivers in facilitating operational efficiency in Industry 5.0.	5	1	**Accepted**
		Global competition is a significant economic factor influencing the transition to Industry 5.0.	4	1	**Accepted**
		The promotion of circular economy practices significantly influences the transition to Industry 5.0, enhancing sustainability.	4	2	**Rejected**
	Global Trends and Challenges	A holistic approach that addresses global challenges, incorporating human centricity at the forefront of innovation, is essential for Industry 5.0 to successfully evolve and adapt.	4,5	1	**Accepted**
		Adoption of advanced automation techniques by companies is driven by customer demands.	4	1,75	**Rejected**
		Digital transformation is not just a trend but a revolution that is radically accelerating the adoption of sustainable practices in Industry 5.0, making it an indispensable driver for achieving environmental goals and operational efficiency.	4	1	**Accepted**
Enablers of Industry 5.0	Key Technologies	Additive manufacturing is a key technology that revolutionizes production processes in Industry 5.0, increasing production flexibility.	4	1	**Accepted**
		The integration of IoT is crucial for the seamless connectivity and real-time data exchange in Industry 5.0, enhancing operational visibility.	5	1	**Accepted**
		Industry 5.0 initiatives that fail to leverage advanced data analytics will be left behind, as these technologies will propel adopters to a significant boost in innovation and operational excellence.	5	1	**Accepted**
		The integration AI is not just beneficial but absolutely essential for accelerating the adoption and effectiveness of Industry 5.0 in practice.	4,5	1	**Accepted**

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	Collaboration	Effective collaboration between industry, government, and academia significantly enhances innovation, supporting the growth of Industry 5.0.	5	1	**Accepted**
		Practical industry-related education will be the linchpin in enhancing collaboration between industry, government, and academia.	4	1,75	**Rejected**
		Proactive government policies will be the catalyst for transforming and successfully implementing Industry 5.0 technologies.	4	0,75	**Accepted**
		The evolution of job roles and skills diversification brought by Industry 5.0 will mandate increased collaboration between industry and educational institutions.	4	1	**Accepted**

			Cohort 1: Consumer Goods		
			Median	**Interquartile Range (IQR)**	**Acceptance / Rejection of the Hypothesis**
Objectives and target image of Industry 5.0	**Purpose**	Industry 5.0 initiatives that prioritize both technological advancement and human-centric innovation will increase adoption rates of the concept and foster a positive perception of the concept.	4	2	**Rejected**
		Resilient business models that support talent development are essential for achieving long-term success in Industry 5.0 initiatives.	4	0,75	**Accepted**
		The implementation of sustainable practices, including the use of renewable energy sources and optimized waste management, is crucial for Industry 5.0 success.	4,5	1,75	**Rejected**
	Economic Growth	Industry 5.0 strategies that integrate innovative technologies with emphasizing energy efficiency will increase economic growth and enhance competitiveness in European industries within the next decade.	3,5	1,25	**Rejected**

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		The integration of AI in Industry 5.0 will optimize production processes and facilitate the development of customer-specific products within the next decade.	5	0,25	**Accepted**
		Efforts in upskilling employees and fostering human-robot collaboration in Industry 5.0 will increase industry resilience.	4	0,25	**Accepted**
Key element: Sustainability, Human centricity, Resilience	**Integration of Practices**	The integration of sustainable practices, including energy-efficient technologies and circular economy principles, is essential for European industries to achieve long-term environmental and economic benefits within Industry 5.0.	4	2,25	**Rejected**
		European industries that fail to adopt energy-efficient technologies and embrace circular economy principles within Industry 5.0 will fall behind.	3	2,25	**Rejected**
	Sustainability Mission	Optimizing raw material utilization will significantly boost companies' success in sustainability.	5	0,25	**Accepted**
		Developing digital skills among employees will position companies better for sustainability success.	4,5	1	**Accepted**
	Redefining Roles	Industry 5.0 initiatives that fail to leverage human creativity, decision-making, and problem-solving abilities will stagnate, whereas prioritizing these aspects will redefine the role of humans in industrial innovation and drive significant advancements.	4	2	**Rejected**
		Without a strong emphasis on human-machine collaboration, Industry 5.0 will fall short of its potential.	4	0,75	**Accepted**
	Impact on Jobs and Skills	Prioritizing skills diversification through strong collaboration between industry and educational institutions will result in a workforce well-equipped for Industry 5.0.	4,5	1	**Accepted**
		Ignoring the development of soft skills will leave the workforce unprepared for the challenges and opportunities of Industry 5.0.	4,5	1,5	**Rejected**

