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RESEARCH ARTICLE

Towards a Taxonomy of Industrial Challenges and Enabling Technologies in Industry 4.0

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ABSTRACT In the era of Industry 4.0 (I4.0), a significant challenge hindering digital transformation is the lack of mutual understanding between academia—particularly within engineering and computer science—and the industrial sector, especially small to medium-sized enterprises (SMEs). This gap can result in industries missing out on the potential benefits of cutting-edge scientific research and innovations that can address their daily concerns. At the same time, academics may struggle to identify real-world application areas for their emerging technological solutions. Moreover, the ever-increasing complexity of industrial challenges and technologies has widened the hiatus. To address this issue, our study introduces a comprehensive taxonomy, developed through a transparent, iterative process and presented via a user-centric web platform. Distinct from existing taxonomies, ours emphasizes practical applicability by categorizing and connecting industrial challenges with I4.0 technologies using articles, best practices, and use cases from academic and grey literature, thereby effectively bridging the academic-industrial communication gap. Its effectiveness and practical utility were validated in a workshop as part of the Erasmus+ project PLANET4, where industry professionals provided positive feedback after applying it to real-world challenges. Future work will include expanding the taxonomy, developing an Industry 4.0 ontology, and further enhancing the usability and maintainability of the developed web platform.

INDEX TERMS Business challenges, enabling technologies, Industry 4.0, taxonomy, web platform.

I. INTRODUCTION

The Fourth Industrial Revolution, commonly referred to as Industry 4.0 (I4.0), stands at the forefront of contemporary technological advancements in the industrial sector [1]. Its emergence is driven by several factors, including a societal transition from physical and social networks to digital interconnections, the shift from paper-based processes to digital workflows, and, crucially, the widespread accessibility of advanced yet affordable smart technologies, such as Artificial Intelligence (AI), Edge Computing (EC), Industrial Internet of Things (IIoT), and Big Data analytics [2], [3]. Unlike the Third Industrial Revolution, which centered on automating production through electronics and information technologies, I4.0 envisages merging the digital, physical, and biological worlds into a single entity referred to as a Cyber-Physical System (CPS). This integration paves the way for innovative models of personalized production and servicing, wherein machines interact autonomously with each other, requiring minimal or no human intervention, to meet

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the growing demands for efficiency, speed, quality, and sustainability [4].

To fully harness the potential of the I4.0 vision, a strong collaboration between academia—especially within engineering and computer science—and industry is required. This collaboration facilitates the transfer of knowledge and technology, fostering informed decision-making and innovative solutions [5]. The industry, with its practical experience and insights into real-world challenges, can guide academic research towards valuable and applicable solutions in industrial settings.

Academia's multifaceted role encompasses three complementary "missions" [6]: education, research, and outreach. The first "mission" involves qualifying human capital through education [7], making universities responsible for training the next generation of workers in the I4.0 context [8]. The second "mission" involves advancing knowledge and developing new technologies through research. In this realm, however, industry has recently taken a leading role in the development of some advanced technologies, outpacing academia in some fields. This shift is mainly due to the industry's superior computing power and access to vast datasets, which are essential resources for modern research and development [9]. Despite this advantage, universities' fundamental role in knowledge advancement, theory development, and expert training remains critical. The interplay between academia's foundational work that underpins technological advancements and the industry's practical applications is critical for the holistic advancement of I4.0. This synergy leads to universities' third mission, which involves socio-economic problems through an entrepreneurial mindset and strategic planning, allowing for the generation, use, application, and exploitation of knowledge with external stakeholders and society [6]. Such partnership between universities and industries enhances the first two missions by promoting knowledge and technology exchange and fostering joint educational and research endeavors [10]. An exemplar of this collaborative ethos is the Triple Helix model of innovation, which intertwines academia, industry, and government, empowering universities to support small and medium-sized enterprises through their technology transfer offices [11], [12].

While the complementary roles of academia and industry are clear, actualizing this synergy into practical collaboration presents challenges, particularly in the context of knowledge and technology transfer. Such transfers are essential for effective corporate knowledge management [13] and university-industry collaboration; however, barriers may arise within the two domains [14]. Although the goals and scope of I4.0 are well understood by industry and academia [3], collaboration can be hindered by a lack of mutual understanding [15], [16]. Academics are commonly inclined towards developing and testing theories without sufficient consideration of the practical applicability of their findings in real-world scenarios [17]. At the same time, some researchers might lack hands-on industrial experience or miss opportunities to collaborate with industry partners on research projects. Such disparities in experience and a limited immersion in practical challenges can impede academics from fully understanding the needs and priorities from an industrial point of view [18].

From an industrial standpoint, two main challenges arise: leveraging insights from academic research and understanding the potential of I4.0 technologies. However, many industry professionals remain uninformed about recent academic discoveries due to challenges in accessing and interpreting them [17]. There's also uncertainty about how to put these findings into practice [19]. This disconnect is because academia is typically perceived as an educational provider rather than a technological one, especially by SMEs, which may not actively seek opportunities to collaborate with universities and research institutes to remain up-to-date on the latest developments [20], [21]. Moreover, while many industries prioritize immediate, cost-effective solutions that offer quick results [22], researchers tend to aim for innovative solutions that, although potentially offering greater long-term benefits, might take longer to realize [23]. Finally, enterprises operating on tight schedules and deadlines cannot afford to allocate resources or time to engage with academia [24], posing a significant obstacle to researchers who require access to industrial settings to test and validate their theories and solutions. Consequently, SMEs and other industrial practitioners may miss the potential benefits of cutting-edge research and technologies that can enhance their operations and increase competitiveness. In conclusion, the lack of mutual understanding and the relative communication gap [25] between academia and industry, which can be attributed to differences in their backgrounds, perspectives, and goals [24], present a significant challenge for adopting and successfully implementing I4.0. Therefore, the following research question (RQ) arises:

> *"How can we address the lack of mutual understanding between academia and industry to facilitate the realization of the I4.0 paradigm?"*

A. STATE-OF-THE-ART & MOTIVATION

To address the above challenges of industry-academia collaboration and promote knowledge exchange, it is essential to initially establish a shared language and terminology that connects the challenges faced by the industry with the technological solutions offered by academia. By standardizing terminologies and achieving consensus on their use, researchers can better understand industrial priorities, while industrial practitioners can access cutting-edge research results. This mutual comprehension paves the way for fruitful collaboration, technology adoption facilitation, and innovative solutions tailored to real-world challenges [26].

Taxonomies serve as an effective tool for organizing and standardizing such a shared vocabulary. They are powerful tools that can communicate complex information and bridge the gap in understanding between the two domains. Specifically, they present a hierarchical structure of categorized elements from the same domain in a subsumptive manner, with parent-child relationships. Each element is defined by its concept and associated terms, ensuring clarity in understanding interrelated concepts. Such a structured approach not only facilitates knowledge exchange but also highlights areas of potential improvement, driving more targeted research and innovation [27]. Furthermore, taxonomies can also support decision-making processes by enabling a better comparative evaluation of available options. For instance, in [27], taxonomies were shown to improve communication between researchers and practitioners in IoT vulnerability management. The authors introduced the "SERP-MENTION" taxonomy, building on the Software Engineering Research and Practice (SERP) architecture. This taxonomy provides a standardized language and structure for discussing key concepts and challenges in software engineering. Its efficacy was showcased in a case study of an ongoing industry-academia research collaboration project, demonstrating its potential to bridge the gap between research and practice. Regarding I4.0, taxonomies have piqued the interest of researchers and proved extremely useful in various aspects. Relevant works are summarized in Tab. 1, where:

- the "Key topics" column refers to the main topics addressed by each study;
- the "Methodology" column lists the development procedures applied in each study;
- the "Presentation" column refers to the final appearance.

Lagorio et al. [28] proposed a taxonomy to categorize the relationships between human factors and technologies in Logistics 4.0. Through a literature review and deductive approach, the authors identified three main categories and ten dimensions. Da Silva et al. [36] performed a systematic literature review of 53 articles to examine energy consumption in the smart industry. They proposed a hierarchical, tree-formed taxonomy that considered "Goals", "Concerns", and "Deployment" (i.e., I4.0 technologies) related to I4.0 energy consumption. Similarly, Raptis et al. [38] conducted a literature review to analyze state-of-the-art research on data management in I4.0. They proposed a comprehensive and holistic hierarchical tree-presented taxonomy based on 316 reviewed articles, which considered all the main enablers, such as "data enabling technologies" and "data-centric services", and presented industrial cases in which data management was applied. In the same field, Manesh et al. performed a bibliometric analysis of 90 papers to create a spatial mapping of the literature on knowledge management in I4.0 [29]. Although the authors did not explicitly present a taxonomy, the results were presented graphically and tabularly by clustering the topics and keywords. Additionally, [39] presented an overview of predictive maintenance in I4.0. After a systematic literature review on the subject, they proposed a taxonomy by applying natural language analysis to 47 articles, clustering the more frequent terms, and mapping them in hierarchical order. Finally, Latino et al. investigated the state-of-the-art I4.0 implementation in agriculture (Agriculture 4.0) [35]. The authors proposed a hierarchical, tree-presented taxonomy of the technologies, processes, issues, and aims involved in Agriculture 4.0 by reviewing and analyzing 1338 studies. They compared the more frequent terms identified in these studies and used an inductive approach by consulting a focus group of experts to perform thematic clustering.

Other researchers have explored the broader implications of I4.0. For instance, Oztemel and Gursev [34] conducted a literature review of 620 papers to develop a taxonomy of I4.0 covering four main aspects, namely "Strategic view", "Managerial view", "Technical view", and "Human Resource view". The authors identified subcategories for each aspect and classified them in a hierarchical-tree order, enabling the analysis of both the business and technological sides of I4.0. However, the mapping of these aspects and subcategories remains unclear. Cammarano et al. [32] presented a framework to investigate the adoption of key technologies and emerging business practices in the broader context of I4.0 (also including domains such as e-commerce, food and beverage) based on a systematic literature review of more than 22,000 scientific articles published from 2019 to 2022. The researchers used an inductive approach -without providing a detailed description of its development method- to define a taxonomy of 11 key technologies, resulting in the identification and categorization of 87 specific technologies. Besides, while the study presented a comprehensive framework in which business and technology factors can be linked, it did not provide a practical way or tool to apply and leverage the findings, particularly in non-academic settings. On the other hand, Wagire et al. [30] used a Latent Semantic Analysis approach to analyze 503 research papers on I4.0, identifying the main research areas and themes of I4.0 addressed by academia. They represented the resulting taxonomy in a three-level pie graphic, blackdenoting "Principal research areas", "Minor research themes", and "Major research themes. However, the order of the circles in the graphic could be misleading, suggesting a tree-like structure and a subsumptive classification scheme. Nazarov and Klarin conducted a scientometric analysis to create a taxonomy of the literature on I4.0, intending to identify the "top trending and top articles" [33]. This study identified clusters of domains addressed in the literature on I4.0, as well as their top terms and articles. Although the study reviewed nearly 3000 articles and aimed to propose a holistic system view of I4.0, the methodology and results appear to align more with a Systematic Literature Review than a taxonomy. Similarly, Cañas et al. [31] reviewed 130 scientific papers to propose a taxonomy of design principles for implementing I4.0. However, they did not translate the results of the classification process into a proper taxonomy and presented them only as a categorization of the literature review.

