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OPERATOR 5.0 IN SMART MANUFACTURING: A LITERATURE REVIEW

The operator plays an integral role in various stages of production processes. Their work is closely connected to the development and integration of new technologies in manufacturing, which they must adapt to and incorporate into their daily tasks. The transition from Industry 4.0 to Industry 5.0 has a global impact on operators, transforming them from Operator 4.0 into Operator 5.0. This process affects many aspects of the operator's development, such as education, professionalism, endurance, safety, health protection, and the working environment, as well as the ability to perform tasks sustainably and with high quality. This literature review article describes the main approaches to the transition from Operator 4.0 to Operator 5.0 in smart manufacturing. In this new transition, numerous tasks arise that need to be structured into a unified solution.

1. INTRODUCTION

The operator is intended as the shop floor operator: the one working in front of machines, production lines, assembly lines, etc. [1]. Field operators represent the front liners in every manufacturing system. This role naturally makes them a bottleneck for operational effectiveness regarding quality, safety, and productivity [2].

A smart and skilled operator who performs not only cooperative work with robots but also work aided by machines as and if needed by means of human cyber-physical systems, advanced human-machine interaction technologies and adaptive automation towards human-automation symbiosis work systems [3]. Operator 4.0 has to have the capability to rapidly adapt his skills to a digital world, where innovations are continuously introduced [4].

The goal of creating Operator 5.0 in a smart manufactory is the need to apply new technologies in production to improve manufacturing performance and working conditions.

Insufficient discussion of the transition from Operator 4.0 to Operator 5.0. The I5.0 focuses can face unforeseen challenges, as the applicability and readiness of I4.0 solutions are still not well discussed in the literature. Therefore, structuring existing knowledge of O4.0

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to prepare for the smooth transition toward Operator 5.0 (O5.0) is crucial [5]. The following problem is identified as a lack of readiness for integrating the human factor from O.4 to O.5. Achieved results suggest that though the O5.0 transition is inevitable, I4.0 technologies are not ready with sufficient human factor integration [5]. Another problem is the lack of foundational and technical readiness for transitioning from O4.0 to O5.0. The transition toward the I5.0 is inevitable with many appearing signs, a lack of foundation and technical readiness for the transition toward O5.0 can be observed [5]. The last problem is that the project team has no standards or guidelines for technology implementation.

At present, the main problem with implementing Operator 5.0 is that this field is still underexplored and involves labor-intensive and large-scale work, both in its research and in its practical application.

The future of Operator 5.0 lies in the fact that it will be easily accessible, applicable, and effective, and will be able to be used in various fields.

The transition toward Operator 5.0 is inevitable, evidenced by many signs of research interest expansion [5]. Throughout this paper, the term Operator 5.0 provides a reference to human centric thinking and is defined as “a smart and skilled operator who uses human creativity, ingenuity, and innovation, aided by information and technology, to overcome obstacles on the way to developing new, cost-effective solutions for ensuring manufacturing operations’ long-term sustainability and workforce well-being in the face of difficult and/or unexpected conditions” [6].

Generation of Operators 4.0 is represented by qualified operators who perform the work with the support of machines; who interact with collaborative robots, advanced systems and sensors; who use augmented and virtual reality and exploit the benefits of the enabling technologies to understand production through context-sensitive information [7], [8].

In this review paper, a transition between the concepts of Operator 4.0 and Operator 5.0 has been identified. Within the framework of this transition, a bridge has been constructed to connect the stage from Operator 4.0 to Operator 5.0. The foundation for building this bridge was based on information about the identified GAP. This GAP, in turn, was defined through the analysis of research problems related to Operator 4.0 and Operator 5.0. These problems were identified by means of a systematic review of scientific articles. A research problem is a specific issue, difficulty, contradiction, or GAP in knowledge that you will aim to address in your research [9]. GAP analysis is either a tool or a process to identify where gaps are and what differences exist between an organization’s current situation and “what ought to be” in place [10].

2. LITERATURE REVIEW

The aim of the literature review is to study the key aspects of the transition from the concept of “Operator 4.0” to “Operator 5.0.” For the search of scientific articles on this topic, the large scientific online platform ScienceDirect was selected, which publishes peer-reviewed scientific articles, books, and reviews. Two terms were chosen as keywords for the search: “Operator 4.0” and “Operator 5.0.” A total of 25 scientific articles were found for each of the keywords “Operator 4.0” and “Operator 5.0” on the ScienceDirect platform. The main objective was to study the selected publications in order to identify: the definition of the term “Operator 4.0”; the definition of the term “Operator 5.0”; the issues related to “Operator 4.0”; the issues related to “Operator 5.0”; the research gap regarding “Operator 4.0”; the research gap regarding “Operator 5.0”; the existing solutions and approaches that form a bridge between the concepts of “Operator 4.0” and “Operator 5.0.” In the following paragraphs, a detailed literature review and discussion is presented [11].

As a result of the analysis of all 50 articles found using the keywords “Operator 4.0” and “Operator 5.0,” the data were obtained and are presented in Table 1 under the title “Literature Review Study (50 articles) for Operator 4.0 and Operator 5.0”.

As a result of the analysis of the data presented in Table 1, descriptions of the problems related to “Operator 4.0” were identified in 9 out of 25 scientific articles, with a total of 26 mentions. Some of these descriptions were repeated across different publications. Specifically, 4 different descriptions were found in the first article, 2 in the second, 7 in the third, 4 in the ninth, 2 in the tenth, 2 in the twelfth, 2 in the fourteenth, 2 in the twentieth, and 1 in the twenty-fifth article. The data presented in the column "Main characteristics of key factors" in Table 1 are based on specific references, which are detailed in the Implementation section, and have served as the basis for compiling this list associated with the keywords indicated in the table.