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	Disruption Preparedness	Fostering human-robot collaboration boosts Industry 5.0's ability to manage disruptions.	5	0,5	**Accepted**
		Prioritizing process standardization will significantly enhance Industry 5.0's preparedness while improving process efficiency.	4,5	1	**Accepted**
	Business Continuity	Integrating autonomous systems is crucial for Industry 5.0 to effectively respond to dynamic market conditions.	4	0,5	**Accepted**
		Failing to foster visibility in leadership roles will undermine employee engagement, whereas promoting these elements will significantly enhance the strategic contribution of human skills.	3,5	1,5	**Rejected**
Triggers of Industry 5.0	Primary Triggers	Technological advancements such as AI, robotics, and IoT are crucial drivers in facilitating operational efficiency in Industry 5.0.	5	0,25	**Accepted**
		Global competition is a significant economic factor influencing the transition to Industry 5.0.	4,5	1,25	**Rejected**
		The promotion of circular economy practices significantly influences the transition to Industry 5.0, enhancing sustainability.	3,5	1,75	**Rejected**
	Global Trends and Challenges	A holistic approach that addresses global challenges, incorporating human centricity at the forefront of innovation, is essential for Industry 5.0 to successfully evolve and adapt.	4,5	1	**Accepted**
		Adoption of advanced automation techniques by companies is driven by customer demands.	3,5	3	**Rejected**
		Digital transformation is not just a trend but a revolution that is radically accelerating the adoption of sustainable practices in Industry 5.0, making it an indispensable driver for achieving environmental goals and operational efficiency.	3,5	1,5	**Rejected**

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Enablers of Industry 5.0	Key Technologies	Additive manufacturing is a key technology that revolutionizes production processes in Industry 5.0, increasing production flexibility.	4	0,5	**Accepted**
		The integration of IoT is crucial for the seamless connectivity and real-time data exchange in Industry 5.0, enhancing operational visibility.	4,5	1	**Accepted**
		Industry 5.0 initiatives that fail to leverage advanced data analytics will be left behind, as these technologies will propel adopters to a significant boost in innovation and operational excellence.	5	0,5	**Accepted**
		The integration AI is not just beneficial but absolutely essential for accelerating the adoption and effectiveness of Industry 5.0 in practice.	4,5	1,5	**Rejected**
	Collaboration	Effective collaboration between industry, government, and academia significantly enhances innovation, supporting the growth of Industry 5.0.	5	0,25	**Accepted**
		Practical industry-related education will be the linchpin in enhancing collaboration between industry, government, and academia.	4	0,25	**Accepted**
		Proactive government policies will be the catalyst for transforming and successfully implementing Industry 5.0 technologies.	3	2,25	**Rejected**
		The evolution of job roles and skills diversification brought by Industry 5.0 will mandate increased collaboration between industry and educational institutions.	4,5	1,25	**Rejected**

			Cohort 2: Life Sciences		
			Median	**Interquartile Range (IQR)**	**Acceptance / Rejection**

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					of the Hypothesis
Objectives and target image of Industry 5.0	**Purpose**	Industry 5.0 initiatives that prioritize both technological advancement and human-centric innovation will increase adoption rates of the concept and foster a positive perception of the concept.	5	1	**Accepted**
		Resilient business models that support talent development are essential for achieving long-term success in Industry 5.0 initiatives.	4	1	**Accepted**
		The implementation of sustainable practices, including the use of renewable energy sources and optimized waste management, is crucial for Industry 5.0 success.	5	0	**Accepted**
	Economic Growth	Industry 5.0 strategies that integrate innovative technologies with emphasizing energy efficiency will increase economic growth and enhance competitiveness in European industries within the next decade.	5	0	**Accepted**
		The integration of AI in Industry 5.0 will optimize production processes and facilitate the development of customer-specific products within the next decade.	4	0	**Accepted**
		Efforts in upskilling employees and fostering human-robot collaboration in Industry 5.0 will increase industry resilience.	5	1	**Accepted**
Key element: Sustainability, Human centricity, Resilience	**Integration of Practices**	The integration of sustainable practices, including energy-efficient technologies and circular economy principles, is essential for European industries to achieve long-term environmental and economic benefits within Industry 5.0.	5	1	**Accepted**
		European industries that fail to adopt energy-efficient technologies and embrace circular economy principles within Industry 5.0 will fall behind.	4	0	**Accepted**