While the above studies have provided valuable insights and taxonomies related to I4.0, they have some limitations. One notable limitation (L1) is the narrow focus of certain

TABLE 1. Comparison of related works.

Paper	Key Topics	Methodology	Presentation
Lagorio *et al.* [28]	Logistics 4.0 Human-centered logistics	Deductive approach Literature review	Table
Manesh *et al.* [29]	I4.0 Knowledge Management	Bibliometric analysis	Cluster visualization
Wagire *et al.* [30]	I4.0 research dynamics	Latent Semantic Analysis	Pie / Table
Cañas *et al.* [31]	I4.0 implementation	Literature review classification	Table
Cammarano *et al.* [32]	I4.0 adoption and emerging business practices	Systematic literature review Not provided for the taxonomy	Textual
Nazarov & Klarin [33]	I4.0 research	Thematic analysis Scientometric analysis	Table / Cluster visualization
Oztemel & Gursev [34]	I4.0 overall landscape	Literature review	Hierarchical tree
Latino *et al.* [35]	Agriculture 4.0	Frequent-terms analysis Experts focus group Inductive approach	Hierarchical tree
da Silva et al. [36]	Smart manufacturing Energy consumption	Systematic literature review	Hierarchical tree
Zhou *et al.* [37]	Smart manufacturing Visualization	Literature review	Table
Raptis *et al.* [38]	I4.0 Data Management	Literature review	Hierarchical tree
Zonta *et al.* [39]	I4.0 Predictive maintenance	Systematic literature review NLP clustering Mapping of clusters	Hierarchical tree
Rico *et al.* [27]	IoT vulnerability management	Interviews with experts Workshop with experts Literature review	Table

studies on specific topics or domains within I4.0. This specificity can limit their ability to provide a comprehensive understanding of the entire field, as seen in works like [28] and [39]. Another concern (L2) arises from studies that either rely on a limited selection of articles or do not take into account industrial case studies, potentially hindering the representation of multifaceted nature and intricacies of Industry 4.0, as evidenced by [29] and [31]. Additionally (L3), some studies do not present a clear methodology for taxonomy development (e.g., [32], [34]), while other studies use the term ‘‘taxonomy’’ merely as a label for their literature categorization, rather than as an actual framework for organizing and classifying concepts or ideas, as observed in [31] and [33]. A further limitation (L4) is the presentation style of some taxonomies, which may not be intuitive or user-friendly, posing challenges for industry professionals aiming to utilize them, as indicated by [32]. Finally (L5), the connection and mapping between the industrial and academic sides of I4.0 are not always clear, which can hinder the identification of appropriate technologies for specific issues, as highlighted by [30].

To address the limitations identified in previous studies, several actions can be taken. The first limitation (L1) can be overcome by conducting a multivocal literature review (MLR), which is a rigorous and transparent method of identifying, evaluating, and synthesizing all relevant research studies on all the topics concerning I4.0 without limiting it to one particular aspect. Importantly, an MLR extends beyond academic sources, incorporating insights from consultancy reports, service providers' case studies, or trade magazines. Such an inclusive approach not only broadens the research base but also integrates invaluable industrial knowledge, effectively addressing the second limitation (L2). Regarding the third limitation (L3), a detailed taxonomy development methodology should be presented to ensure transparency and clarity. The methodology should also consider the mapping between industrial challenges and technological solutions while categorizing them, addressing limitation (L5). Additionally, to make the taxonomy more leverageable in real-world scenarios, a user-friendly taxonomy presentation can be developed to address the fourth limitation (L4). One way to present the taxonomy is through a search engine that can help users navigate through categories, subcategories, and indexed articles quickly and efficiently, which can overcome the limitations of previous studies and provide a more comprehensive understanding of I4.0.

B. CONTRIBUTION

This paper proposes a knowledge exchange and communication environment for industry experts and academics/researchers, aiming to bridge the communication gap in addressing Industry 4.0 challenges/needs. Inspired by the Esperanto language, this communication environment aims to blend humanistic and engineering techniques applied to technology, entrepreneurship, and industrial domains to facilitate the broad adoption of Industry 4.0. Central to this proposal is the creation of a taxonomy: a structured, indexable collection of real-world industrial challenges/needs and their associated enabling technologies. This taxonomy is envisioned as a nexus where stakeholders from both industry and academia converge, fostering collaborative efforts for a smooth digital transformation of industries. Building upon the foundational research in [40], this paper describes the rationale behind building this taxonomy,

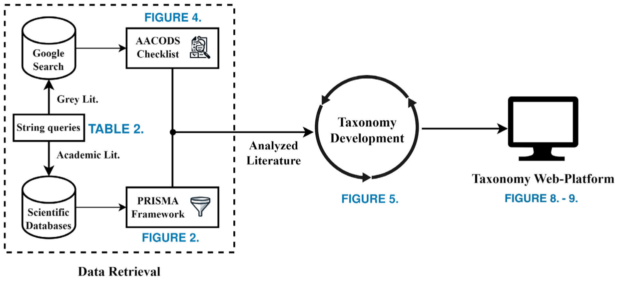


FIGURE 1. **High-level flow chart of the proposed methodology.**

which assorts more than 32 real-world industrial challenges/needs and links them with 147 enabling technologies through their associated success stories. This initiative was undertaken as part of the Erasmus+ PLANET4 project (https://www.planet4project.eu/). The key contributions of this paper include:

- Methodological approach to build a taxonomy of industrial challenges/needs and I4.0-enabling technologies.
- A first version of the taxonomy of Industry 4.0 and the corresponding web platform.
- Presentation of taxonomy applications to example industrial challenges/needs.

The remainder of the paper is organized in the following manner. Sec. II describes the approach used to build the proposed taxonomy. Sec. III presents the obtained results, how this taxonomy was transformed into a usable web tool and its evaluation in two real scenarios. Finally, Sec. V concludes the paper, highlights the limitations encountered, and proposes future work directions.

II. METHODOLOGY

This section presents the detailed methodology for constructing the proposed taxonomy, as illustrated in the flowchart in Fig. 1. The methodology commences with a comprehensive Multivocal Literature Review (MLR), which involves the systematic collection of data from both academic publications and grey literature, ensuring the thoroughness and methodological rigor of the dataset used. Subsequently, the process delves into examining the theoretical foundations of taxonomies and their interoperability, which is crucial for understanding taxonomy's structure and function. The final phase encompasses the iterative development of the taxonomy, which allows for continuous refinement and adaptation of this knowledge repository to new insights. The resultant taxonomy effectively categorizes and links industrial challenges with corresponding enabling technologies and serves as a valuable tool for academic research and practical applications.

A. MULTIVOCAL LITERATURE REVIEW PROCESS

The development of the taxonomy is structured into three distinct steps:

Step 1: *"Identify the main needs and challenges that SMEs/industries/businesses can address by adopting I4.0."*

Step 2: *"Identify the enabling technologies behind the solutions capable of solving such needs and challenges."*

Step 3: *"Link those business challenges/needs and their corresponding enabling technologies to create a tool of shared knowledge to bridge the gap between academia and industry, advancing the implementation of the I4.0 paradigm."*

For the initial two steps, it's imperative to incorporate insights from both the internal perspective of firms and research community publications [41]. This means that the analysis should encompass not only scientific research papers but also grey literature (GL) - documents produced by individuals or organizations closely associated with the subject matter. To ensure this holistic understanding, a Multivocal Literature Review (MLR) was conducted to analyze both state-of-the-art and state-of-practice in the industrial sector [42]. The MLR process started in March 2021 and ended in April 2022. The proposed methodology is illustrated in Fig. 1.

To gather relevant academic literature, we utilized prominent online scientific search engines, such as Google Scholar, Scopus, ResearchGate, IEEE Xplore, and ScienceDirect. These platforms were accessed through an API interface, allowing for the use of keywords, filters, and logical conditions to select appropriate articles. For the academic literature extraction, we developed a query string tailored to our study's goal of facilitating Industry 4.0 adoption in small and medium-sized enterprises (SMEs). This query was designed to encompass the critical technical, human, and innovation-oriented aspects essential for this transition. To comprehensively cover all facets of organizational transformation towards an advanced, interconnected industrial paradigm, we selected specific management terms: 'Change Management,' 'Digital Management,' 'Innovation Management,' and 'Technological Management' [43]. Change management is crucial, as it addresses the human and cultural aspects needed to adapt to smart technologies and interconnected systems, ensuring workforce readiness and support for these significant changes. Furthermore, Digital Management plays a key role by overseeing digital assets and operations, which is a cornerstone of Industry 4.0's data-driven decision-making and automation. In parallel, Innovation Management is pivotal for developing new business models and product-service systems, enabling companies to stay competitive and agile in a rapidly evolving market. Lastly, Technological Management is integral for selecting and integrating Industry 4.0 technologies into existing systems, ensuring seamless technological adoption. These selected terms provided a holistic framework for comprehensively understanding the intricacies of Industry 4.0 adoption in SMEs, thus providing a nuanced exploration of challenges rather than a generic overview of industry requirements.