Table 1. Literature Review Study (50 articles) for Operator 4.0 and Operator 5.0

Main characteristics of key factors	Keyword	Category	Number of appearance [corresponding litterature ref.]																									Total
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Human, Education, Standardization, Management, Performance	Problem	Operator 4.0	4[11]	2[12]	7[14]						4[5]	2[22]		2[49]		2[4]						2[21]					1[20]	26
Human, Integration, Standardization, Management, Performance	Problem	Operator 5.0	3[26]					1[23]		3[5]			1[2]		2[32]						9[33]			1[6]	1[37]			21
Not defined	GAP	Operator 4.0																										0
Human, Technology, Management, Strategy	GAP	Operator 5.0						1[23]		3[5]		1[41]		2[42]		1[24]			1[25]		2[33]			1[45]	5[37]			17
Human, limitations, methods	Bridge	Operator 4.0									3[5]			1[49]	1[48]													6
Human, Technology, Implementation	Bridge	Operator 5.0								4[5]				2[42]		1[24]					2[33]			1[39]	1[37]			11
Not defined	Definition	Operator 4.0		1[12]		1[26]		2[29]			1[5]			1[49]		4[4]	1[1]			3[7]	2[28]	2[21]			1[27]			19
Not defined	Definition	Operator 5.0									1[30]										1[33]				3[37]			5

A similar analysis was conducted for the keyword “Operator 5.0.” Descriptions of problems related to “Operator 5.0” were identified in 8 out of 25 articles, with a total of 21 mentions. In particular, 3 descriptions were found in the first article, 1 in the sixth, 3 in the eighth, 1 in the eleventh, 2 in the thirteenth, 9 in the nineteenth, 1 in the twenty-second, and 1 in the twenty-third article.

When analysing the research gaps (GAP) for “Operator 4.0,” it was found that none of the 25 reviewed articles directly addressed the GAP (0 identified cases). The literature is to be examined with regard to the state of the art, focal points, and research gaps [31]. In contrast, the GAP for “Operator 5.0” was found in 9 out of 25 articles, with a total of 17 mentions. Specifically, 1 mentions of GAP were found in the sixt article, 3 in the eighth, 1 in the tenth, 2 in the twelfth, 1 in the fourteenth, 1 in the seventeenth, 2 in the nineteenth, and 1 in the twenty-second article, 5 in the twenty-third article. An important part of the study was the identification of publications describing the existing “bridge” between the concepts of “Operator 4.0” and “Operator 5.0.” For “Operator 4.0,” information about the bridge was found in 3 out of 25 articles, with a total of 5 mentions: 3 in article 9, 1 in article 12, and 1 in article 11. For “Operator 5.0,” the number of articles mentioning the bridge was 6 out of 25, with a total of 11 mentions: 4 in article 8, 2 in article 12, 1 in article 14, 2 in article 19, 1 in article 22, and 1 in article 23.

An analysis of the definitions of the terms was also conducted. The definition of “Operator 4.0” was identified in 11 out of 25 articles, with a total of 19 mentions: 1 in article 2, 1 in article 4, 2 in article 6, 1 in article 9, 1 in article 12, 4 in article 14, 1 in article 15, 3 in article 18, 2 in article 19, 2 in article 20, and 1 in article 23. This indicates a relatively high level of theoretical development of this term.

The definition of “Operator 5.0” appeared significantly less frequently – only in 3 articles, with a total of 5 mentions: 1 in article 9, 1 in article 19, and 3 in article 23. This confirms the relatively low degree of elaboration and the novelty of the concept.

Thus, it can be concluded that scientific publications related to “Operator 4.0” contain a significant amount of research addressing the transition toward “Operator 5.0.”

3. IMPLEMENTATION

The reviewed literature enables the development of an initial framework of interconnections describing the transition from Operator 4.0 to Operator 5.0 in smart manufacturing. There is currently the need for further investigation here [32]. This framework includes components that influence its formation (Fig, 1). These components represent the challenges associated with Operator 4.0, the challenges associated with Operator 5.0, as well as the GAP and the Bridge between them.

Based on the problems presented in Fig. 1, Operator 4.0 is associated with seven main problems, which were formulated through a literature review and quantitatively analysed, as shown in Table 1. The formation of the first problem, **Education and qualification of operators**, was derived from six main problems, one of which is Sustainable human development: It is imperative for industries to address human sustainability and adopt a human-centered production approach that aims to enhance workers’ skills, health, and safety [33]. The next problem**, Integration of humans and technologies**, includes one of the identified problems, such as Insufficient attention to human integration: little attention is still paid to the correct integration of humans in the emerging context of Smart Factories [34]. The problem **Technological compatibility and standardization** for Operator 4.0 includes Compatibility issues for diverse data sources, which in turn confirms the relevance and significance of the existing problem. The variety of sources often poses significant interoperability problems, which require standard and safe solutions to be solved [14].