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	Sustainability Mission	Optimizing raw material utilization will significantly boost companies' success in sustainability.	4	0	**Accepted**
		Developing digital skills among employees will position companies better for sustainability success.	5	0	**Accepted**
	Redefining Roles	Industry 5.0 initiatives that fail to leverage human creativity, decision-making, and problem-solving abilities will stagnate, whereas prioritizing these aspects will redefine the role of humans in industrial innovation and drive significant advancements.	4	1	**Accepted**
		Without a strong emphasis on human-machine collaboration, Industry 5.0 will fall short of its potential.	4	2	**Rejected**
	Impact on Jobs and Skills	Prioritizing skills diversification through strong collaboration between industry and educational institutions will result in a workforce well-equipped for Industry 5.0.	5	1	**Accepted**
		Ignoring the development of soft skills will leave the workforce unprepared for the challenges and opportunities of Industry 5.0.	4	0	**Accepted**
	Disruption Preparedness	Fostering human-robot collaboration boosts Industry 5.0's ability to manage disruptions.	4	1	**Accepted**
		Prioritizing process standardization will significantly enhance Industry 5.0's preparedness while improving process efficiency.	3	1	**Rejected**
	Business Continuity	Integrating autonomous systems is crucial for Industry 5.0 to effectively respond to dynamic market conditions.	4	0	**Accepted**
		Failing to foster visibility in leadership roles will undermine employee engagement, whereas promoting these elements will significantly enhance the strategic contribution of human skills.	4	0	**Accepted**

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Triggers of Industry 5.0	**Primary Triggers**	Technological advancements such as AI, robotics, and IoT are crucial drivers in facilitating operational efficiency in Industry 5.0.	5	1	**Accepted**
		Global competition is a significant economic factor influencing the transition to Industry 5.0.	4	1	**Accepted**
		The promotion of circular economy practices significantly influences the transition to Industry 5.0, enhancing sustainability.	4	1	**Accepted**
	Global Trends and Challenges	A holistic approach that addresses global challenges, incorporating human centricity at the forefront of innovation, is essential for Industry 5.0 to successfully evolve and adapt.	5	1	**Accepted**
		Adoption of advanced automation techniques by companies is driven by customer demands.	4	1	**Accepted**
		Digital transformation is not just a trend but a revolution that is radically accelerating the adoption of sustainable practices in Industry 5.0, making it an indispensable driver for achieving environmental goals and operational efficiency.	5	1	**Accepted**
Enablers of Industry 5.0	**Key Technologies**	Additive manufacturing is a key technology that revolutionizes production processes in Industry 5.0, increasing production flexibility.	4	0	**Accepted**
		The integration of IoT is crucial for the seamless connectivity and real-time data exchange in Industry 5.0, enhancing operational visibility.	5	0	**Accepted**
		Industry 5.0 initiatives that fail to leverage advanced data analytics will be left behind, as these technologies will propel adopters to a significant boost in innovation and operational excellence.	4	0	**Accepted**
		The integration AI is not just beneficial but absolutely essential for accelerating the adoption and effectiveness of Industry 5.0 in practice.	4	1	**Accepted**

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	Collaboration	Effective collaboration between industry, government, and academia significantly enhances innovation, supporting the growth of Industry 5.0.	4	1	**Accepted**
		Practical industry-related education will be the linchpin in enhancing collaboration between industry, government, and academia.	3	2	**Rejected**
		Proactive government policies will be the catalyst for transforming and successfully implementing Industry 5.0 technologies.	4	1	**Accepted**
		The evolution of job roles and skills diversification brought by Industry 5.0 will mandate increased collaboration between industry and educational institutions.	4	0	**Accepted**