On the other hand, for the technologies side, some key I4.0 technologies, such as wireless sensor networks (WSNs), IoT, CPSs, and smart factories, were listed. These technology terms were selected based on their fundamental role in integrating physical and digital systems in contemporary industrial processes. Our emphasis on these terms was derived from the seminal definition of I4.0 by Kagermann et al. [44], as well as Nazarov's definition [33], which highlight the significance of networking, CPS, and IoT in revolutionizing industries and society, while the specific usage of the term "Wireless Sensor Network" is attributed to its foundational role in any Industrial IoT system [45]. This enabled us to establish a query string that consists of the fundamental components of I4.0, which in turn support the implementation of all other related technologies, such as AI, Cloud Computing, and Big Data analytics. Before finalizing our search queries, they were validated by academic and industrial experts from the PLANET4 project. Each technology-related term was queried using the logic operator "OR" due to the high possibility of these technologies' presence in the articles compared to more uncertain business categories. To this end, a data extraction pipeline was created. Different terms from the technology and business dictionary were combined to compose the query and extract the results from scientific databases. The list of the employed query strings is presented in Tab. 2.

The total number of academic articles exported from the search was 2823. However, before using the studies in the review, they were critically appraised for quality and risk of bias. Consequently, the PRISMA (Preferred Reporting Items around Systematic Reviews and Meta-Analyzes) framework was utilized [46]. PRISMA offers a structured methodology based on formulated inclusion and exclusion criteria to systematically assess the quality of the chosen papers, determining their suitability for inclusion or exclusion. The PRISMA flowchart is based on four stages:

- **Identification:** Identify the papers based on search strategies.
- **Screening:** Use the inclusion or exclusion criteria and the quality checklist to exclude irrelevant papers.
- **Eligibility:** Prioritize using the quality checklist to find the papers' eligibility.
- **Included:** Review the papers critically to address the aim of the current study.

During this process (Fig. 2), duplicate articles were initially removed from the dataset, as well as non-English writings. Subsequently, the eligibility of the selected papers was checked based on the quality checklist items and exclusion criteria: a) date of publication, b) availability of the abstract, c) access to the full text, d) relevancy with the predefined scope, e) possibility of applying the proposed technological solutions to real industrial challenges/needs, and f) comprehensive analysis of the results. Of particular significance is criterion (e), which is central to the objectives and scope of our research. This criterion underscores the necessity of selecting academic sources that not only recognize industrial challenges but also propose feasible, actionable solutions. The emphasis on practical applicability aligns with our commitment to bridge the gap between academic insights and industrial implementation.

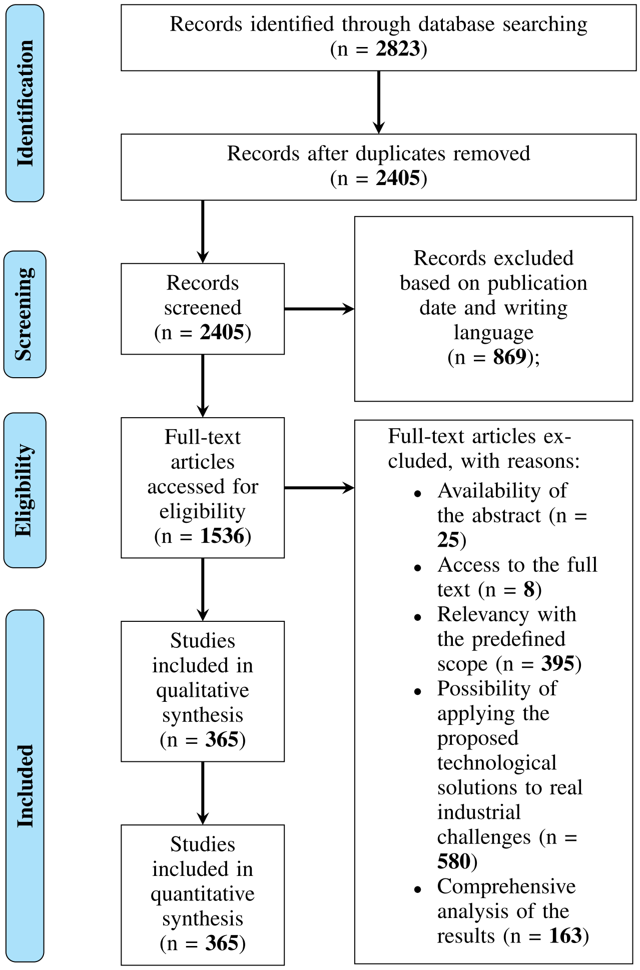


FIGURE 2. PRISMA flow diagram of academic literature selection.

Following this selection process, a total of 365 academic articles were identified and deemed suitable for inclusion in our study. Our analysis revealed that the journals *Computers and Industrial Engineering* and the *Journal of Intelligent Manufacturing* are frequently cited in this context. Other notable scientific journals with high citation rates include *IEEE Transactions on Industrial Informatics*, *Computers in Industry*, the *International Journal of Advanced Manufacturing Technology*, and *Procedia CIRP*.

Regarding collecting and evaluating GL, the guidelines provided by Garousi et al. [47] were followed. Given that GL is not usually indexed in conventional academic databases, we utilized Google's general web search engine for data collection. To ensure comprehensive and accurate results, two distinct query strings were employed: one focusing on industrial challenges/needs and the other on enabling I4.0 technologies (Tab. 2). These query strings were formed based on a preliminary search that identified various

TABLE 2. Search queries for academic and grey literature via academic databases and Google.

Query/Queries	Search Engine(s)	Results
Academic Literature:		
(“*Internet of Things*” **OR** “*IoT*” **OR** “*Smart Factory*” **OR** “*Industry 4.0*” **OR** “*Cyber Physical System*” **OR** “*Wireless Sensor Network*”) **AND** ("*Change Management*" **OR** "*Digital Management*" **OR** "*Innovation Management*" **OR** "*Technological Management*")	Scopus	209
	SpringerLink	1241
	IEEE Xplore	488
	Science Direct	22
	ResearchGate	863
Grey Literature:		
“*Industrial*” **AND** (“*Problems*” **OR** “*Needs*” **OR** “*Issues*” **OR** “*Challenges*”)	Google	107
(“*Industry 4.0*” **OR** “*Smart Manufacturing*” **OR** “*Smart Industry*”) **AND** (“*Solutions*” **OR** “*Technologies*” **OR** “*Examples*” **OR** “*Usecases*” **OR** “*Projects*” **OR** “*Products*” **OR** “*Case studies*” **OR** “*News*”)		126

synonyms and related terms for each domain to include all relevant information.

The employed queries resulted in a very high number of results: over a billion for the first query and over 40 million for the second query. To manage this, we decided to limit our primary review to the first 50 pages, equating to 1000 results. During this phase, we conducted searches in the incognito mode to prevent personalized results and to ensure we obtained more generalized results applicable to anyone conducting the search. We also meticulously filtered out sponsored content and academic literature to maintain objectivity and avoid overlapping with previously collected scientific data. Finally, each title from this subset of results was carefully evaluated for its relevance to our study, with unrelated materials, such as commercial or multimedia content, being discarded.

The depth of our analysis within this confined dataset enabled us to reach a point of ‘theoretical saturation’. In other words, through a detailed and exhaustive examination of these 1000 results, we found that additional searching within this set did not contribute further new insights or concepts, suggesting that we had effectively captured the breadth of relevant GL within this scope. As a result, we concluded our search with a comprehensive understanding of the field, identifying 233 sources most pertinent to our research objectives. To assess the quality and relevance of these sources, we employed the ‘AACODS’ checklist proposed by Tyndall [48], as they typically undergo little or no review before publication. This checklist serves as a well-developed evaluation tool for assessing the quality of grey information based on specific eligibility criteria:

- **Authority:** Who is responsible for the intellectual content?
- **Accuracy:** Is it representative of work in the field?
- **Coverage:** Are any limits clearly stated?
- **Objectivity:** Is there any bias?
- **Date:** Have key contemporary material been included?
- **Significance:** Is the source meaningful?

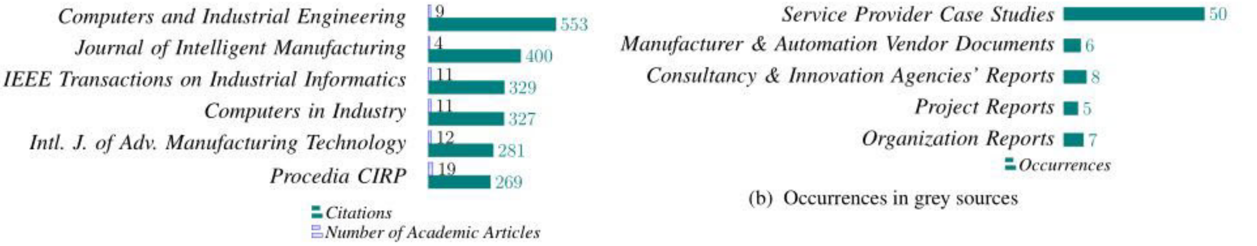
The evaluation process consisted of six stages. The first stage involved examining the accessibility of the collected grey sources, whereby one source was excluded. Next, all sources whose authors lacked expertise in the field of I4.0, such as nonprofit organizations and media, among others, were excluded. The focus then shifted to sources that specifically addressed particular technologies or industrial challenges. The depth and breadth of information provided by these sources were critically assessed, leading to the exclusion of those that offered only superficial insights. Finally, each source’s “**Practical Applicability**” was a crucial criterion, as the sources needed to be relevant to targeted problem-solving and provide practical solutions for industrial challenges. Fig. 4 summarizes the number of grey sources excluded during each process stage. Ultimately, 76 distinct sources were selected for analysis, including manufacturer and automation vendor documents, service provider case studies, consultancy reports, innovation agencies’ material, project reports, articles from accounting and business advisory firms, and whitepapers written by relevant organizations such as the European Union’s EIT Manufacturing.

Fig. 3 provides a comprehensive overview of the findings from both the academic and grey literature analyses. This figure presents a range of statistics that shed light on various aspects of the industrial challenges and I4.0 enabling technologies. Key insights highlighted include:

- The most frequently cited articles
- The industrial needs that are most commonly discussed.
- Industrial problems that currently have the fewest technological solutions.
- The technologies that are most frequently mentioned as enabling solutions.
- The technologies that are most commonly implemented, including combinations of multiple technologies.