The problem **Knowledge and process management** includes one of the identified problems, namely Dynamics of processes, products, management, and the use of new technologies: On the other hand, such digitalized environment has raised complexities related to dynamics of processes and products, as well as the way in which operators have to manage and use new technologies [35]. The problem **Monitoring and efficiency** includes Absence of real-time data and anomaly monitoring: This problem is highly relevant when using intelligent equipment, since arising from the absence of real-time data and the monitoring of anomalies [12]. The problem **Health, social and sustainability aspects** contains the wearing of sensors and the ergonomic performance of actions: Wearing and using wearable sensors was considered uncomfortable by many of the interviewees and performing activities in an ergonomic way resulted in a significant lengthening of the time spent completing the activity [15]. The final problem of Operator 4.0 is **Organizational and managerial problems**, which includes one of the identified problems, such as Lack of readiness for transition: though the transition toward the I5.0 is inevitable with many appearing signs, a lack of foundation and technical readiness for the transition toward O5.0 can be observed [5].

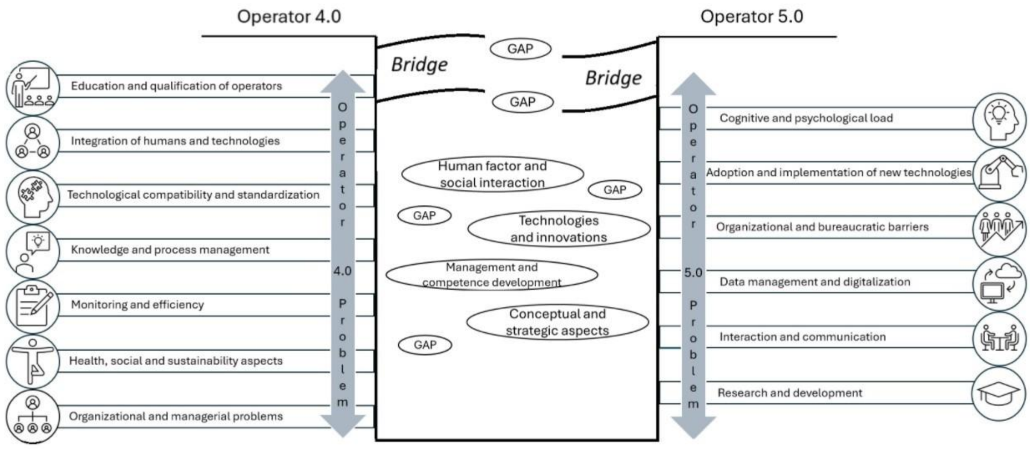

Fig. 1. Initial framework of interconnections describing the transition from Operator 4.0 to Operator 5.0 in smart manufacturing

Thus, we proceed to the consideration of the problems related to Operator 5.0, which are presented in Fig. 1. Following the same principle as in the previous description related to the problems of Operator 4.0, despite the fact that a significant number of references associated with the formulation of these problems were identified, we select only a limited number of representative sources highlighting the main underlying causes, without repeating identical descriptions found in other literature sources. The first problem refers to **Cognitive and psychological load**; this problem was formed based on Cognitive load for operators: it is important to highlight as Operation & Maintenance (O&M) field is seeing a profound transformation: remote monitoring, telecontrol or even onsite labour-intensive activities are now characterized by large use of smart devices and equipment that affect or lead to unbearable cognitive workload for the operators [16]. The problem **Adoption and implementation of new technologies** includes Retraining of personnel and implementation of new technologies: (i) Workforce reskilling: Implementing the Operator 5.0 concept requires significant reskilling of the workforce. Workers need to be equipped with a broader range of skills, including problem-solving, critical thinking, and creativity, in addition to technical expertise; (ii) Adoption of new technologies: Operator 5.0 requires the use of new technologies, such as artificial intelligence and robotics, to be integrated into the workforce. Operators are challenged with handling unexpected stops caused by machine failures and the following error recovery process of automated production systems [18]. The problem

Organizational and bureaucratic barriers includes Bureaucratic obstacles in production: A skilled workforce is expected to swiftly make hard operational decisions to continuously alter the course of production in the short and middle term. However, in many cases, those decisions are hindered through prolonged bureaucratic communication that increases the reaction time and reduces the overall efficiency of production significantly [2]. The problem **Data management and digitalization** contains System failure issues: System failure issues may arise due to the inability to anticipate a problem before it occurs, to perceive a problem that has actually occurred, and to solve a problem once it is detected. Moreover, has identified three stops on the road to failure of any system: (i) failing to anticipate a problem before it has arrived, (ii) failing to perceive a problem that has actually arrived, and (iii) failing to attempt to solve a problem once it has been perceived [36]. The problem **Interaction and communication** includes Collaboration between workers themselves is deteriorating: While majority of studies (e.g., [37, 38]) based on developed technologies focused on how to improve the collaboration between human and intelligent systems, the collaboration among the human workers themselves is falling apart. The problem **Research and development** includes Lack of research focus: Missing research orientations including integrated sustainability from the human perspective, or system resilience, concerning drivers and restrainers for technology adoption [5].

For the GAP related to Operator 5.0, only the main concepts are considered, as outlined below. **Human factor and social interaction**, within which one representative reference was selected. Empowerment of workers: Overall, worker augmentation aims to empower workers by leveraging technology to enhance their capabilities and efficiency in the manufacturing environment [19]. **Technologies and innovations,** which include Mastery of advanced technologies and high-quality service: Operator 5.0, one must have a variety of skills, including proficiency in advanced technologies such as AI, automation, and machine learning, as well as strong problem-solving abilities, adaptability, communication skills, and a willingness to learn and embrace new technologies. It is also important to focus strongly on customer experience, operational efficiency, and continuous improvement [18]. For the GAP **Management and competence development**, the following aspect is identified: Analysis and reconfiguration of weaknesses: Co-authorship of the work process. To foster the collaboration between humans and machines, future operators must need to see themselves as the co-creators in the work process [17]. Finally, within the GAP **Conceptual and strategic aspects**, the following concept is highlighted: Resilience and flexibility: The goal is to create a more sustainable and resilient industrial landscape, where organizations and individuals can thrive and prosper in the face of ongoing disruption [39].

