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Charting the Path of Technology-Integrated Competence in Industrial Design during the Era of Industry 4.0

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Abstract: The fusion of emerging technologies with industrial design has catalyzed a fundamental shift in the aesthetics, user experiences, and service frameworks of products in the Industry 4.0 era. Simultaneously, this convergence has heightened the demands placed on the technological integration competencies of designers. Consequently, there exists a necessity to articulate a precise developmental trajectory for proficiency in industrial design that incorporates these novel technologies. This study initiates with a bibliometric analysis to quantify the scholarly literature relevant to this research domain. Subsequently, leveraging the insights from this analysis, semi-structured interviews were conducted with 15 experts spanning the United States, Europe, South Korea, and China. Our conclusions show the following: (1) Co-word analysis and cluster analysis techniques are applied to identify 80 technologies and four technological clusters that demonstrate strong associations with industrial design in the Industry 4.0 era. (2) Employing coding techniques and thematic analysis, four distinct skill domains emerge for technology-integrated industrial design: Industrial Design Skills, Industrial Design Knowledge, Ethical Considerations in Industrial Design, and Industrial Design Industry Insight. Furthermore, a limitation that affects these competencies is identified. (3) A recommended methodology for assessing these competencies is proposed. This study represented an expansion upon existing industrial design competencies. The empirical data generated herein serves as a valuable resource for practitioners and educators within the field of industrial design. Furthermore, it provides a theoretical groundwork for future models addressing technology-infused industrial design capabilities.

Keywords: technology integration; industrial design competence; industry 4.0; ethical considerations in design; innovation in design; interdisciplinary design

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1. Introduction

The emergence of Industry 4.0, characterized by its attributes of "hyper-connectivity, hyper-intelligence, and hyper-convergence", has profoundly reshaped human existence [1]. Industry 4.0 represents the fusion of information and communication technologies with Cyber-Physical Systems (CPS), creating virtual systems within networked environments. This integration bridges the physical and digital realms, facilitating the transition from traditional manufacturing to intelligent manufacturing [2]. Technology stands at the forefront as the driving force behind this transformation [3]. The advent of new technologies has played a pivotal role in advancing intelligent design, processing, and production [4,5]. Industrial design, a critical component in achieving manufacturing objectives [6], is likewise influenced by these technological advancements, promising novel aesthetics, functionality, and service models through digital technologies and innovative materials. Moreover, the integration of artificial intelligence (AI) technology has the potential to boost designers' efficiency and enhance creative design and program development [7]. The convergence of new technologies with industrial design has emerged as a pivotal focus for fostering innovative design practices and reinforcing the role of industrial design in the broader smart manufacturing system [8]. However, as this integration opens up vast opportunities for the advancement of industrial design, it concurrently places higher demands on the technological competencies of industrial designers. Therefore, it becomes imperative to elucidate the pathway to technological integration capabilities that industrial designers need to possess in the era of Industry 4.0. This endeavor is poised to enhance practitioners' design proficiency, elevate design quality, and unlock the inherent value within industrial design.

In the current landscape of research related to integrating technological capabilities in industrial design during the Industry 4.0 era, some studies have focused on specific new technologies' integration with industrial design [9–11]. For instance, Terkowsky et al. highlighted a shift in the role of designers in this new era, indicating the need for industrial design practitioners to augment their skills with manufacturing, technical, and engineering capabilities to address emerging technological changes [12]. In the digital technology realm, Jeong et al. explored the influence of artificial intelligence on the domain of industrial designers, proposing a future where designers base their creativity on a deep understanding of users and collaborate with artificial intelligence to drive design innovation [13]. Cantamessa et al. identified the impact of digitally driven design development on designers, emphasizing the need for both designers and educators to acquire digital-technology-related skills [14].

Regarding material processing technology, some studies suggest that future industrial designers should possess additive manufacturing capabilities, proposing the inclusion of additive manufacturing technology courses in design education to meet the challenges of this new era [15]. Additionally, research indicates that enhancing understanding of materials and material engineering capabilities in product design education can enhance user experiences and promote sustainable design development [16]. These studies collectively affirm the necessity of industrial designers in the Industry 4.0 era augmenting their capabilities with new technological skills. However, most studies have concentrated on individual technological capabilities, lacking an exploration into the integration of new technologies tailored specifically to industrial design in the Industry 4.0 era.

Moreover, some studies suggest that interdisciplinary capabilities in the Industry 4.0 era enable more effective utilization of new technologies [17,18]. Scholars like Self et al. identified through literature research that design professionals should possess comprehensive abilities spanning technology, culture, systems, and society in this era of integration [19]. Others, including Umachandran et al. [20] and Zhou et al. [21], underscored the importance of incorporating interdisciplinary competencies, especially those related to new technologies, into industrial design to effectively address the challenges presented by the Industry 4.0 era.