			Cohort 3: Heavy Industry		
			Median	**Interquartile Range (IQR)**	**Acceptance / Rejection of the Hypothesis**
Objectives and target image of Industry 5.0	**Purpose**	Industry 5.0 initiatives that prioritize both technological advancement and human-centric innovation will increase adoption rates of the concept and foster a positive perception of the concept.	4	0	**Accepted**
		Resilient business models that support talent development are essential for achieving long-term success in Industry 5.0 initiatives.	4	1	**Accepted**
		The implementation of sustainable practices, including the use of renewable energy sources and optimized waste management, is crucial for Industry 5.0 success.	4	1	**Accepted**
	Economic Growth	Industry 5.0 strategies that integrate innovative technologies with emphasizing energy efficiency will increase economic growth and enhance competitiveness in European industries within the next decade.	4	0	**Accepted**

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		The integration of AI in Industry 5.0 will optimize production processes and facilitate the development of customer-specific products within the next decade.	5	1	**Accepted**
		Efforts in upskilling employees and fostering human-robot collaboration in Industry 5.0 will increase industry resilience.	4	0	**Accepted**
Key element: Sustainability, Human centricity, Resilience	**Integration of Practices**	The integration of sustainable practices, including energy-efficient technologies and circular economy principles, is essential for European industries to achieve long-term environmental and economic benefits within Industry 5.0.	4	0	**Accepted**
		European industries that fail to adopt energy-efficient technologies and embrace circular economy principles within Industry 5.0 will fall behind.	4	1	**Accepted**
	Sustainability Mission	Optimizing raw material utilization will significantly boost companies' success in sustainability.	3	1	**Rejected**
		Developing digital skills among employees will position companies better for sustainability success.	4	1	**Accepted**
	Redefining Roles	Industry 5.0 initiatives that fail to leverage human creativity, decision-making, and problem-solving abilities will stagnate, whereas prioritizing these aspects will redefine the role of humans in industrial innovation and drive significant advancements.	4	0	**Accepted**
		Without a strong emphasis on human-machine collaboration, Industry 5.0 will fall short of its potential.	4	1	**Accepted**
	Impact on Jobs and Skills	Prioritizing skills diversification through strong collaboration between industry and educational institutions will result in a workforce well-equipped for Industry 5.0.	4	1	**Accepted**
		Ignoring the development of soft skills will leave the workforce unprepared for the challenges and opportunities of Industry 5.0.	4	0	**Accepted**

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	Disruption Preparedness	Fostering human-robot collaboration boosts Industry 5.0's ability to manage disruptions.	4	0	**Accepted**
		Prioritizing process standardization will significantly enhance Industry 5.0's preparedness while improving process efficiency.	4	0	**Accepted**
	Business Continuity	Integrating autonomous systems is crucial for Industry 5.0 to effectively respond to dynamic market conditions.	4	0	**Accepted**
		Failing to foster visibility in leadership roles will undermine employee engagement, whereas promoting these elements will significantly enhance the strategic contribution of human skills.	4	1	**Accepted**
Triggers of Industry 5.0	Primary Triggers	Technological advancements such as AI, robotics, and IoT are crucial drivers in facilitating operational efficiency in Industry 5.0.	5	1	**Accepted**
		Global competition is a significant economic factor influencing the transition to Industry 5.0.	4	1	**Accepted**
		The promotion of circular economy practices significantly influences the transition to Industry 5.0, enhancing sustainability.	4	2	**Rejected**
	Global Trends and Challenges	A holistic approach that addresses global challenges, incorporating human centricity at the forefront of innovation, is essential for Industry 5.0 to successfully evolve and adapt.	4	1	**Accepted**
		Adoption of advanced automation techniques by companies is driven by customer demands.	4	2	**Rejected**
		Digital transformation is not just a trend but a revolution that is radically accelerating the adoption of sustainable practices in Industry 5.0, making it an indispensable driver for achieving environmental goals and operational efficiency.	4	1	**Accepted**
Enablers of	Key Techn	Additive manufacturing is a key technology that revolutionizes	3	1	**Rejected**