Since no significant volume of scientific sources was identified for the Bridge for Operator 4.0, it was not possible to form separate groups. Therefore, the relevant aspects are listed below. **Limitation in the study:** Limitations of prior work and future research directions [20]. Formation of new research directions to accelerate the transition from Operator 4.0 to Operator 5.0, which, in turn, will positively contribute to an effective transition. **Development of new tools and methodologies:** New tools and methodological approaches need to be developed to adapt to the new industrial scenario [21]. **Structuring of knowledge about Operator 4.0.:** The I5.0 focus can face unforeseen challenges, as the applicability and readiness of I4.0 solutions are still not well discussed in the literature.

Therefore, structuring existing knowledge of O4.0 to prepare for the smooth transition toward Operator 5.0 (O5.0) is crucial [5]. **Integration of the human factor:** Achieved results suggest that though the O5.0 transition is inevitable, I4.0 technologies are not ready with sufficient human factor integration [5]. **The need to facilitate the transition:** Fostering the O5.0 transition is necessary for industrial stakeholders and requires knowledge of the favorable context and corresponding enablers [5].

For Bridge 5.0, eleven key directions have been identified and can be jointly described as follows. **Structuring of knowledge:** Structuring existing knowledge of O4.0 to prepare for the smooth transition toward Operator 5.0 (O5.0) is crucial [5]. **Formation of favorable conditions:** To prepare for O5.0, discussed O4.0 drivers can help to shape the favorable conditions, and the restrainers should be mitigated before adopting human-centric technologies [5]. **Contribution of the European Union:** From organizational contribution, the EU is the first player in the field with tremendous corporate efforts to establish and facilitate the transition [5]. **Outdated use of Operator 5.0 in the USA:** Recent studies report a limited practical relevance of the Operator 5.0 approach in the US [5], based on the analysis of major smart manufacturing initiatives and industry reports [40,41]. **Ergonomics in Logistics 5.0 and Industry 5.0:** Ergonomics, aimed at ensuring safe and comfortable working environments, proves to be crucial in the context of Logistics 5.0, where the adoption of advanced technologies requires special attention to the physical and cognitive needs of operators [42]. **Creativity in problem-solving:** Pointed out that the operators of the future need to become “makers” by working alongside digitalized and automated production systems and using creativity to solve unexpected and unforeseen challenges [13]. **Smart workforce:** By integrating intelligent machines, the goal should be to enhance both skills and knowledge of operators, leading to the smarter workforce [17]. **Trustful relationships between humans and machines:** A Next-Generation Operator, which evolves from the Operator 4.0 vision that aims to build trusting relationships (interaction-based) between humans and machines (incl. automation, robotic, and artificial intelligence systems), making it possible for those truly smart resilient manufacturing systems to capitalize not only on smart machines’ strengths and capabilities but also to empower their smart operators with new skills and gadgets to fully capitalize [43]. **Comprehensive approach to transition:** The transition to a resilient Operator 5.0 necessitates a more comprehensive approach that prioritizes the human element alongside the technological advancements [18].

Briefly, we consider the transition from Industry 4.0 to Industry 5.0, as this transformation is closely related to the shift from Operator 4.0 to Operator 5.0, the reasons for this transition, the external and internal forces driving it, its advantages and disadvantages, the development of key benefits to maximize value, the advancement of relevant disciplines to mitigate negative impacts, as well as the main achievements associated with Industry 4.0 and Industry 5.0. The reviewed scientific literature, the references to which are provided below in this chapter, is not included in the literature analysis presented in Table 1.

Industry 4.0 (I4.0) and Industry 5.0 (I5.0) represent milestones in global industrial development, signalling changes in the design, management, and optimization of production processes [44]. The **transition from I4.0 to I5.0** marks a significant milestone in technological evolution with a notable impact on manufacturing and industrial processes [44]. I5.0 would be a logical continuation of I4.0, which would inevitably occur due to technological evolution, impacting socio-cultural values and economic structures in a new economy [45]. Adopting the concept of Industry 5.0 becomes absolutely necessary, promoting an industry that is responsible towards human well-being, the environment, and resilient in terms of the value chain [46]. **Internal forces** driving the transformation from Industry 4.0 to Industry 5.0 include the rapidly growing demand for the adoption of advanced technologies and technical solutions aimed at improving and optimizing production processes, as well as enhancing productivity and product quality. **External forces** driving the transformation from Industry 4.0 to Industry 5.0 include the emergence of new technologies and technical solutions that become available for implementation and integration into existing production systems, including those based on traditionally used technologies that lag behind in terms of development. The **advantages** of the transformation are associated with its contribution to the optimization of production processes and the working environment, while simultaneously improving economic performance, as well as the volume and quality of output. The **disadvantages** of the transformation lie in the fact that the implementation of new technologies requires the restructuring of traditional production methods, which entails temporary financial costs for both equipment modernization and the retraining of personnel involved in the new transformation processes. Another weakness lies in the insufficient attention given to human factors, labour, and broader social dynamics [47-49]. To **fully benefit** from the development of the transformation, it is necessary to advance disciplines such as education and research in production management, engineering fields including automation, industrial robotics, and information technologies, as well as management. In turn, this is associated with achieving improved products and enhanced product quality during the production process, improving the working environment, reducing risks, and increasing economic performance. Disciplines that require further development to **avoid negative consequences** include risk management, technical operation, reliability theory, production management, and quality management. In turn, this is associated with areas such as risk analysis for prevention purposes, the analysis of operational capabilities (i.e., the service life of new equipment considering the use of advanced technologies), as well as reliability, efficiency, and quality. **Industry 4.0 achieving** superior performance and competitiveness [50]. The primary findings show that I4.0 results in various innovation types including process, product, business model, supply chain, organizational, open, and marketing innovations that advance triple bottom line (TBL) sustainability, circular economy (CE), sustainable business models (SBMs) and achievement of sustainable development goals (SDGs) [51]. The main **achievements of Industry 5.0** are human-centricity, synergy with technologies, sustainability. Also is inclusiveness, and resilience [52]. Importantly, Industry 5.0 does not reject the achievements of Industry 4.0 but develops them in a more sustainable, inclusive, and crisis-resilient direction, using advanced technologies not only to enhance efficiency but also to improve quality of life, protect the environment, and strengthen economic structures [53].