Certain scholars propose that design professionals, alongside engineering technical capabilities, should also possess skills in user analysis, market insights, and corporate innovation [22,23]. These studies emphasize that industrial design and new technologies are intertwined, necessitating knowledge and skills from psychology, sociology, economics, and other disciplines for effective integration with new technologies. Despite the potential to drive the evolution of designers, current research predominantly focuses on individual technological domains and the study of interdisciplinary competencies. Currently, there is a dearth of literature consolidating the unified integration of technology in the Industry 4.0 era and industrial design capabilities within the same framework. Thus, the primary objective of this study is to address and narrow this existing gap.

This research revolves around exploring the directions of technology-integrated industrial design capabilities in the context of the Industry 4.0 era. The primary focus encompasses two research questions: (1) What are the new technologies closely associated with the Industry 4.0 era and how will they impact industrial design in various aspects? (2) What are the directions and specific competencies of technology-integrated industrial design capabilities in the Industry 4.0 era? To tackle these research questions, this research commences with a comprehensive literature review using bibliometrics, focusing on keywords such as “Industry 4.0,” “technology,” “design,” and “capability.” Co-word analysis is employed to identify new technologies closely associated with industrial design in the context of Industry 4.0. Cluster analysis is utilized to examine the various ways in which these new technologies influence industrial design. Based on the findings from the bibliometric analysis, a semi-structured interview guide is developed. Subsequently, a series of semi-structured interviews are conducted with designers and design researchers specializing in the field of industrial design under the guidance of experts in the field. Data from these interviews are then subjected to coding and thematic analyses to identify the specific technical competencies deemed essential for industrial designers in the context of Industry 4.0.

The innovation within this study is twofold: (1) While prevailing research has typically concentrated on individual technologies and their isolated effects on industrial design capabilities, our study uniquely integrates multiple new technologies of the Industry 4.0 era. We explore their interrelationships and impact mechanisms on industrial design capabilities, offering a more multifaceted perspective that transcends the limitations of examining singular technological capabilities. (2) Numerous existing studies examining the integration of new technologies into industrial design capabilities have heavily relied on qualitative research methods or expert opinions. In contrast, our study employs a blended quantitative and qualitative research approach. Additionally, we conduct consistency checks on qualitative analysis outcomes, ensuring research objectivity and bolstering result accuracy.

The contributions of our study can be outlined as follows: (1) Our work marks the inaugural comprehensive integration of new technologies within the industrial design domain during the Industry 4.0 era. This integration is contextualized within design capabilities, establishing crucial correlations between Industry 4.0’s new technologies and industrial design capabilities. The outcomes of this research expand the existing landscape of industrial design capabilities. (2) We delineate the trajectory of technology-integrated industrial design capabilities in the Industry 4.0 era, delving into the impact mechanisms of these capabilities on industrial design. For professionals in design, this study’s findings offer valuable insights for enhancing the evolving technology-integrated design skills demanded by Industry 4.0. These findings facilitate agile and efficient design processes, empowering practitioners to align industrial design with contemporary demands. In academia, this study serves to illuminate the direction of industrial design competencies within the Industry 4.0 landscape. This clarity aids in refining teaching materials, adapting curricula, fostering interdisciplinary collaboration, and bolstering students’ aptitude in industrial design to meet the challenges of this era. Consequently, it catalyzes advancements in design education, enabling students to adeptly navigate the complexities of Industry 4.0. Elevating the proficiency of design professionals and fortifying the standard of design education act as catalysts for the accelerated evolution of product and service design. This, in turn, amplifies production efficiency, fuels economic growth, and advocates for the sustainable development of society. (3) Building upon our research findings, we propose a framework outlining technology-integrated industrial design capabilities in the Industry 4.0 era. This framework serves as a theoretical underpinning for developing further models of technology-integrated capabilities within this era.

2. Methodology

This study adopts a mixed research method combining quantitative and qualitative aspects, and the details of the research methodology and research procedures are shown in Figure 1.

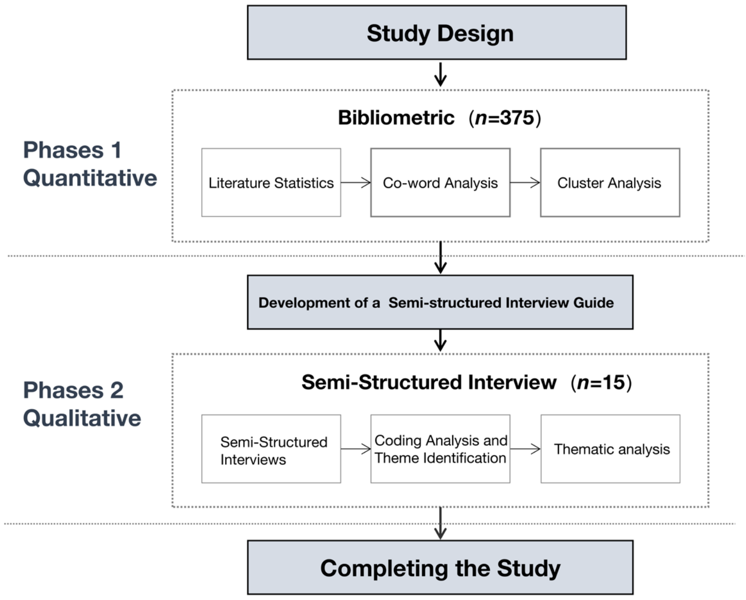

Figure 1. Flow chart of the study.