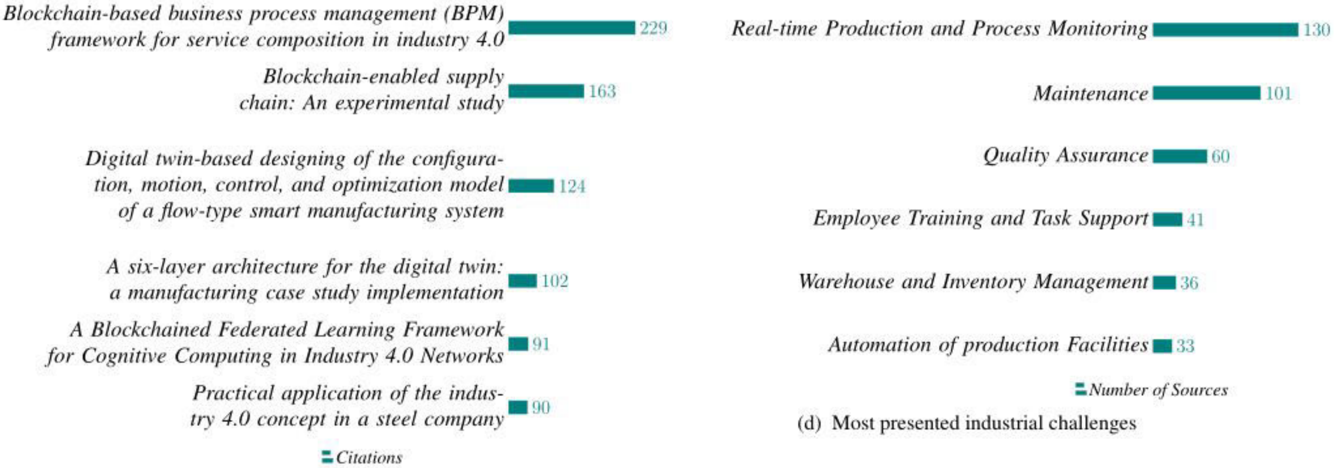
B. THEORETICAL FRAMEWORK OF TAXONOMIES AND THEIR INTEROPERABILITY

Once the literature to be studied was determined through the MLR process, described in Sec. II-A, the challenges/needs faced by the manufacturing industry and their technological solutions were extracted by reading each source. Subsequently, the identified business challenges/needs and technologies were organized in a taxonomic hierarchy created from intuitive and generic logic and in-depth analysis of articles, surveys, business reviews, technical reports, case studies, and whitepapers with the same objective [49], [50].



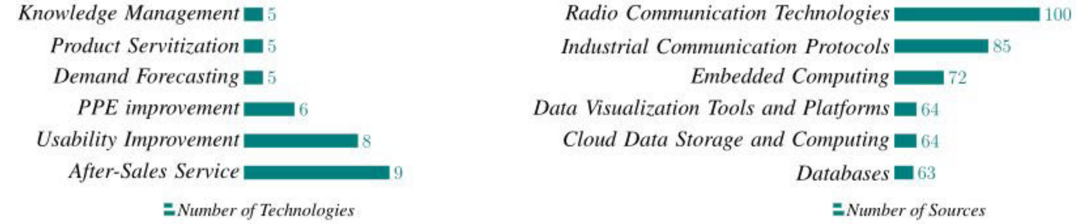
(a) Most cited academic journals and conferences

(b) Occurrences in grey sources



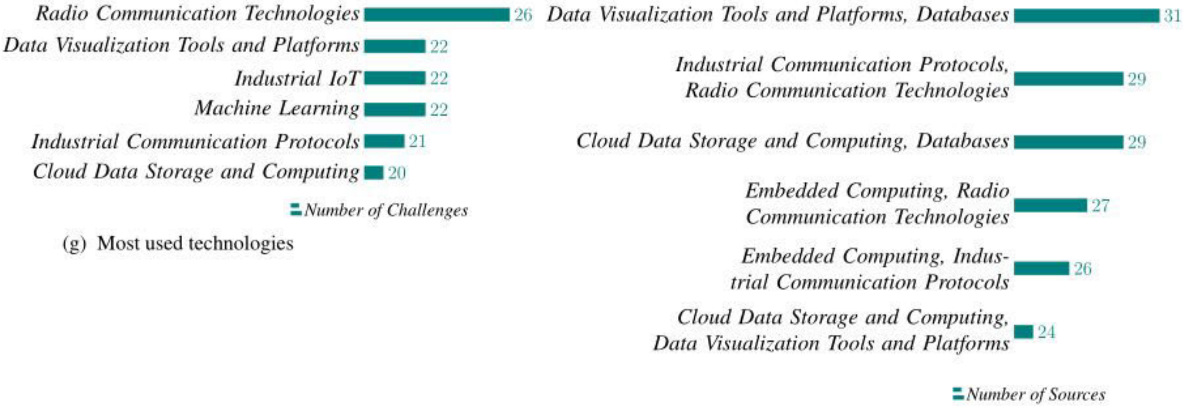
(c) Most cited articles

(d) Most presented industrial challenges



(e) Industrial challenges with the fewest technological solutions

(f) Most presented technologies



(g) Most used technologies

(h) Most used combinations of technologies

FIGURE 3. Fragment of derived statistics during taxonomy development.

The term taxonomy can be described as a scheme for the classification of concepts to represent their relationships. Usually, a taxonomy defines only a narrow set of relationships (parent-child or hierarchical). However, in Information Architecture, the term is often used to describe a general form of "organizing concepts of knowledge"

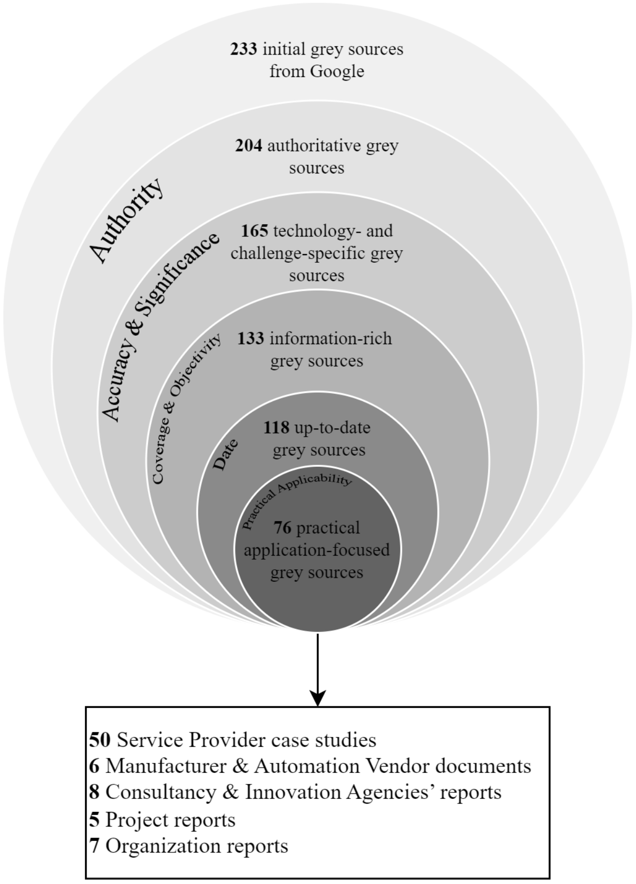


FIGURE 4. Output of the grey literature review.

[51]. Indeed, a broader definition of taxonomy defines it as a logical structure that gives meaning to what is being presented [52] or "as a knowledge organization system or knowledge organization structure" [51]. Here "taxonomy" will be used in the narrower sense of the term, distinguishing it from thesauruses and ontologies (in which there are more relationship types).

Each taxonomy element is defined by its concept, i.e., the idea or the thing identified, and one or more terms (synonyms), i.e., the label that describes the concept. Usually, only one preferred term will designate a concept. As already mentioned, a taxonomy presents a hierarchical structure that categorizes elements of the same domain in a subsumptive manner, i.e., a concept of a higher-order level will be broader and more generic, and a concept of a lower level will be narrower and more specific [53].

As previously anticipated, other classification schemes have more typologies for the relationship between their concepts, thesauruses, and ontologies. Unlike taxonomies, thesauruses are controlled vocabularies "arranged in a known order and structured so that the various relationships among terms are displayed clearly and identified by standardized relationship indicators" [53], i.e., providing three types of standard relationships (hierarchical, associative, and equivalence). Finally, ontologies provide non-standard, domain-specific relationships defined by ontology creators [51].

For the purpose and scope of this research, we preferred to use a simpler version of the knowledge organization structure: taxonomy. This choice was led by the goal of classifying the main concepts concerning the challenges/needs and technologies of I4.0 in a tree structure by employing only the most used terms that usually identify these concepts in academia and the business world.

Given the twofold scope of this taxonomy, two separate structures would describe the domains of the challenges/needs and technologies related to I4.0. Therefore, it is necessary to investigate how these two structures, which precisely identify the two different taxonomies, could become interoperable. Hedden explains that combining two or more taxonomies is feasible by utilizing 3 possible procedures [51]: Integration, Merging and Mapping.

Merging refers to the action of combining two or more taxonomies into a single one, focusing on the equivalence relationship between their concepts (thus making the original structures disappear). Mapping refers to linking taxonomic concepts with each other (i.e., establishing a semantic correspondence between them) and maintaining the original structures. Integration permits the combination of additional taxonomies into a new master taxonomy. As the two taxonomies about I4.0 business challenges/needs and enabling technologies had to be linked but remained distinct in their structures, we first excluded the merging procedure. However, integrating the taxonomies would have led to the encapsulation of one taxonomy into the other, for example, adding it as a new branch. Finally, mapping was not possible because there was no exact match between the concepts (e.g., PPE Improvement is not a synonym for IoT, and vice versa).

Nevertheless, mapping is only a specific type of link, which, in its broadest sense, appears to be the type of link that insists on the concepts of the two taxonomies in general. In this work, the studied articles and documents were considered to establish the connection between two or more concepts belonging to the two taxonomies. This (associative) relationship allows bidirectional linking between their concepts.

C. METHODOLOGY FOR THE TAXONOMY DEVELOPMENT

Following the existing design standards for taxonomy building [53] as guidelines for this work, we also incorporated some of the methodologies from the field of Information Systems, such as that presented by Nickerson et al. [54] and the updated version by Kundisch et al. [55]. More precisely, we considered the principles from the Information Architecture field as the general philosophy and structure for taxonomy building and presentation. In contrast, Information Systems have inspired us in the taxonomy development process. This allowed us to determine a precise methodology for developing the taxonomy, building it as a controlled vocabulary of terms.