4. RESULT AND METHOD

After conducting a qualitative synthesis of the scientific literature described in the

Implementation section, involving the identification, comparison, and thematic grouping of recurring concepts related to Operator 4.0 and Operator 5.0, Fig. 2 was developed to represent the overall state of Operator 4.0 and Operator 5.0 and the key changes defining their transition.

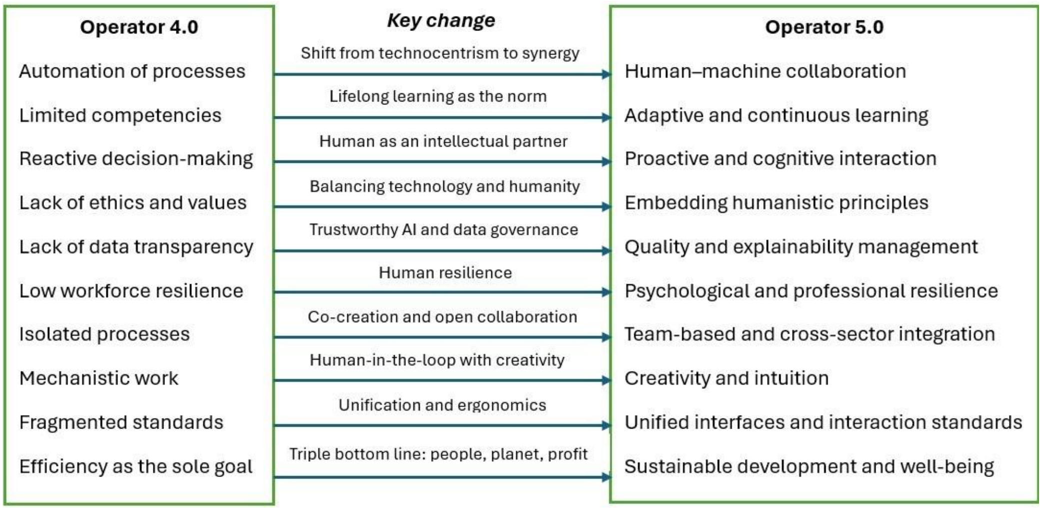

Fig. 2. Transition between Operator 4.0 and Operator 5.0

The relevant GAP 5.0 correspond to the state of Operator 5.0 **according to the corresponding state in Fig. 2, where each line represents a paired state of Operator 4.0 and Operator 5.0 connected through a specific key change.** Trustful human–machine relations; intuitive interfaces; co-decision; Smart workforce; empowerment; continuous learning frameworks; Creativity in problem-solving; co-authoring of processes; knowledge-driven AI; Human-centered approach; ethical governance; EU policy alignment; Comprehensive data governance; standards and explainability (Trustworthy AI); Ergonomics; resilience and flexibility; well-being at work; Teamwork and collaboration; co-creation; organizational enablers; Maker mindset; empowerment; use of intuition and creativity; EU-led standardization; favorable adoption conditions; Sustainability principles; comprehensive socio-technical transition. The final GAPs and transitions from Operator 4.0 to Operator 5.0 were developed not only based on the references found in the 50 analysed scientific articles, but also on the formation of GAPs derived from the identified referenced problems, which in turn, in their totality, resulted in the optimization of all obtained data, as illustrated in Fig. 2.

The Relevant Bridges (Transition) represent the key elements and principles that connect the state of Operator 4.0 with that of Operator 5.0, thereby ensuring a smooth and coherent transition between the two paradigms. From automation of processes to human–machine collaboration, the transition is guided by the Bridge (5.0) – Trustful relationships, and the Bridge (4.0) – New tools and methods. From limited competencies to adaptive and continuous learning, it relies on the Bridge (5.0) – Smart workforce, and the Bridge (5.0) – Empowerment of employees. From reactive decision-making to proactive and cognitive interaction, the transformation involves the Bridge (5.0) – Creativity, the Bridge (4.0) – Limitations, and the Bridge (4.0) – Structuring of knowledge. From lack of ethics and values to embedding human principles, it is achieved through the Bridge (5.0) – Human-centered approach, the Bridge (5.0) – EU contribution, and the Bridge (4.0) – Human factor integration. From lack of data transparency to quality and explainability management, the change is supported by the Bridge (5.0) – Comprehensive approach, the Bridge (5.0) – EU contribution, and the Bridge (5.0) – Favorable conditions. From low workforce resilience to psychological and professional resilience, it is facilitated by the Bridge (5.0) – Ergonomics, and the Bridge (5.0) – Empowerment of employees. From isolated processes to team-based or cross-sector integration, the transition depends on the Bridge (5.0) – Comprehensive approach, and the Bridge (5.0) – Favorable conditions. From mechanistic work to creativity and intuition, it is enabled by the Bridge (5.0) – Creativity, and the Bridge (5.0) – Empowerment of employees. From fragmented standards to unified interfaces and interaction standards, the transition occurs through the Bridge (5.0) – EU contribution (standardization), and the Bridge (5.0) – Favorable conditions. Finally, from efficiency as the sole goal to sustainable development and well-being, the transformation is realized by the Bridge (5.0) – Human-centered approach, the Bridge (5.0) – Comprehensive approach, and the Bridge (4.0) – Need to facilitate transitions.