2.1. Bibliometric

This study utilized bibliometrics to explore the current status, dynamics, and trends of emerging technologies within the realm of industrial design amid the Industry 4.0 era. As defined by Webster and Watson [24], a systematic literature review requires a well-defined plan and sequential steps aligned with the research objectives. Additionally, such a review necessitates meticulous consideration of the review strategy, involving critical assessment of documents, studies, their formal outcomes, and research relevant to the specific subject. It further entails establishing criteria ensuring reproducibility and clarity in study selection [25].

The literature selection criteria for this study were as follows:

(a) Database selection: The selection of the Web of Science (WoS) database stemmed from its publication by Thomson Reuters and its encompassing of SCIE, SSCI, and A&HCI databases, aggregating an extensive collection of approximately 2.6 million publications. Recognized as one of the most comprehensive scientific databases and citation indexing services, the WoS database stands out as a reliable resource [26]. Specifically, the 'Science Citation Index Expanded' (SCI-EXPANDED) within the WoS database indexes high-impact academic journals in the natural sciences, offering authoritative and referential statistical results [27]. These considerations influenced the formulation of our semi-structured interview guide and the conduct of subsequent interviews. While studies suggest comparable coverage between Scopus and WoS databases in the field of Natural Sciences and Engineering (NSE), any discrepancies in bibliometric outcomes can be deemed negligible [28]. Given these factors, our study opted for the WoS database.

(b) Timeframe selection: Commencing the search from 2013 aligns with the formal introduction of the 'Industry 4.0' concept at the Hannover Messe in Germany, marking a pivotal milestone [27].

(c) Search terms selection: The search terms were meticulously chosen to align with the research topic, incorporating terms such as 'Industry 4.0', 'technology', 'industrial design', and 'capabilities'. These terms were interconnected using the 'OR' connector to pinpoint relevant documents.

(d) Document type selection: Retaining articles featuring the search terms in their title, abstract, and keywords, alongside forthcoming articles and reviews, was integral to prevent overlooking crucial literature [29].

Following the established literature selection criteria, we conducted literature retrieval, filtering, and analysis: (1) A search was executed in the WoS database, utilizing keywords like "Industry 4.0", "technology", "industrial design", and "competence", yielding 673 relevant documents. (2) Each of the 673 documents underwent individual scrutiny based on their titles, keywords, and abstracts. Documents with limited relevance to the research topic were excluded, ultimately leaving 385 pertinent documents. (3) To delve deeper, VOSviewer was deployed to perform co-word analysis on the 385 documents. This process led to the identification of 80 new technologies closely linked to the Industry 4.0 era and industrial design. (4) Subsequently, Pajek was employed for cluster analysis, classifying the 80 new technologies into 4 clusters. (5) The outcomes of the co-word analysis and cluster analysis were then visually depicted through graphical representations. These statistical results address the first research question. Figure 2 provides an overview of the literature search process and subsequent filtering.

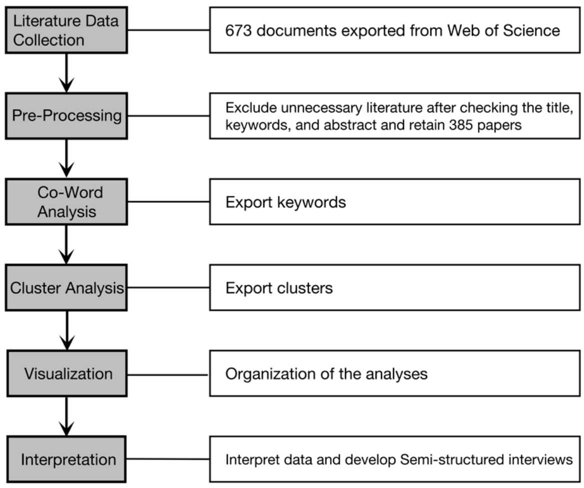

Figure 2. Overview of the literature search process and filtering.

2.2. *Semi-Structured Interview*

Given the limitations associated with bibliometric methods and the imperative need for a comprehensive evaluation [30], we conducted semi-structured interviews with professionals immersed in the field of industrial design, aligning the insights gained from these interviews with the results obtained from the literature statistics. This interview format is semi-open in nature, affording interviewees the flexibility to offer perspectives relevant to the research topic without being confined by preconceived answers. Such an approach fosters a more profound comprehension of the subject under investigation [31].