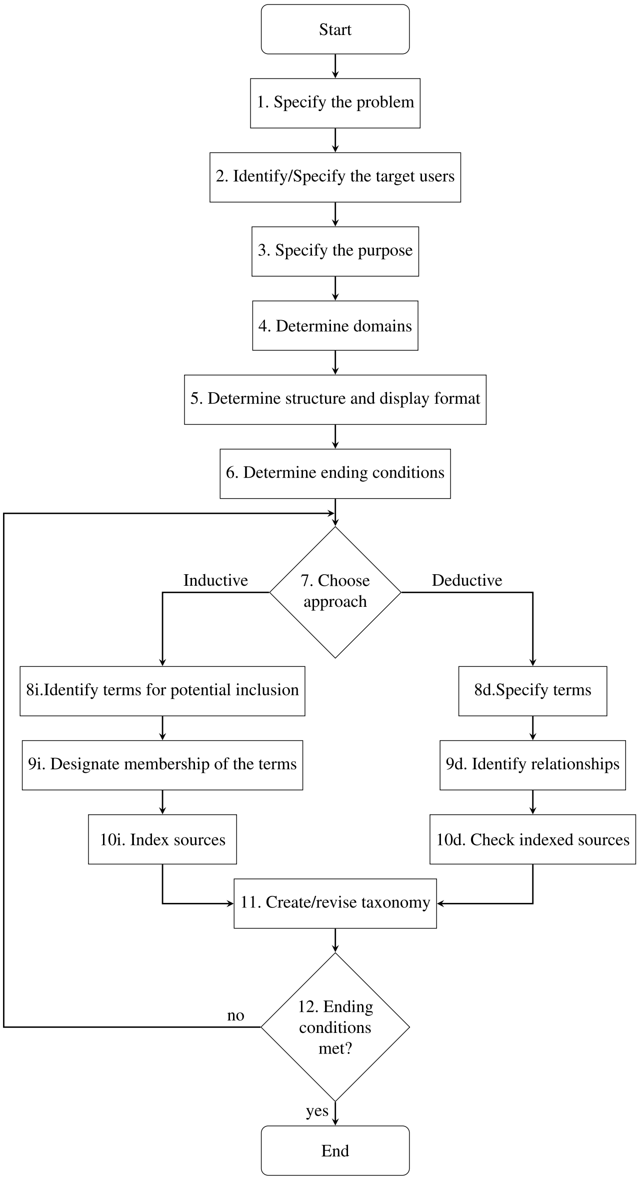


FIGURE 5. **Taxonomy development methodology.**

Fig. 5 illustrates the process adopted in the development of the taxonomy. The first three steps help in identifying ''why'' (''Specify the problem''), what the intention is (''Specify the purpose''), and for whom this new taxonomy is intended (''Identify/Specify the target users''). These steps have been addressed in the Introduction.

The following three steps (4-5-6) help us better understand and identify how the taxonomy is intended to be developed. In our two-fold taxonomy, two domains are determined instead of only one. This poses a problem for the object we have developed: one or two taxonomies. As already argued previously, from a purely theoretical perspective, having two separate domains with their respective structures, we consider them as two separate taxonomies. Nevertheless, the purpose of viewing the two domains together and the process brought us to develop the taxonomies jointly and consider them as a single integrated taxonomy for I4.0 solutions. The two domains are industrial needs and I4.0-enabling technologies (i.e., the technologies that constitute the foundations of I4.0 solutions).

As for the structure and display format, given the intention to build a hierarchy and make explicit primarily by using the term taxonomy in a narrow sense, the choice fell on a tree structure. The ending conditions provide a means of understanding when the taxonomy construction process can be declared complete or reiterated. Similar to the rest of the methodology, the adopted ending requirements were inspired by the criteria indicated by Nickerson et al. [54] and ANSI/NISO standards [53]. The final criteria were as follows:

- The terms must be consistent with the domain and the structure (e.g., ensure that there are no duplicates, wrong hierarchical relationships, etc.).
- The terms must be clear and validated according to reference texts, technical dictionaries, expert advice or common usage.
- No term must be without source/s or children.
- All the sources identified must be associated (indexed) with one or more terms.
- The terms must have definitions.
- No new terms or sources were added in the last iteration (a new term requires old sources to be checked for possible matchings, a new source could identify new terms).

The following steps (7-12) were used as the iterative part of the methodology. The work of Nickerson et al. and the ANSI/NISO standards refer to two possible courses of action: the deductive (or conceptual-to-empirical) approach and the inductive (or empirical-to-conceptual) approach. Although the two methodologies differ in some of their details, that is, in Nickerson, the deductive process does not contemplate the examination of the objects (the literature in our case), while the ANSI/NISO standards are the first step, they could be integrated as needed. For example, in the first iteration of the taxonomy, we followed a deductive approach, as indicated by ANSI/NISO standards, beginning with the extraction of terms with the assistance of topic modelling algorithms. Afterwards, we first classified those terms, starting from the broader concepts to the narrower (top-down approach), based on their use in the sources, common usage in their fields, and expert advice. Regarding the industrial challenges were initially classified following Kinkel et al. [56], while the I4.0 enabling technologies using the European Commission Report for I4.0 technologies [57].

The inductive approach involves adding new relevant terms encountered in the examined literature, first identifying the narrower concepts and then finding the broader ones (bottom-up approach). As stated in the ending conditions, each analyzed source must be associated or, more appropriately, indexed under at least one term to achieve the goal of a taxonomy based on real-world, data-powered, and proven applications. Because the inductive approach is based only on the analysis of objects (the literature), indexing the sources was mainly included in this procedure branch. During this process, the following issue appeared: regarding GL, due to its heterogeneous nature, many sources deal with many topics (i.e., solving various industrial challenges with disparate technologies), presenting them in the same writing. Therefore, the above sources were indexed multiple times (with different reference numbers), each corresponding to one challenge with the related technologies used to solve it. However, when iterating on terms with the deductive approach, it is also necessary to review references that are already indexed.

Moving back and forth between deductive and inductive approaches also affects the taxonomy's final granularity, namely the number of subcategories within each primary category. This implies that when using a deductive approach (such as extracting knowledge from reference texts or experts) to describe a category with high granularity, it is necessary to justify this level of detail in the inductive approach by comparing it with the literature retrieved. Therefore, while acknowledging that some terms may have narrower terms (subcategories), these were omitted from the taxonomy if they were inconsistent with the literature surveyed and, thus, did not align with the practical purpose of this research.

Finally, after each iteration, the final conditions are tested to verify the development status. A new iteration is required if it does not meet the criteria; otherwise, the process is considered to end.

III. RESULTS

This section presents the two taxonomies developed for the study and the bidirectional linking between their concepts. Section III-A provides an overview of the identified industrial challenges and needs, while Section III-B examines the Industry 4.0 technologies that have been identified. Fig. 6 illustrates the conceptual diagram of the two linked taxonomies, emphasizing that they are components of a unified framework rather than separate entities. Due to the granularity of the I4.0 technologies taxonomy, only the first three levels are included here. The full taxonomies, complete with definitions and bibliographic sources linking the terms, can be accessed online at https://github.com/HumanCenteredTechnology/api_search_engine/tree/master/data/PDF_versions. Additionally, this section details a web platform created to assist in the adoption of the proposed taxonomies and concludes with two case studies that demonstrate their practical application.

A. OVERVIEW OF THE INDUSTRIAL CHALLENGES

During the implementation of **Step 1**, we propose grouping industrial challenges. According to Kinkel et al., innovation activities in the manufacturing industry are distinguished as process and product innovation, comprising both technological and organizational innovations [56]. Therefore, industrial challenges/needs are divided into two main categories: **Process Optimization** and **Product Innovation**. The identified subcategories of the former category are as follows:

- *Equipment and Process Efficiency Improvement*: Concerns activities related to manufacturing ecosystem connectivity for alerting, running data analytics processes, and all maintenance processes that ensure continuous readiness and operation of industrial equipment without unplanned disruptions. It also concerns the need to shorten the processing time, efficiently allocate equipment and human resources, make informed decisions about tasks, and implement initiatives for employing industrial units that work independently without human intervention, legacy system modernization and retrofitting, and commissioning processes.
- *Worker Security Improvement and Accident Prevention*: Needs for preserving the safety of employees and, more generally, creating a safe workplace.
- *Supply Chain Improvement*: The need to improve and update the supply chain to cope with the increasing complexity and interconnectedness of modern manufacturing processes as well as the growing demand for real-time data and agility. This enables effective adaptation to dynamic market conditions and the optimization of operations.
- *Mass Customization*: The need to produce personalized products that meet the needs of specific customers at lower costs while still involving mass production volumes.
- *Quality Assurance*: Preventing the production of non-compliant or defective products to ensure that products meet or exceed industry standards and customer expectations.
- *Sustainable Industrial Practices*: The need for efficient and responsible use of resources in manufacturing to reduce waste and minimize negative impacts on the environment.
- *Employee Training and Task Support*: It refers to providing employees with adequate training and support to perform their industrial duties efficiently and effectively. It aims to improve the training of employees and assist them in industrial tasks, including manual assembly, inspection and maintenance activities, and order picking.
- *Knowledge management*: The manufacturing companies' needs on the acquisition, organization, and automatic retrieval of information from different content resources, such as technical documentation, videos, images, schematics, audio, web pages and much more, in the different phases of installation, servicing, break/fix, and parts knowledge

On the other hand, the latter category has the following subcategories:

- *Product Servitization*: The necessity to innovate a company's capabilities and processes to enhance the creation of mutual value by transitioning from selling

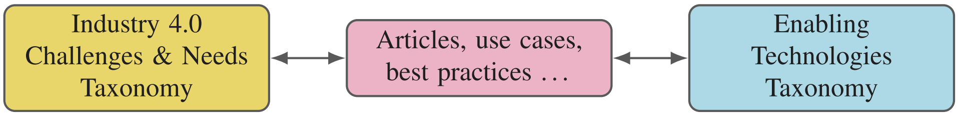


FIGURE 6. Conceptual diagram of the two linked taxonomies.

products to offering product-service systems that cater to a broader spectrum of customer requirements.

- *Usability Improvement*: The need to improve the user experience and facilitate the completion of tasks with effectiveness, efficiency, and satisfaction while using the manufactured product.
- *Smart products*: It refers to the need for disruptive initiatives aimed at building a new generation of digital, connected, intelligent, and responsive products.
- *Components Reduction and Cost Optimization*: The need to optimize the product bill of materials (BOM), thereby reducing product and production management costs.
- *After-Sales Service*: The need to improve all services that bind the customer to the production company after selling the product (e.g., complaint management, warranty, field technical assistance responsible for installation, check-ups, out-of-warranty repairs and product disposal, usage monitoring, user analytics and profiling, automatic consumables reorder).