5. CONCLUSION

Since the main goal of the scientific article was to identify the transition from Operator 4.0 to Operator 5.0 based on the study of scientific sources, it can be confidently stated that the set goal has been achieved and the obtained result is relevant for use both at present and in the future.

The number of scientific articles used was optimally effective, as it made it possible to identify the information necessary for analysis, which in turn allowed the integration of all factors and aspects of the transition from Operator 4.0 to Operator 5.0 in smart manufacturing. The formation of these data will serve as a foundation for future developments and integration in this field, as the new understanding of transitions will enable or facilitate the resolution of many problems faced by integrators of new technologies in production environments with various technological processes.

The transition method is universal and suitable for all levels of personnel in production. When this method is applied in the transition to smart manufacturing, many specialists, including programmers, will be able to ensure a smooth transition from Operator 4.0 to Operator 5.0, creating new algorithms for the collaborative work of Operator 5.0 with the production systems.

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REFERENCES

[1] LONGO F., NICOLETTI L., PADOVANO A., 2022, *New Perspectives and Results for Smart Operators in Industry 4.0: A Humancentered Approach*, Computers & Industrial Engineering 163, 107824, https://doi.org/10.1016/j.cie.2021.107824.

[2] CIMINO A., ELBASHEER M., LONGO F., NICOLETTI L., PADOVANO A., 2023, *Empowering Field Operators in Manufacturing: A Prospective Towards Industry 5.0.*, Procedia Computer Science 217, 1948–1953, https://doi.org/10.1016/j.procs.2022.12.395.

[3] ROMERO D., BERNUS P., NORAN O., STAHRE J., FAST-BERGLUND Å., 2016, *The Operator 4.0: Human Cyber-Physical Systems & Adaptive Automation Towards Human-Automation Symbiosis Work Systems*, Production Management Initiatives for a Sustainable World, Springer, IFIP, AICT 488, 677–686.

[4] GALLOA T., SANTOLAMAZZA A., 2021, *Industry 4.0 And Human Factor: How is Technology Changing the Role of the Maintenance Operator*?, Procedia Computer Science 180, 388–393. https://doi.org/10.1016/j.procs.2021.01.364.

[5] GLADYSZ B., TUAN-ANH T., ROMERO D., ERP T.V., ABONYI J., RUPPERT T., 2023, *Current Development on the Operator 4.0 and Transition Towards the Operator 5.0: A Systematic Literature Review in Light of Industry 5.0.*, Journal of Manufacturing Systems 70, 160–185, https://doi.org/10.1016/j.jmsy.2023.07.008.

[6] ROMERO D., STAHRE J., 2021, *Towards the Resilient Operator 5.0: The Future of Work in Smart Resilient Manufacturing Systems*, Procedia CIRP, 104, 1089–1094.

[7] ZOLOTOVA I., PAPCUN P., KAJATI E., MISKUF M., MOCNEJ J., 2020, *Smart and Cognitive Solutions for Operator 4.0: Laboratory H-CPPS Case Studies*, Computer and Industrial Engineering, 139, 105471.

[8] ROMERO D., et al., 2016, *Towards an Operator 4.0 Typology: a Humancentric Perspective on the Fourth Industrial Revolution Technologies*, CIE 2016 46th Int. Conf. Comput. Ind. Eng.

[9] THAKUR H.K., 2021, *Research Methodology in Social Sciences*, New Delhi: Corvette Press, 36–52.

[10] KIM S., JI Y., 2018, *GAP Analysis*, The Chinese University of Hong Kong, China.

[11] MOURTZIS D., 2021, *Towards the 5th Industrial Revolution: a Literature Review and a Framework for Process Optimization Based on Big Data Analytics and Semantics*, Journal of Machine Engineering, 21/3, 5–39, https://doi.org/10.36897/jme/141834.

[12] FABIO G., GIUDITTA C., MARGHERITA P., RAFFAELI R., 2025, *A Human-Centric Methodology for the Co Evolution of Operators' Skills, Digital Tools and User Interfaces to Support the Operator 4.0.*, Robotics and Computer–Integrated Manufacturing 91102854.

[13] MARK P. TAYLOR, PETER BOXALL, JOHN J. J. CHEN, XUN XU, ANGELA LIEW, ADEBAYO ADENIJI. Operator 4.0 or Maker 1.0? Exploring the implications of Industrie 4.0 for innovation, safety and quality of work in small economies and enterprises" Computers & industrial engineering, 139: 105486, 2020.