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		production processes in Industry 5.0, increasing production flexibility.			
		The integration of IoT is crucial for the seamless connectivity and real-time data exchange in Industry 5.0, enhancing operational visibility.	4	1	**Accepted**
		Industry 5.0 initiatives that fail to leverage advanced data analytics will be left behind, as these technologies will propel adopters to a significant boost in innovation and operational excellence.	5	0	**Accepted**
		The integration AI is not just beneficial but absolutely essential for accelerating the adoption and effectiveness of Industry 5.0 in practice.	5	1	**Accepted**
	Collaboration	Effective collaboration between industry, government, and academia significantly enhances innovation, supporting the growth of Industry 5.0.	5	2	**Rejected**
		Practical industry-related education will be the linchpin in enhancing collaboration between industry, government, and academia.	4	2	**Rejected**
		Proactive government policies will be the catalyst for transforming and successfully implementing Industry 5.0 technologies.	4	0	**Accepted**
		The evolution of job roles and skills diversification brought by Industry 5.0 will mandate increased collaboration between industry and educational institutions.	4	1	**Accepted**

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Reference	Trigger						Strategic objectives			Enabler				
	Acute crises	Market Changes	Talent Recruiting & Retention	Political Volatility & Crises	Planetary Boundaries	Ethical Challenges & Social Responsibilities	Resilience	Human-centricity	Sustainability	Anchoring I5.0 Objectives in Strategy	Upskilling and Enablement of workforce	Leveraging Interdisciplinary Synergies of Organizations & Institutions	Deploying Enabling Technologies	IMplementing Policies and Regulatory Structures
Adel 2022	●	●	○	○	◑	○	○	●	●	◑	●	◑	◑	○
Aheleroff et al. 2022	●	●	●	○	◑	●	◑	◑	●	○	◑	◑	●	◑
Alojaiman 2023	◑	◑	●	●	◑	◑	○	●	◑	◑	●	◑	◑	◑
Alves et al. 2023	◑	◑	●	○	◑	◑	◑	●	◑	●	◑	○	◑	○
Bajic et al. 2023	○	○	○	○	○	◑	◑	◑	○	○	○	○	●	○
Banholzer 2022	◑	○	○	○	○	◑	●	●	●	○	●	○	○	◑
Chandel et al. 2023	●	●	◑	○	○	○	◑	●	○	●	◑	○	◑	○
Chander et al. 2022	○	◑	○	○	○	○	○	●	◑	◑	◑	○	●	○
Costa et al. 2023	○	●	○	○	●	○	○	●	○	●	◑	○	○	○
De Felice & Petrillo 2023	○	○	○	○	○	○	○	●	◑	●	○	○	◑	○
De Giovanni 2023	○	○	◑	○	◑	◑	○	○	●	○	○	●	◑	○