The needs/challenges of the manufacturing industry classified according to the above categories are illustrated in Fig. 7.

B. OVERVIEW OF THE ENABLING TECHNOLOGIES

Following the procedure presented in Sec. II-B, the **Step 2** was completed. The most significant difficulty did not appear in the technology identification but their cataloging and organizing so that they can be navigated and explored intuitively for educational purposes. The research results and the categorization of the technological solutions are shown in Tab. 3. Precisely, nine groups of technologies were identified:

- *Big Data*: Technologies related to acquiring large amounts of data from various sources, their ongoing analysis, evaluation, storage, retrieval and visualization.
- *Artificial Intelligence (AI)*: Methods for building computerized systems that reason, learn from historical data, and act intelligently with little or no human intervention.
- *Cloud Computing*: The offering of computing services over the Internet (“the cloud”), including servers, storage, databases, networking, software, analytics, and intelligence, to provide rapid innovation, more flexible resources, and economies of scale.
- *IoT and IoE*: IoT is an interconnection of various smart devices that interact with each other and the external environment via the internet. In contrast, Internet of Everything (IoE) extends IoT, emphasizes machine-to-machine communication, and describes a more complex system that includes people and their processes.
- *Digital Twins*: The virtualization of a physical object or process to analyze and simulate its behavioral model.
- *Industrial Robotics*: The technologies that allow the robot to be prepared to perform production tasks and then run smoothly.
- *Augmented Reality (AR) and Virtual Reality (VR)*: Technologies that work with the simulation and augmentation of the real environment.
- *Additive manufacturing*: The technique of constructing a 3D object one layer - by - layer.
- *Cybersecurity Technologies*: Technologies to defend against cyber attacks on systems, networks, programs, devices, and data.

Tab. 3 shows the I4.0 enabling technologies grouped into specific categories that underpin the industrial needs. The whole taxonomy, the studied literature and the definitions of all terms are given in [58].

C. TAXONOMY WEB PLATFORM

To turn the developing taxonomy into a valuable tool for academia and industry, a web platform called “Planet4 Taxonomy Explorer” was developed. This platform offers a comprehensive and user-friendly interface for intended users to explore the taxonomy and access its associated references, ultimately facilitating the communication of I4.0 concepts between academia and industry. Users can access the platform through the provided link (http://taxonomy.planet4project.eu/) and are greeted with a search bar and tree-view representation of the taxonomy structure (Fig. 9a). Through this bar, users can enter keywords or phrases related to specific industrial challenges or technological solutions, such as “Maintenance” or “Deep Learning.” The platform utilizing a TagMe API-powered search engine [59] understands the user’s query input by searching for related references in an extensive Wikipedia database. It subsequently compares these references to the I4.0 taxonomy to identify matches. The I4.0 taxonomy is stored in a SQLite database comprising three tables. One table contains the complete taxonomy of industrial challenges and enabling technologies. Another table displays the connections between the taxonomy’s terms, the articles, and their corresponding indexation within the taxonomy. The third table compiles articles and their key details, including title, author/s, and publication date. These functionalities have been incorporated into the platform’s backend, developed using Flask, a Python web framework. In addition, the back end has API endpoints that allow for easy and seamless communication with the front end for AJAX requests.

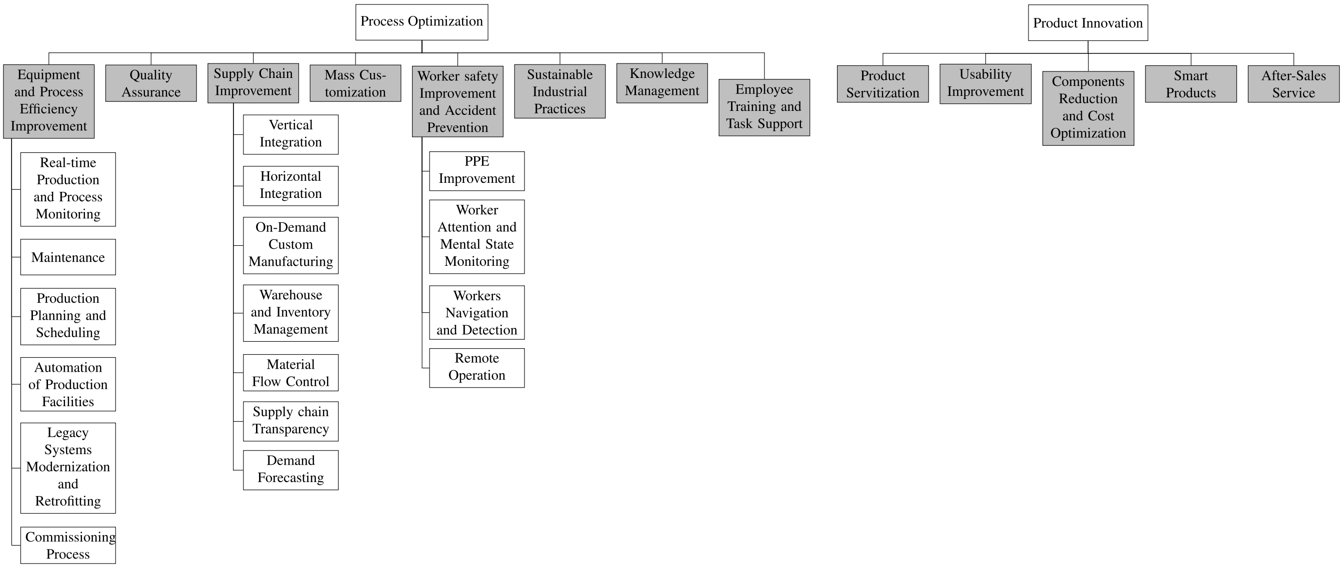


FIGURE 7. Identified industrial needs and challenges.

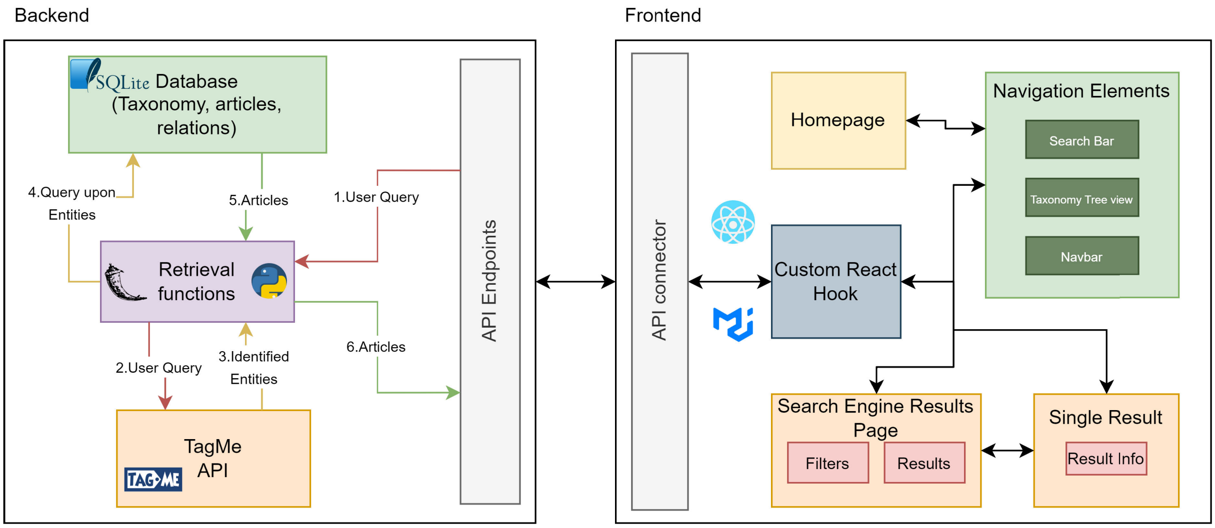
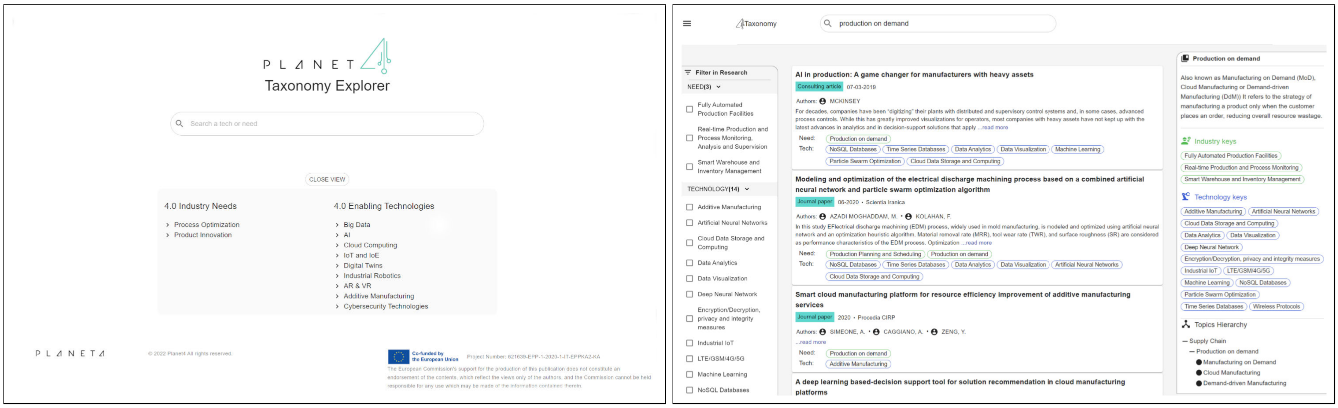


FIGURE 8. Architecture of the web platform of the taxonomy.

Finally, the retrieved information, including academic and grey sources associated with fundamental terms from the taxonomy, is then presented on a dedicated page (Fig. 9b). On this page, each source is presented with its associated taxonomic terms displayed as keywords, allowing users to quickly identify and filter significant articles based on specific challenges, needs, or technologies identified in the taxonomy. The web platform also offers additional filtering options to further refine the search results, enabling users to explore and find solutions or deepen their knowledge in a targeted manner. The user interface of the web platform was developed using frameworks and libraries such as React and MUI. The architecture of the backend and frontend of the taxonomy web platform is displayed in figure 8. The search engine and taxonomy database are available in the GitHub repository [58], which ensures the transparency and accessibility of the underlying technology and data.