2.2.1. Participants

To procure the most up-to-date insights on emerging technology-integrated industrial design capabilities, specific inclusion criteria were established for interview participants as follows: (a) possessing a master's degree or higher in industrial design or a related interdisciplinary field, (b) specializing in fields such as industrial design, service design, experience design, or interdisciplinary work, (c) frontline designers boasting more than 5 years of extensive experience in industrial design, university educators equipped with practical design experience and expertise in design education, or ongoing PhD candidates within the field, as well as professionals and researchers from diverse disciplines actively involved in interdisciplinary projects linked to industrial design during the Industry 4.0 era. The final cohort of interview participants was carefully selected from diverse countries and regions, encompassing the United States, Europe, South Korea, and China. For precise demographic information, please refer to Table 1.

Table 1. Semi-structured interview demographics (n = 15).

Participant	Research Field	Age	Qualification	Workplace	Qualifications for Employment	Location
P1	Experience Design	29	Master	Experience Designer, Alibaba Group	Designer with 5 years of experience	China
P2	CMF Design	30	Master	Product Designer, Xiaomi Group	Designer with 8 years of experience	China
P3	Railway Product Design	31	Master	Industrial Designer, BYD Group	Designer with 6 years of experience	China
P4	Innovative Experience Design	30	Master	Design Supervisor of European Design Team, Huawei Group	Designer with 6 years of experience	Europe
P5	System Design	30	PhD	PhD at Tongji University and University of Barcelona	Designer with 2 years of experience	China/ Spain
P6	Product Design	30	PhD	PhD at Hanyang University	Designer with 1 years of experience and 3 years as lecturer	South Korea
P7	UX Design	30	Master	Senior UX Designer, Walmart Global Tech	Designer with 5 years of experience	USA
P8	Product Design	30	Master	Industrial Designer, Midea Group	Designer with 6 years of experience	China
P9	Industrial Design	32	PhD	PhD at China Academy of Art	Designer with 1 years of experience and 1 years as lecturer	China
P10	Service Design	28	PhD	PhD at Hanyang University	Designer with 1 years of experience	South Korea
P11	Design Management	30	PhD	University lecturer	Designer with 1 years of experience and 1 years as lecturer	China
P12	Industrial Engineering	33	Master	Industrial Engineers, Huawei Group	Engineer with 8years of experience	China
P13	Service Design	27	PhD	Experience Designer, Huawei Group	Designer with 1 years of experience	China
P14	Design Methodology	33	PhD	University lecturer	Designer with 2 years of experience and 1 years as lecturer	China
P15	Materials Science	34	PhD	University lecturer	Engineer with 2 years of experience and 1 years as lecturer	China

2.2.2. Data Collection and Analysis Procedure

The process of collecting and analyzing data from interviews followed these steps:

(a) Crafting a semi-structured interview guide was the initial step, drawing insights from bibliometric analysis. This guide underwent iterative refinement through three rounds of pilot interviews. Comprising three sections, the guide began with demographic information encompassing participants' age, education, workplace, position, work experience, and research areas. The second section featured four semi-open-ended questions, aligned with the identified technology clusters from the bibliometric analysis. Throughout the interviews, additional probing questions were introduced to deepen responses, such as 'Could you describe the role of these technologies in the design process?' and 'What specific requirements do these technologies impose on design practitioners?' The third section presented an open-ended question, encouraging participants to freely discuss key terms like 'new technologies', 'industrial design', and 'capabilities'. This iterative refinement process was conducted across three rounds of pilot interviews.

(b) Formal interviews were conducted with 14 participants between 20 July 2023 and 20 August 2023, a sample size typical in phenomenological research, emphasizing depth and quality over quantity [32]. Given the diverse geographical locations of the participants, a combination of online (using Zoom and Tencent Meeting) and offline methods was employed. The interview durations ranged from 40 to 95 min, with an average duration of approximately 65 min. All interviews were recorded and transcribed verbatim.

(c) Employing Braun and Clarke's six-stage analysis method [33], the researcher utilized qualitative analysis software, NVivo 12, for thematic analysis of the interview data. To ensure analysis validity, two researchers independently conducted thematic analysis and cross-verified outcomes. Ultimately, the thematic analysis revealed the trajectories of technology-integrated industrial design capabilities within the context of Industry 4.0, addressing our second research question.

3. Results

3.1. Co-Word Analysis

Co-word analysis serves as a valuable tool for illuminating the distribution of research topics and hotspots [34]. In this study, co-word analysis was conducted on the 385 documents extracted from the WoS, resulting in the identification of 83 keywords closely associated with new technologies. To enhance clarity and precision, redundant keywords such as "Industry 4.0", "design", and "technology" were excluded. Consequently, a total of 80 distinct keywords were identified with weights exceeding 10, as presented in Table 2. Among these, the top 10 keywords with the highest frequencies are "smart manufacturing systems", "big data analytics", "digital twins", "cyber-physical systems", "internet of things", "3D printing", "additive manufacturing", "innovation", and "sustainability". Each of these keywords occurred in the dataset more than 28 times, underscoring their significant roles as crucial technologies and focal points closely intertwined with industrial design in the context of the Industry 4.0 era.