Demir & Cicibaş 2017	○	◑	○	○	◑	◑	○	○	●	●	◑	○	◑	○
Doyle-Kent & Kopacek 2020	○	●	◑	○	◑	◑	○	●	◑	◑	◑	○	◑	◑
Fraga-Lamas et al. 2021	◑	○	◑	○	◑	○	◑	◑	●	○	◑	○	●	○
Frutos-Bencze et al. 2022	◑	○	●	○	○	◑	◑	●	○	○	◑	○	○	○
Ghobakhloo et al. 2022	◑	◑	○	○	●	●	◑	●	●	◑	◑	◑	●	◑
Ghobakhloo et al. 2023	◑	○	◑	○	◑	◑	●	●	●	●	○	○	◑	●
Hicking et al. 2020	○	○	○	○	◑	○	●	◑	◑	◑	◑	○	◑	○
Hofmann et al. 2019	○	○	○	○	◑	◑	◑	◑	◑	○	●	◑	◑	○
Hol 2021	○	○	○	○	○	◑	○	●	●	●	◑	○	◑	●
Huang et al. 2022	○	○	◑	●	◑	◑	◑	●	○	●	◑	○	◑	○
Iqbal et al 2022	○	◑	◑	○	●	◑	◑	●	●	●	◑	◑	●	◑
Ivanov 2022	○	○	○	○	○	○	●	●	●	●	○	○	○	○
Jafari et al. 2022	○	◑	○	○	◑	○	●	●	●	○	●	○	●	○
Joglekar et al. 2023	○	○	◑	○	◑	◑	○	●	○	○	◑	○	●	○
John et al. 2020	○	○	○	○	○	○	○	●	○	○	○	○	○	○
Kasinathan et al. 2022	●	◑	○	●	◑	◑	○	●	●	○	◑	◑	◑	◑
Leng et al. 2022	●	◑	●	○	◑	◑	●	●	●	●	◑	●	●	●
Longo et al. 2020	○	○	○	○	○	◑	○	●	◑	◑	●	●	●	○
Lu et al. 2022	○	○	●	○	○	◑	○	●	○	○	●	○	◑	○
Maddikunta et al. 2022	○	●	◑	○	○	○	●	●	●	◑	◑	○	●	●
Madsen & Slåtten 2023	◑	◑	○	○	○	○	●	●	●	●	◑	○	◑	○
Majerník et al. 2022	○	○	◑	○	◑	◑	◑	○	●	●	◑	○	○	○
Martín-Gómez et al. 2024	○	◑	○	○	●	●	●	●	●	●	○	○	●	◑
Mattila et al. 2022	○	◑	○	○	◑	◑	○	○	●	○	○	○	●	○
Mishra & Paul 2023	○	●	◑	○	○	○	○	●	◑	○	◑	○	◑	◑
Mitschell & Guile 2022	◑	○	○	○	○	●	●	●	◑	○	◑	○	○	○
Möller et al. 2022	○	○	○	○	◑	○	○	●	●	●	◑	○	◑	○
Mourtzis et al. 2022	○	◑	○	○	○	○	●	●	●	◑	●	○	●	○
Nahavandi 2019	○	◑	◑	○	◑	◑	○	●	●	○	◑	○	◑	●
Noble et al. 2022	●	○	○	○	◑	◑	○	◑	●	○	◑	○	◑	○
Ordieres-Meré et al. 2023	○	○	◑	○	○	◑	●	●	●	◑	○	○	●	○
Özdemir & Hekim 2018	○	○	◑	○	○	●	○	◑	○	○	◑	○	◑	○
Pang et al. 2023	○	○	○	○	○	●	●	●	●	○	◑	○	◑	○
Patil et al. 2022	○	○	◑	○	◑	○	◑	●	●	○	●	○	◑	○
Peças et al. 2023	○	○	○	○	●	◑	◑	◑	●	○	○	○	●	○
Petrescu et al. 2023	◑	○	○	○	◑	●	◑	●	●	○	○	○	◑	○
Pizoń et al. 2022	○	○	○	○	○	○	○	●	●	●	●	○	◑	○
Rajumesh 2024	○	●	○	○	●	●	◑	◑	◑	◑	◑	◑	●	○
Ramachandran et al. 2023	○	◑	●	○	○	◑	○	●	◑	◑	◑	○	◑	○
Saniuk et al. 2022	◑	◑	◑	●	◑	●	●	●	●	○	●	○	◑	○
Sarfraz et al. 2021	●	◑	○	○	○	○	●	●	○	○	○	○	◑	○
Schuh et al. 2020	◑	◑	○	○	◑	○	●	◑	◑	○	◑	○	●	○
Simion et al. 2022	◑	○	◑	●	◑	◑	●	●	●	●	◑	◑	◑	◑
Sindhwani et al. 2022	●	◑	○	○	●	○	●	●	●	○	◑	○	◑	◑
Suciu et al. 2023	◑	◑	●	○	○	○	●	●	●	○	●	●	◑	●
Tavares et al. 2022	○	◑	●	○	◑	◑	○	●	●	○	●	◑	◑	○
Trstenjak et al. 2023	◑	◑	●	○	◑	○	○	●	●	●	●	○	◑	●
Verma et al. 2022	○	◑	○	○	○	○	○	○	◑	◑	●	○	◑	○
Vougaridis et al. 2022	○	○	○	○	●	○	○	○	●	○	○	○	◑	○
Zizic et al. 2022	●	◑	◑	○	○	◑	●	●	●	●	●	○	●	○