[14] LONGO F., MIRABELLI G., NICOLETTI L., SOLINA V., 2022, *An Ontology-Based, General-Purpose and Industry 4.0-Ready Architecture for Supporting the Smart Operator (Part I – Mixed Reality Case)*, Journal of Manufacturing Systems 64, 594–612, https://doi.org/10.1016/j.jmsy.2022.08.002.

[15] VALENTINA D.P., VALENTINA D.S., SALVATORE M., STEFANO R., 2021, *Smart Operators: How Industry 4.0 is Affecting the Worker's Performance in Manufacturing Contexts*, Procedia Computer Science, 180, 958–967, https://doi.org/10.1016/j.procs.2021.01.347.

[16] OLIVERI L.M., LO IACONO N., CHIACCHIO F., FACCHINI F., MOSSA G., 2024, *A Decision Support System Tailored to the Maintenance Activities of Industry 5.0 Operators*, PapersOnLine, 58/8, 186–191, https://doi.org/10.1016/j.ifacol.2024.08.118.

[17] BECHINIE C., ZAFARI S., KROENINGER L., PUTHENKALAM J., TSCHELIGI M., 2024, *Toward Human-Centered Intelligent Assistance System in Manufacturing: Challenges and Potentials for Operator 5.0*, Procedia Computer Science, 232, 1584–1596, https://doi.org/10.1016/j.procs.2024.01.156.

[18] HATTINGER M., STYLIDIS K., 2023, *Transforming Quality 4.0 Towards Resilient Operator 5.0 Needs*, Procedia CIRP, 120, 1600–1605, https://doi.org/10.1016/j.procir.2023.12.002.

[19] PADOVANO A., CARDAMONE M., KLAESS J., 2024, *Empowering Operator 5.0: Human-Centric Design of an Augmented Reality Tool for a Learning Factory*, PapersOnLine 58–8, 180–185,,https://doi.org/10.1016/j.ifacol.2024.08.117.

[20] KHEIRI S.K., VAHEDI Z., SUN H., MEGAHED F.M., CAVUOTO L.A., 2023, *Human Reliability Modeling in Occupational Environments Toward a Safe and Productive Operator 4.0,* International Journal of Industrial Ergonomics, 97, 103479, https://doi.org/10.1016/j.ergon.2023.103479.

[21] CICCARELLI M., PAPETTI A., GERMANI M., 2023, *Exploring How New Industrial Paradigms Affect the Workforce: A Literature Review of Operator 4.0,* Journal of Manufacturing Systems, 70, 464–483, https://doi.org/10.1016/j.jmsy.2023.08.016.

[22] GAZZANEO L., PADOVANO A., UMBRELLO S., 2020, *Designing Smart Operator 4.0 for Human Values: A Value Sensitive Design Approach*, Procedia Manufacturing 42, 219–226, https://doi.org/10.1016/j.promfg.2020.02.073.

[23] VITTI M., PADOVANO A., FACCHINI F., *A Review on Cognitive Workload for Industry 5.0. 2025*, https://doi.org/10.1016/j.cie.2025.111350.

[24] MONFERDINI L., TEBALDI L., BOTTANI E., 2025, *From Industry 4.0 To Industry 5.0: Opportunities, Challenges, and Future Perspectives in Logistics*, Procedia Computer Science, 253, 2941–2950.

[25] SBARAGLI A., TOMELLERI F., PICARIELLO F., PICARIELLO E., PILATI F., 2024, *Safe Operator 5.0 Digital Architecture: Towards Resilient Human-Centric Manufacturing Systems,* IFAC PapersOnLine 58–19, 265–270.

[26] CIMINO A., LONGO F., MIRABELLI G., SOLINA V., VERTERAMO S.V., 2024, *An Ontology-Based, General-Purpose and Industry 4.0-Ready Architecture for Supporting the Smart Operator (Part II – Virtual Reality Case),* Journal of Manufacturing Systems. 73, 52–64, https://doi.org/10.1016/j.jmsy.2024.01.001.

[27] SEGURA A., DIEZ H.V., BARANDIARAN I., ARBELAIZ A., ALVAREZ H., SIMOES B., POSADA J., GARCIA-ALONSO A., UGARTE R., 2020, *Visual Computing Technologies to Support the Operator 4.0.*, Computers & Industrial Engineering, 139, 105550, https://doi.org/10.1016/j.cie.2018.11.060.

[28] CIMINI C., LAGORIO A., ROMERO D., CAVALIERI S., STAHRE J., 2020, *Smart Logistics and the Logistics Operator 4.0.*, IFAC PapersOnLine, 53–2, 10615–10620.

[29] LÖCKLINA A., JUNGA T., JAZDIA N., RUPPERTB T., WEYRICHA M., 2021, *Architecture of a Human-Digital Twin as Common Interface for Operator 4.0 Applications,* Procedia CIRP, 104, 458–463.

[30] BATTINI D., BERTI N., CELLA C., FARONI M., GARZA P., GUIDOLIN M., MOOS S., OLIVETTI E.C., REGGIANI M., SARDINI E., TONELLO S., 2024, *Designing the Operator of the Future: The Architecture of Human Digital Twin Systems*, IFAC PapersOnLine 58–19, 355–360.

[31] STRÖBEL R., MAU M., DIEBOLD M., PUCHTA A., FLEISCHER J., 2025, *Review of Process Monitoring and Anomaly Detection Applications for CNC Milling Machines in Highly Flexible Production*, Journal of Machine Engineering, 25/4, 33–52.

[32] HOLLAS L., SCHENKE C.-C., HELLMICH A., 2023, *Approach of a Model Extension for Virtual Commissioning to Predict Energy Consumption of Production Systems*, Journal of Machine Engineering, 23/4, 77–88.