Table 2. Keywords with weights exceeding 10 in technology-integrated industrial design.

No.	Label	Occurrences Weight	No.	Label	Occurrences Weight
1	Smart Manufacturing Systems	100	16	Product-Service Systems	18
2	Big Data Analytics	57	17	Integration	17
3	Cyber-Physical System	56	18	4D Printing	16
4	Digital Twins	50	19	Augmented Reality	16
5	Internet	48	20	Blockchain	15
6	Internet of Things	46	21	Artificial Intelligence	14
7	3D Printing	31	22	Servitization	14
8	Additive Manufacturing	31	23	Smart Materials	14
9	Sustainability	29	24	Supply Chain	13
10	Innovation	28	25	Product Lifecycle Management	12
11	Management	25	26	Co-Creation	11
12	Simulation	22	27	Cloud Computing	10
13	Smart Factory	21	28	Digitization	10
14	Circular Economy	20	29	Shape-Memory Polymer	10
15	Machine Learning	18			

Moreover, the analysis results indicate that keywords such as "smart factories", "blockchain", "rapid prototyping", and "wearables", although not considered as dominant technologies within the industrial design field, still bear some relevance to industrial design. The keyword visualization map is illustrated in Figure 3. In this map, distinct colors represent different clusters, with keywords sharing the same color exhibiting a closer semantic association. The likelihood of keywords appearing within the same research theme is higher when they share the same color.

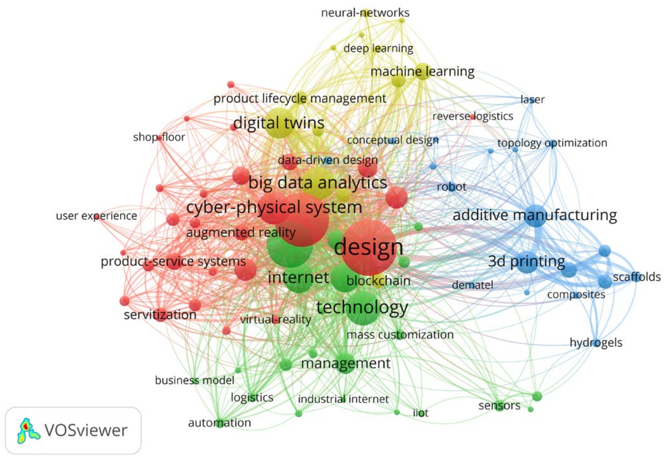

Figure 3. Co-word map of key words in technology-integrated industrial design.

The overlay visualization of time zones in co-word analysis allows for the identification of the years when keywords gained prominence [35]. The results of the time zone overlay visualization (depicted in Figure 4) reveal that keyword such as "user experience", "mass personalization", "digital technologies", "digital servitization", "industry Internet", "customization", "smart textiles", "microstructure", "genetic algorithm", and "artificial intelligence" represent the most recent keywords related to technology-integrated industrial design, with notable activity observed after 2022. Additionally, keywords like "virtual reality", "simulation", "product service systems", "digital twins", "blockchain", "circular economy", and others are relatively recent terms with relevance to technology-integrated industrial design, emerging between May 2021 and 2022. Furthermore, keywords such as "smart material", "robot", and "4D printing" are linked to the period around 2020.

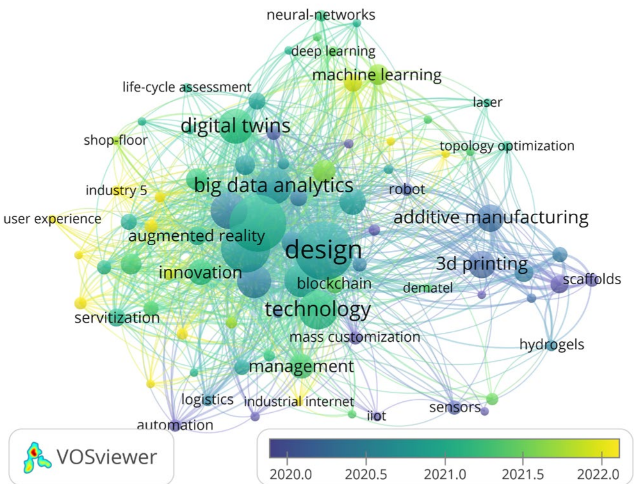

Figure 4. Co-word map of overlay visualization of time zones in technology-integrated industrial design.

It is important to highlight that active keywords change annually, signifying the ongoing emergence of new technologies in the Industry 4.0 era, all of which have the potential to influence design practices. Moreover, even keywords with the longest historical activity span to date are less than four years old, emphasizing the rapid pace of technological advancements in recent years. This suggests that in the coming years, new technologies will continue to exert a significant impact on the field of industrial design.