○ No focus ● High focus ◖ Low focus

Figure 32 Consolidated Analysis of the Systematic Literature Review (own depiction)

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Table 7 Detailed Breakdown of Literature Identified in the Systematic Literature Review

No	Source	No	Source
1	Adel (2022a)	35	Mattila, Gauri, Dwivedi (2022)
2	Aheleroff, Huang, Xu, Zhong (2022)	36	Mishra, Paul (2023)
3	Alojaiman (2023)	37	Mitchell, Guile (2022)
4	Alves, Lima, Gaspar (2023)	38	Möller, Vakilzadian, Haas (2022)
5	Bajic, Suzic, Moraca, Stefanović, Jovicic, Rikalovic (2023)	39	Mourtzis, Angelopoulos, Panopoulos (2022)
6	Banholzer (2022)	40	Nahavandi (2019)
7	Chandel, Sharma (2023)	41	Noble, Mende, Grewal, Parasuraman (2022)
8	Chander, Pal, De, Buyya (2022)	42	Ordieres-Meré, Gutierrez, Villalba-Díez (2023)
9	Costa, Amorim, Reis, Melão (2023)	43	Özdemir, Hekim (2018)
10	De Felice, Petrillo (2023)	44	Pang, Lee, Murshed (2023)
11	De Giovanni (2023)	45	Patil, Thakir, Gandhi, Savale, Sayyed (2022)
12	Demir, Cicibas (2017)	46	Peças, John, Ribeiro, Baptista, Pinto, Dias, Henriques, Estrela, Pilastri, Cunha (2023)
13	Doyle-Kent, Kopacek (2020)	47	Petrescu, Neacșa, Laudacescu, Tănase (2023)
14	Fraga-Lamas, Lopes, Fernández-Caramés (2021)	48	Pizoń, Cioch, Kański, Sánchez García (2022)
15	Frutos-Bencze, Sokolova, Zubr, Mohelska (2022)	49	Rajumesh (2024)
16	Ghobakhloo, Iranmanesh, Mubarak, Mubarik, Rejeb, Nilashi (2022)	50	Ramachandran, Nagarjuna, Akram, Bhalani, Raju, Ponnusamy (2023)
17	Ghobakhloo, Iranmanesh, Tseng, Grybauskas, Stefanini, Amran (2023)	51	Saniuk, Grabowska, Straka (2022)
18	Hicking, Wenger, Abbas, Benning, Bremer, Clemens (2020)	52	Sarfraz, Sarfraz, Iftikar, Akhund (2021)
19	Hofmann, Sternberg, Chen, Pflaum, Prockl (2019)	53	Schuh, Anderl, Dumitrescu, Krüger, Hompel (2020)
20	Prasant, Sain, Al-Absi, Kumar, 2021	49	Rajumesh (2024)
21	Huang, Wang, Li, Zheng, Mourtzis, Wang (2022)	50	Ramachandran, Nagarjuna, Akram, Bhalani, Raju, Ponnusamy (2023)
22	Iqbal, Lee, Ren (2022)	51	Saniuk, Grabowska, Straka (2022)
23	Ivanov (2023)	52	Sarfraz, Sarfraz, Iftikar, Akhund (2021)
24	Jafari, Azarian, Yu (2022)	53	Schuh, Anderl, Dumitrescu, Krüger, Hompel (2020)
25	Joglekar, Kadam, Dharmadhikari (2023)	54	Simion, Avasilcai, Alexa
26	John, Adarsh, Pattali (2020)	55	Sindhwani, Afridi, Kumar, Banaitis, Luthra, Singh (2022)
27	Kasinathan, Pugazhendhi, Elavarasan, Ramachandaramurthy, Ramanathan, Subramanian, Kumar, Nandhagopal, Raghavan, Rangasamy, Devendiran, Alsharif (2022)	56	Suciu, Plesea, Petre, Simion, Mituca, Dumitrescu, Bocaneala, Moroianu, Nasulea (2023)
28	Leng, Sha, Wang, Zheng, Zhuang, Liu, Wuest, Mourtzis, Wang (2022)	57	Tavares, Azevedo, Marques (2022)
29	Longo, Padovano, Umbrello (2020)	58	Trstenjak, Hegedić, Tošanović, Opetuk, Đukić, Cajner (2023)
30	Lu, Zheng, Chand, Xia, Liu, Xu, Wang, Qin, Bao (2022)	59	Verma, Bhattacharya, Madhani, Trivedi, Bhushan, Tanwar, Sharma, Bokoro, Sharma (2022)
31	Maddikunta, Pham, B, Deepa, Dev, Gadekallu, Ruby, Liyanage (2022)	60	Voulgaridis, Lagkas, Sarigiannidis (2022)
32	Madsen (2019)	61	Zizic, Mladineo, Gjeldum, Celent (2022)
33	Majerník, Daneshjo, Malega, Drábik, Barilová (2022)		
34	Martín-Gómez, Agote-Garrido, Lama-Ruiz (2024)		

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PROSPECTS 5.0

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