[33] GREGORI F., PAPETTI A., PANDOLFI M., PERUZZINI M., GERMANI M., 2017, *Digital Manufacturing Systems: A Framework to Improve Social Sustainability of a Production Site*, Procedia CIRP, 63, 436–442, https://doi.org/10.1016/j.procir.2017.03.113.

[34] PACAUX-LEMOINE M.P., TRENTESAUX D., ZAMBRANO REY G., MILLOT P., 2017, *Designing Intelligent Manufacturing Systems Through Human-Machine Cooperation Principles: A Human-Centered Approach*, Comput. Ind. Eng., 111, 581–595, https://doi.org/10.1016/j.cie.2017.05.014.

[35] FUSKO M., RAKYTA M., KRAJCOVIC M., et al 2018, *Basics of Designing Maintenance Processes in Industry 4.0.,* MM Sci. J.,:2252–2259, https://doi.org/10.17973/MMSJ.2018_03_2017104.

[36] DIAMOND J., 2011, *Collapse: How Societies Choose to Fail of Succeed, Second Edition*; Viking Press.

[37] LENG J., SHA W., WANG B., ZHENG P., ZHUANG C., LIU Q., WANG L., 2022, *Industry 5.0: Prospect and Retrospect*, Journal of Manufacturing Systems, 65, 279-295.

[38] LU Y., ZHENG H., CHAND S., XIA W., LIU Z., XU X., BAO J., 2022, *Outlook on Human 1596 Manufacturing Towards Industry 5.0.,* Journal of Manufacturing Systems, 62, 612–627.

[39] ROMERO D., STAHRE J., 2021, *Towards the Resilient Operator 5.0: the Future of Work in Smartresilient Manufacturing Systems,* Procedia CIRP, 104,1089–94.

[40] II Consortium, 2022, *Compilation of Views on The Smart Manufacturing Industry*, URL https://www.iiconsortium.org/wpcontent/uploads/sites/2/2022/07/GIO Smart-Manufacturing, 2022-06-15.pdf.

[41] II Consortium, 2022, *Digital Transformation in Manufacturing: Key Insights Future Trends*, URL https://www.iiconsortium.org/pdf/IICDX-in-Manufacturing Insights-Trends-Tech-Brief.pdf.

[42] PEREIRA C., ALVES A.C., AREZES E.P., 2023, *Augmented Reality in a Lean Workplace at Smart Factories: A Case Study*, Applied Sciences, 13, fasc., 16, 9120.

[43] ROMERO D., BERNUS P., NORAN O., STAHRE J., BERGLUND AF., 2016, *The Operator 4.0: Human Cyber-Physical Systems & Adaptive Automation Towards Humanautomation Symbiosis Work Systems*, IFIP Adv. Inf. Commun. Technol., 488:677–86.

[44] JAIME A., OSORIO-SANABRIA M.A., BERNAL TORRES D.Y., 2026, *Similarities and Differences Between Industry 4.0 And Industry 5.0,* Towards a transitioning model, https://doi.org/10.1016/j.jik.2025.100921.

[45] RORATO FOGACA D., GRIJALVO M., SACOMANO NETO M., 2025, *What Are Industry 4.0 And Industry 5.0 All About?,* An Integrative Institutional Model for the New Industrial Paradigms, https://doi.org/10.3390/admsci15040118.

[46] GIL G., JOSE M., VILA-GUTIERREZA., JESUS M., MARTIN-GOMEZ, MANUEL A., MARTIN-GOMEZ, MANUEL A., 2024, *From Industry 4.0 to Industry 5.0:* A Study and Perspectives on Technological Evolution.

[47] NEUMANN W.P., WINKELHAUS S., GROSSE E.H., GLOCK C.H., 2021, *Industry 4.0 and the Human Factor—a Systems Framework and Analysis Methodology for Successful Development*, International Journal of Production Economics, 233, 1079929.

[48] SONY M., 2020, *Pros and Cons of Implementing Industry 4.0 for the Organizations: A Review and Synthesis of Evidence*, Production & Manufacturing Research, 8/1, 244–272.

[49] ZORZENON, R., LIZARELLI, F. L., DE A., MOURA D.B.A., 2022, *What is the Potential Impact of Industry 4.0 on Health and Safety at Work?* Safety Science, 153, 105802.

[50] SIDHARTHA S., SOUMYATANU MUKHERJEE P., CHENG T.C.E., 2024, *Optimal Investment Decision for Industry 4.0 Under Uncertainties of Capability and Competence Building for Managing Supply Chain Risks*, https://doi.org/10.1016/j.ijpe.2023.109067.

[51] KHAN I.S., AHMAD M.O., MAJAVA J., 2023, *Industry 4.0 Innovations and Their Implications: An Evaluation from Sustainable Development Perspective*, https://doi.org/10.1016/j.jclepro.2023.137006.

[52] HERMAWATI S., CORREA R., MOHAN M., LAWSON G., HOUGHTON R., 2024, *Defining Human- Centricity in Industry 5.0 and Assessing the Readiness of Ergonomics/Human Factors Communities in the UK*, Ergonomics, 1–20.

[53] GHOBAKHLOO M., IRANMANESH M., FATHI M., REJEB A., FOROUGHI B., NIKBIN D., 2024, *Beyond Industry 4.0: A Systematic Review of Industry 5.0 Technologies and Implications for Social, Environmental and Economic Sustainability*, Asia-Pac. J. Bus. Adm. ahead-of-print.