3.2. Cluster Analysis

Keyword cluster analysis is a statistical method that simplifies the intricate relationships among a multitude of keywords by using co-occurring keywords as the units of analysis [36]. In this study, we employed VOSviewer version1.6.19 and Pajek version 5.17 software to generate four clusters (depicted in Figure 5) through co-word analysis of 80 keywords. After eliminating keywords redundant to the research focus, such as "design", "industry 4.0", and "technology", we retained the top five keywords in each cluster based on their weight values, as presented in Table 3. Based on the characteristics of the keywords in each cluster and the keywords with higher weights, we named the four clusters as follows: "Digital Technology and Service Experience", "Smart Manufacturing and Personalization", "Additive Manufacturing and Material Processes", and "Data Analysis and Artificial Intelligence".

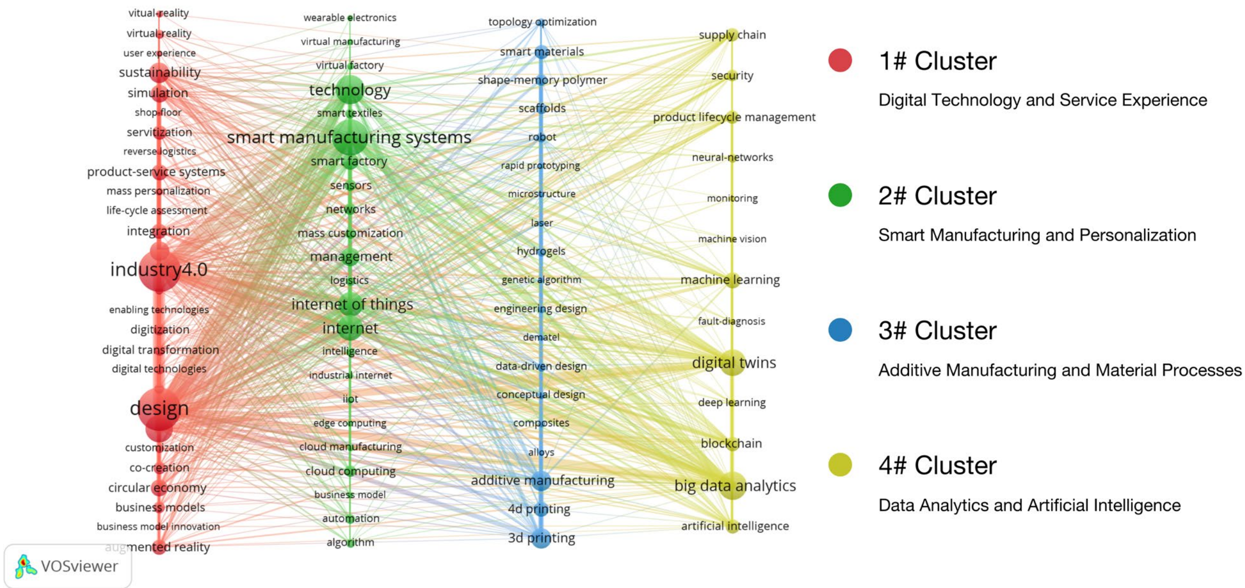

Figure 5. Cluster map of key words in technology-integrated industrial design.

Table 3. Top five keywords in each cluster based on weight values.

Cluster	Sequences	Label	Weight
Cluster1 Digital Technology and Service Experience	1	Augmented Reality	142
	2	Business Model Innovation	134
	3	Co-Creation	28
	4	Customization	22
	5	Digital Servitization	17
Cluster2 Smart Manufacturing and Personalization	1	Smart Manufacturing Systems	100
	2	Smart Factory	21
	3	Cloud Computing	10
	4	Sensors	9
	5	Mass Customization	8
Cluster3 Additive Manufacturing and Material Processes	1	Additive Manufacturing	31
	2	3D Printing	31
	3	4D Printing	16
	4	Smart Materials	14
	5	Shape-Memory Polymer	10
Cluster4 Data Analysis and Artificial Intelligence	1	Big Data Analytics	57
	2	Digital Twins	50
	3	Machine Learning	18
	4	Blockchain	15
	5	Artificial Intelligence	14

3.2.1. Cluster 1: Digital Technology and Service Experience

This cluster underscores the influence of new technologies in the Industry 4.0 era on industrial design, particularly in augmenting user experiences, advancing service design, and streamlining service management processes. The pervasive adoption of digital technologies has profoundly altered consumer expectations regarding products and services. Research indicates that personalized experiences and immediate gratification play pivotal roles in meeting these expectations [37]. Furthermore, digital technologies have ushered in unparalleled prospects for customization within the service industry. Here, user engagement in design via digital platforms or a more profound comprehension of user behavior and preferences through data analytics techniques can substantially augment the overall user experience. For example, cutting-edge technology, such as big data analysis, can identify user preferences and usage patterns, providing personalized content tailored to their interests. Mobile payment solutions simplify complex payment procedures, offering users a more convenient shopping and travel experience. Virtual reality technology has the capacity to seamlessly merge the virtual and physical realms, creating immersive experiences that transcend time and space. Digital technologies also enable automation of service processes, reducing errors associated with manual intervention and improving overall service efficiency. The findings from this cluster underscore the significance, from an industrial design perspective, of comprehending how various digital technologies can be harnessed to enhance user experiences in the Industry 4.0 era.