D. TAXONOMY APPLICATION IN PROBLEM-SOLVING

To solve industrial challenges/needs or identify real-world industrial scenarios for I4.0 enabling technologies using the developed taxonomy, users can search the website platform by inputting sentences that best reflect their queries (business challenges or technologies). This will lead them to relevant publications that address similar problems and mention the necessary technologies. Information about the technologies needed can help assess whether the company has the necessary resources to solve the problem on its own,



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AI in production: A game changer for manufacturers with heavy assets

Consulting article 07-03-2019

Authors: MCKINSEY

For decades, companies have been "digitizing" their plants with distributed and supervisory control systems and, in some cases, advanced process controls. While this has greatly improved visualizations for operators, most companies with heavy assets have not kept up with the latest advances in analytics and in decision-support solutions that apply ...read more

Need: Production on demand

Tech: NoSQL Databases, Time Series Databases, Data Analytics, Data Visualization, Machine Learning, Particle Swarm Optimization, Cloud Data Storage and Computing

Modeling and optimization of the electrical discharge machining process based on a combined artificial neural network and particle swarm optimization algorithm

Journal paper 06-2020 • Scientia Iranica

Authors: AZADI MOGHADDAM, M. • KOLAHAN, F.

In this study EFlectrical discharge machining (EDM) process, widely used in mold manufacturing, is modeled and optimized using artificial neural network and an optimization heuristic algorithm. Material removal rate (MRR), tool wear rate (TWR), and surface roughness (SR) are considered as performance characteristics of the EDM process. Optimization ...read more

Need: Production Planning and Scheduling, Production on demand

Tech: NoSQL Databases, Time Series Databases, Data Analytics, Data Visualization, Artificial Neural Networks, Cloud Data Storage and Computing

Smart cloud manufacturing platform for resource efficiency improvement of additive manufacturing services

Journal paper 2020 • Procedia CIRP

Authors: SIMEONE, A. • CAGGIANO, A. • ZENG, Y.

...read more

Need: Production on demand

Tech: Additive Manufacturing

A deep learning based-decision support tool for solution recommendation in cloud manufacturing platforms

Production on demand

Also known as Manufacturing on Demand (MoD), Cloud Manufacturing or Demand-driven Manufacturing (DdM)) It refers to the strategy of manufacturing a product only when the customer places an order, reducing overall resource wastage.

Industry keys: Fully Automated Production Facilities, Real-time Production and Process Monitoring, Smart Warehouse and Inventory Management

Technology keys: Additive Manufacturing, Artificial Neural Networks, Cloud Data Storage and Computing, Data Analytics, Data Visualization, Deep Neural Network, Encryption/Decryption, privacy and integrity measures, Industrial IoT, LTE/GSM/4G/5G, Machine Learning, NoSQL Databases, Particle Swarm Optimization, Time Series Databases, Wireless Protocols

Topics Hierarchy

- Supply Chain
  - Production on demand
    - Manufacturing on Demand
    - Cloud Manufacturing
    - Demand-driven Manufacturing

(a) Homepage (b) Search Engine Results Page

FIGURE 9. Interface presentation of the taxonomy web platform.

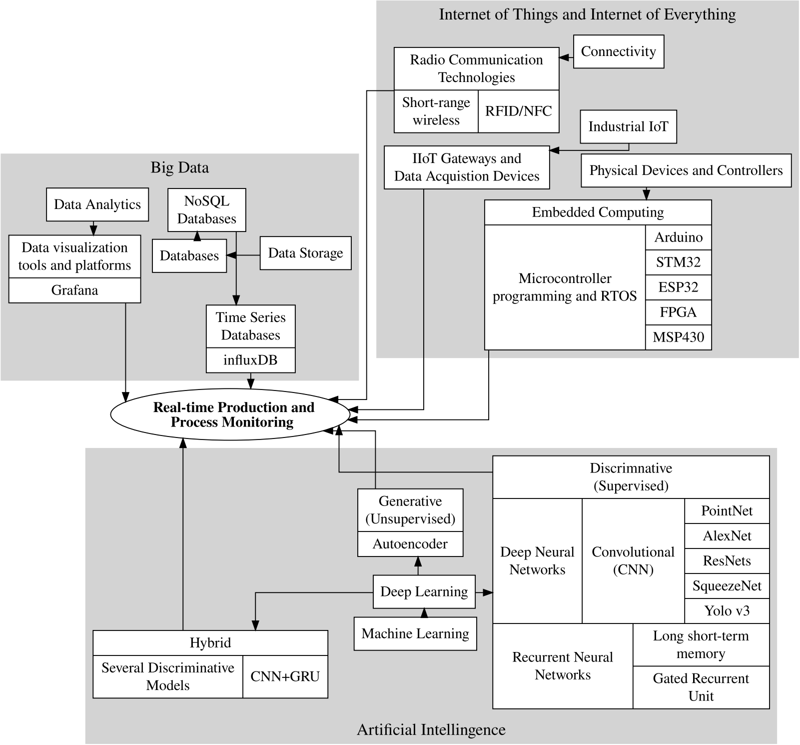

FIGURE 10. Fragment of the taxonomy with the solution of the production flow monitoring challenge.

whether external help is required, and to what extent. If the company has the appropriate epistemological background but inadequate experience, company specialists can study the indicated publications, which may help them solve problems independently.

The first example of applying taxonomy presents a problem with production flow monitoring. The challenge was identified by a furniture manufacturer operating in Poland that produces furniture fronts and complete furniture systems and supplies its products to the Polish, Czech, Slovak, and Ukrainian markets. The company wanted to monitor a) the production flow of all types of furniture fronts, b) the order status, c) the location of each production batch, and d) the time remaining until the end of production of a given batch.

Analyzing the challenge description and the industrial challenges and needs classified in the taxonomy, it follows that the challenge matches the subcategory "Real-time Production and Process Monitoring". During the review of the sources indicated by the taxonomy for solving this problem, 12 publications related to RFID tags and readers were identified. In turn, 12 sources stated the possibility of using RTOS in the discussed problem. Five publications

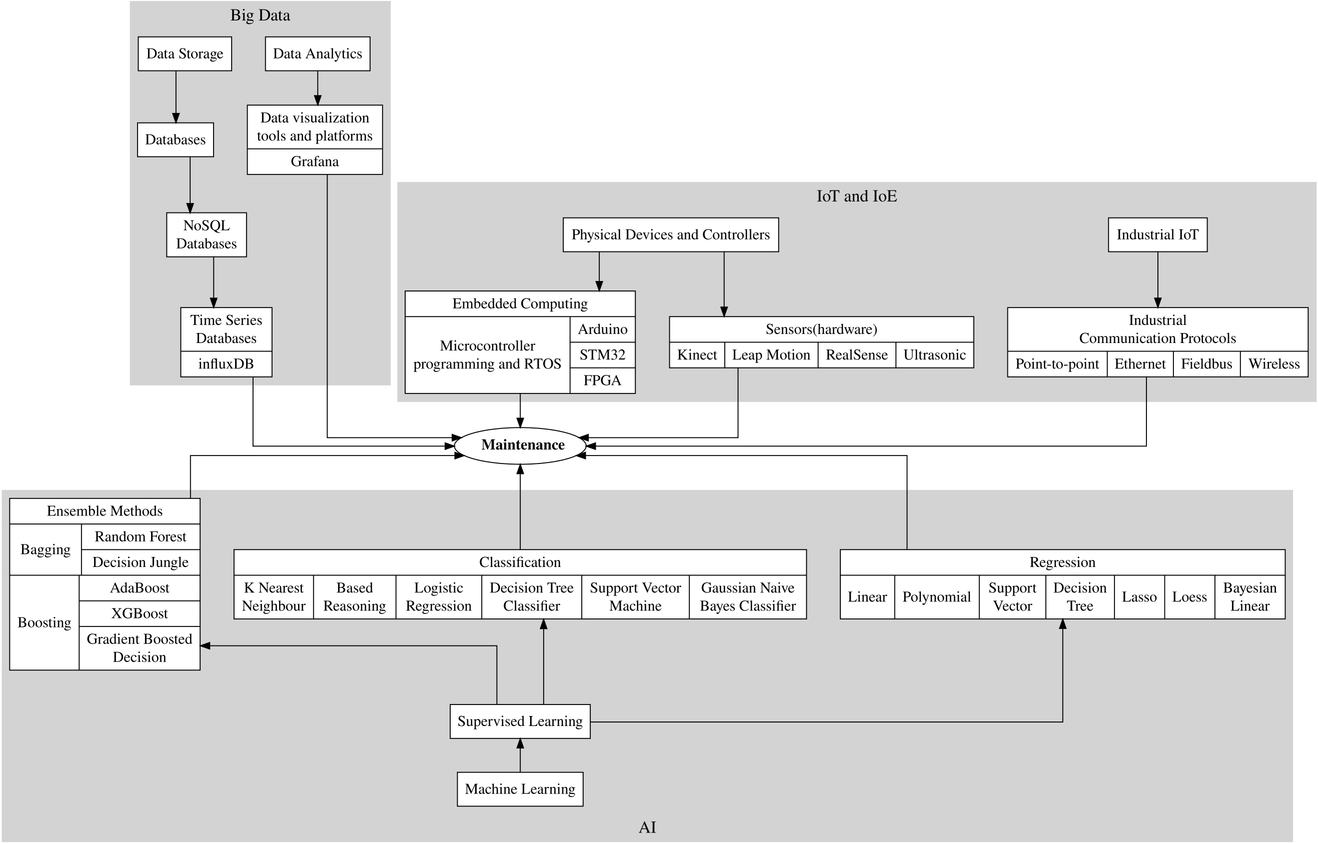

FIGURE 11. Fragment of the taxonomy with the solution of the predictive maintenance challenge.

indicated the need for Time Series Databases. At the same time, 40 studies proposed Machine Learning methods to predict the remaining time to complete a production order. Deep Learning techniques are the most widely used in such problems (13 sources), followed by Supervised Learning techniques (10 sources). The last element of the challenge solution proposal is Grafana, which is indicated by two sources. Therefore, the following solution is proposed as the starting point:

- Edge device:
  - Attach RFID tags to containers or products for capturing information about their status and location. RFID readers should be located at the indicated points in the process.
  - Use the real-time operating system (RTOS) to maintain batch location information and enable real-time alert systems during delays.
- Cloud service that:
  - Uses the Time Series Database (TSDB) to store the incoming data.
  - Runs Deep Learning models that predict the time remaining to complete a production order.
  - Sends this data to the Grafana engine to visualize the data in dashboards for the end-user.