3.2.2. Cluster 2: Smart Manufacturing and Personalization

Intelligent manufacturing introduces automation technology to achieve intelligence and automation of the entire manufacturing process from design to production to logistics [38]. Industrial design, as the foundational stage in manufacturing, plays a crucial role in integrating and applying new technologies throughout various phases of the manufacturing process, fostering the development of intelligent manufacturing systems. Furthermore, the evolution of smart manufacturing enables customized production, which in turn facilitates personalized design to meet the unique requirements of individual users. Intelligent manufacturing systems offer a broader range of possibilities for personalized customization, and the model of personalized customization holds the potential to reduce overproduction and inventory, thereby enhancing resource utilization and aligning with the principles of sustainable design. This highlights the pivotal role of the integration of industrial design with new technologies in not only advancing smart manufacturing but also driving the progression of design itself. The results of this cluster emphasize that, in the Industry 4.0 era, industrial design should prioritize concepts such as intelligent manufacturing systems, smart manufacturing processes, and smart factories. Defining the role and significance of industrial design within intelligent manufacturing systems is essential, alongside a heightened focus on customized product design.

3.2.3. Cluster 3: Additive Manufacturing and Material Processes

The relationship between industrial design and materials and processes is intricate, as they can profoundly affect a product's functionality, aesthetics, and manufacturability. Material choices and manufacturing techniques can impact a product's form and texture, influencing its visual appeal and user experience. Material properties such as strength, durability, and heat resistance can dictate a product's lifespan, while the method of material processing can determine whether a product can be successfully produced. In addition to influencing product design, additive manufacturing technology affords a high degree of customization for products [39]. Rapid prototyping and other processing techniques accelerate the product development cycle, thereby reducing the costs associated with design iterations [40]. The findings of this cluster emphasize that, in the Industry 4.0 era, significant attention should be directed toward the application of intelligent materials and innovative technologies like additive manufacturing in industrial design. This underscores the need to explore the possibilities they bring to industrial design.

3.2.4. Cluster 4: Data Analysis and Artificial Intelligence

The amalgamation of big data technology and AI leverages data analysis to extract insights into customer preferences and needs. Digital twins enable real-time data analysis to monitor and optimize physical entities. Neural networks, consisting of interconnected artificial neurons, are applied for data analysis, with applications in fields such as speech recognition, natural language processing, and medical diagnostics. Deep learning and machine learning, integral to AI, empower computers to learn from extensive data, enhancing their task-processing capabilities. Deep learning, building upon machine learning, incorporates multi-layered neural networks, enabling more sophisticated task handling. Tesla's Full Self-Driving (FSD) technology harnesses classical cases of deep learning and neural network applications. Neural networks assume a pivotal role in the Full Self-Driving (FSD) system, actively engaging in the processing of sensor data to discern intricate details such as road configurations, obstacles, signage, and the presence of other entities in traffic. These neural networks undergo extensive training regimens, facilitating adaptability across diverse road typologies and traffic scenarios. This amalgamation of neural network and deep learning technologies serves as a cornerstone, augmenting the efficacy of Tesla's autonomous driving system in real-world operational environments.

Data analysis and AI complement each other, where data analysis provides the foundation for AI, and AI, in turn, enhances data analysis by making it more intelligent and automated. Together, they offer efficient problem-solving and analysis capabilities. The results of this cluster suggest that, in the Industry 4.0 era, the application of data analysis and AI technologies in industrial design can foster product diversification and intelligence. Therefore, industrial designers should possess a comprehensive understanding of the principles and application methods of data analysis and AI technologies.

3.3. Thematic Analysis

The thematic analysis method is an approach utilized to identify, analyze, and elucidate themes or key insights within the collected data [41]. In this study, the qualitative analysis software NVivo 12 was employed to execute a coding analysis and recognize the underlying themes within the textual data gathered from the semi-structured interviews. The outcomes of this thematic analysis were integrated with the findings from the previous cluster analysis, ultimately condensing the four clusters into two primary themes: "Industrial Design Skills" and "Industrial Design Knowledge." Furthermore, three new themes emerged: "Ethical Considerations in Industrial Design," "Industrial Design Industry Insights," and "Limitations affecting competency." A comprehensive summary of the results of the coding analysis and theme recognition is presented in Table 4.