Fig. 10 presents a fragment of the taxonomy that includes the described proposal to solve the problem of production flow monitoring.

The second example considered a problem related to predictive maintenance. This challenge was proposed by a Polish company, which is a pioneer in the production of fasteners. The company would like to implement a system that prevents machine failures and minimizes the number and duration of failures. The company has 60 modern presses that are monitored during production to ensure process stability.

Analyzing the challenge description and the industrial challenge and needs classified in the taxonomy, it follows that the challenge matches the subcategory Maintenance (Fig. 7). The taxonomy exploration revealed 16 publications that used sensors and Industrial Communication Protocols for Predictive Maintenance. Of the above, 10 publications concerned Microcontroller programming and RTOS employment, while Time Series Databases were recommended in 13 publications. At the same time, 67 sources present Machine Learning approaches for such tasks. Supervised Learning is the most widespread Machine Learning task, with 18 references, followed by Deep Learning, with 11 references. Finally, two sources indicate the need to use Grafana in this problem. Hence, the following solution is proposed as the starting point:

TABLE 3. List of I4.0 enabling technologies.

Big Data	**Artificial Intelligence**	**Cloud Computing**
• Big Data Frameworks • Data Sources/Ingestion – Streaming and Messaging – Orchestration and Pipelines – Query/Data Flow • Data Storage – Databases – Data Warehouses • Data Analytics – Unified Data Analytics Engines – Unified stream-processing and batch-processing frameworks – Business Intelligence (BI) Tools – Data Visualization Tools and Platforms – Logging and Monitoring – Spreadsheet Applications – Data Mining – Process Mining	• Machine Learning – Supervised Learning – Unsupervised Learning – Deep Learning – Transfer Learning – Reinforcement Learning – Deep Reinforcement Learning – Semi-Supervised Learning – Federated learning • Computer Vision • Natural Language Processing, Natural Language Generation • Intelligent Agents and Multiagent Systems • Soft Computing – Fuzzy Set Theory – Neurocomputing – Optimization Techniques – Probabilistic Reasoning	• Infrastructure as a Service (IaaS) – Cloud Data Storage and Computing • Platform as a Service (PaaS) – Device Management – Operating System • Software as a Service (SaaS) – Media Streaming Software Platforms – Website Building – IoT Analytics Software and Platforms • Infrastructure as Code (IaC) – Provisioning Tools • Container Technology (Container as a Service) – Containerization Platform – Container Orchestration • Serverless Programming • Edge Computing • Fog Computing
IoT and IoE	**Digital Twins**	**Industrial Robotics**
• Industrial IoT – Industrial Communication Protocols – Industrial (IoT) Gateways and Data Acquisition Devices – Software Data Adapters • Physical Devices and Controllers – Embedded Computing – Sensors (hardware) • Signal Processing • Connectivity – Radio Communication Technologies – Optical Communication Technologies – IoT Messaging Protocols – Application Programming Interfaces and Programming Tools • IoE (Internet of Everything)	• Computer-aided design (CAD) Software • Finite Element Analysis (FEA) Software • Simulation Software • DTs Management and Orchestration Frameworks • Digital Twin Data Modelling • Virtual Process Controllers (VPC)	• Offline Programming and Simulation • Middleware
Augmented Reality (AR) and Virtual Reality (VR)	**Additive Manufacturing**	**Cybersecurity Technologies**
• VR – VR glasses • AR – AR glasses – AR Software Development Kits • AR and VR Software development, Platforms and Technologies	• 3D Printers • 3D Printing Technologies	• Security Virtualization – Virtual Machine Monitor (VMM) • Data Protection – Secure Communication Protocols – Key Management System (KMS) – Public Key Infrastructure (PKI) – Encryption – Tokenization – Blockchain • Identity and Access Management – Protocols – User Management – Authentication – Authorization • Security Operations – Change Management – Threat Detection and Analysis • Foundational Security – Network

- Edge device:
  - Identify sensors already embedded in machines for data extraction, and connect additional sensors where needed. Then, communicate with the machines' control system using industrial communication protocols.
  - Use a real-time operating system (RTOS) to collect and process data on measured parameter values over time and enable real-time alert systems.
- Cloud / Edge service that:
  - Uses the Time Series Database (TSDB) to store the incoming data.
  - Runs Supervised Learning models that predict the possibility of a failure and will indicate the predicted failure location and proposed actions.
  - Sends this data to the Grafana engine to visualize the data in dashboards for the end-user.

Fig. 11 shows a fragment of the taxonomy containing the described proposal to solve the problem of predictive maintenance.

IV. DISCUSSION

The *Planet4 Workshop on Industry 4.0* (https://www.planet4project.eu/2023/05/26/workshop/), held on May 31, 2023, served as a testing ground for the taxonomy developed in this study. Eighteen industry professionals from various sectors, including digital transformation, IT, industrial automation, and manufacturing, used the taxonomy to address real-world industrial challenges, providing an opportunity to assess its effectiveness beyond the theoretical framework.

Participants evaluated the taxonomy through a structured questionnaire assessing aspects such as the workshop's clarity, level of interaction, and overall usefulness for career development. A critical component of this evaluation was the rating of tools provided for analyzing and solving industrial challenges, which reflects the taxonomy's practical value. As Fig. 12 demonstrates, the feedback was highly positive, with the average rating signalling a strong participant satisfaction. This quantitative endorsement is complemented by qualitative data from open-ended responses, suggesting enhancements to the web platform's user interface and a call

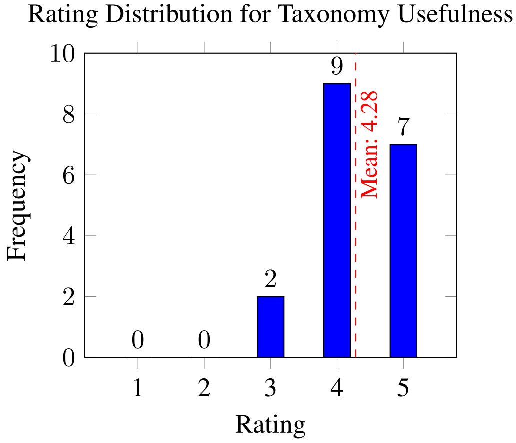

FIGURE 12. **Distribution of scores for the quality of tools provided for analyzing and solving the challenges in Industry 4.0.**

to include more papers in the future to augment taxonomy's usability.

These findings confirm that the taxonomy not only overcomes the limitations identified in existing taxonomies, as discussed in the 'State of the Art & Motivation' subsection, but also establishes a practical link between academic research and industrial challenges/needs. The workshop's feedback highlighted areas for refinement that are vital for the taxonomy's ongoing evolution to align with the dynamic landscape of I4.0. The results of the workshop can be consulted in [58].

V. CONCLUSION

A. GENERAL CONCLUSION

This paper attempts to address the lack of mutual understanding between academia and industry regarding the I4.0 paradigm implementation by developing a taxonomy that links industrial needs/challenges with available technological solutions, following a systematic process based on the analysis of 441 academic and grey sources. Unlike other studies, this work presents a holistic view of I4.0 by considering non-academic sources, while it presents a detailed methodology for developing the proposed taxonomy, ensuring transparency and clarity. Finally, a user-friendly web platform was implemented to enhance the tool's usability, and its application to two real-world use cases was detailed to validate its efficiency. This tool will help academics and industry stakeholders identify the relevant business scenarios in the context of I4.0 and design/deploy their solutions based on the latest technologies and existing works documented in the literature.

B. WORK LIMITATIONS

The developed taxonomy exhibits three phases of subjectivity during its development and use by stakeholders. The full involvement of the human factor in taxonomy development implies that (phase 1) the taxonomic classification and conceptualization of needs and technologies and (phase 2) the manual attribution of each bibliographic source was at the authors' discretion. Therefore, it is understandable that there were difficulties in finalizing the taxonomy, particularly regarding industrial needs. A representative example was articles dealing with monitoring industrial equipment's condition, which some consider belonging to the "Real-time Production and Process Monitoring" category, while others felt it belongs to the "Maintenance" category. In the next phase (phase 3), companies that pilot used the taxonomy assigned the same challenge to different taxonomy concepts because of the different approaches. For example, industries that wanted to estimate the maintenance time of a failed industrial equipment either chose "Maintenance" as the concept that best reflects their problem or "Production Planning and Scheduling". To deal with the difficulty of the subjective nature of challenges categorization and to avoid confusion, we maintained the hierarchy at three levels (Fig. 7), in contrast to technologies for which their categorization is more settled. At the same time, the definitions clarified the subchallenges included in each category.

C. FUTURE WORK

The taxonomies presented here can be the starting point for building an I4.0 ontology, thus allowing for an even more formal and standardized representation. At the same time, it would be possible to link it to other already existing ontologies to achieve interoperability and address knowledge domains not dealt with in this study but still linked to the general topic of I4.0. Moreover, an ontology would form the basis for building the knowledge graph, allowing the retrieval of information on the web platform and enabling new features, such as adding and indexing new content and better maintainability and updatability.

Future research should prioritize the expansion of the current taxonomy by incorporating an increased number of sources and updating its structure. In this regard, relevant articles such as Herrmann's study [60] can serve as a source of inspiration, particularly in rapidly evolving fields such as AI, to integrate additional layers and dimensions.

Updates should also regard the web platform's interface and the capabilities to provide a more scalable and maintainable data structure that offers users a more consistent and understandable presentation of its content.

One such functionality is the dynamic calculation and display (based on the current status of the database) of the statistics presented in Fig. 3. The second is importing new sources (either by researchers or automatically) to maintain the knowledge base constantly up-to-date, which is in the immediate plans. We can also deal with the development of a set of taxonomy application examples that would make it easier for users to use the taxonomy for various business needs. Such examples could appear on the web platform as a "case studies" section. Therefore, in an effort to develop a tool that will contribute to the realization of the

I4.0 vision from the industry and academia perspective, any contributions from the scientific community are welcome.

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