Table 4. Summary of the results of the coding analysis and theme recognition.

	Thematic	Code	Frequency	Source of Data
(1)	Industrial Design Skill	New Technologies as Design Innovation Methods	12	P1. P2. P3. P4. P5. P6. P8. P10. P11. P13. P14. P15
		New Technologies as Design Aids	11	P1. P2. P3. P4. P6. P7. P8. P10. P11. P13. P15
(2)	Industrial Design Knowledge	Knowledge of Smart Manufacturing System	7	P2. P3. P4. P6. P10. P11. P13. P15
		Interdisciplinary Knowledge	8	P2. P4. P6. P8. P9. P13. P14. P15
(3)	Ethical Considerations in Industrial Design	Privacy Equality Social	5	P4. P6. P7. P9. P11
(4)	Industrial Design Industry Insights	Technology Trends Economic Fluctuations	3	P1. P3. P4

3.3.1. Consistency Test

To ensure the reliability and effectiveness of the thematic analysis results, two researchers independently conducted a coding analysis and identified themes. The consistency of the analysis results was assessed using Cohen's kappa coefficient (K-value), a widely recognized measure for evaluating the agreement between two or more independent observers in relation to categorical outcomes [42]. The K-value is calculated based on a confusion matrix, which illustrates how observers classify different categories, including true positives, false positives, true negatives, and false negatives [43]. The formula for calculating the K-value is as follows:

$$K = \frac{p_o - p_e}{1 - p_e}$$

The value of p_o can be computed based on the number of true positives and true negatives in the confusion matrix, representing the actual agreement in classification by observers or models. On the other hand, p_e signifies the probability of classification agreement under purely random conditions and is typically calculated by summing the products of the probabilities of classification for each category in the confusion matrix.

The K-value typically falls within the range of -1 to 1. When the K-value is less than 0.4, it signifies poor consistency in the research results, thus failing the consistency test. A K-value between 0.4 and 0.75 suggests that the research results are generally robust and can pass the consistency test. When the K-value exceeds 0.75, it indicates a very high level of consistency in the research results, and they can successfully pass the consistency test. Table 5 presents the average for all nodes and sources in the thematic analysis conducted by the two researchers, with a K-value of 0.8126. This high K-value signifies a remarkable level of consistency in the thematic analysis results, rendering them eligible for the consistency test.

Table 5. Kappa coefficient of consistency test.

	Kappa	**Agreement (%)**
Average for all nodes and sources	0.8126	97.56

3.3.2. Thematic Analysis Results

Theme 1: Industrial Design Skills

The theme of Industrial Design Skills comprises two sub-themes: Skills in New Technologies as Design Innovation Methods and Skills in New Technologies as Design Aids.

(1) New Technologies as Design Innovation Methods

Among the 15 interviewees, 12 (80%) noted that integrating new technologies with industrial design can profoundly impact the user experience (P3, P13, P10, P6), product aesthetics, and functionality (P1, P2, P8, P14, P6, P11, P5, P15). It can also facilitate personalization (P1, P3, P6, P13, P15). Hence, new technologies serve as a method for design innovation, and design professionals should acquire the relevant capabilities.

Enhancing the user experience: Another participant highlighted that, in the context of automotive design, "incorporating autonomous driving technology to replace traditional driving can enhance the user experience when using the car" (P3). Some interviewees have also been involved in developing digital office systems, which "greatly improved work efficiency and convenience" (P13). However, it is essential to remain cautious because the integration of new technologies with industrial design may also have adverse effects on the user experience. For example, fully automated designs in hotels, such as automatic curtains, lights, and wake-up functions, might inconvenience some hotel guests. Therefore, "designers should consider the diverse needs of users and possess the ability to accurately assess user requirements" (P6).

Innovation in product appearance and function: Several interviewees believed that new materials and processes could revolutionize the aesthetics of products (P1, P8). For instance, “Tesla’s car bodies are produced using a one-piece stamping technique” (P8), and “Samsung’s foldable smartphones and LG’s rollable televisions have achieved unprecedented aesthetic innovation through the use of flexible OLED (Organic Light-Emitting Diode) materials” (P1, P8). Moreover, new materials and technologies can also impact how products are used. For example, digital technology allows couriers to scan customer information on delivery boxes and send it to computer systems, thereby altering the work process of couriers (P1). The emergence of wearable materials with characteristics such as flexibility, comfort, and durability has provided opportunities for the development of wearable devices (P15). When additive manufacturing technology is combined with bio-materials in medical products, it can lead to the creation of more usable medical products (P13).

Realizing the demand for private customization: Five interviewees emphasized the growing importance of customized product design due to the increasing demands for personalized solutions. For instance, this could involve production processes like additive manufacturing, 3D printing, 4D printing, and others (P3). Comprehending and adeptly utilizing additive manufacturing and 3D printing technologies facilitates swift prototyping and tailored production within precision manufacturing (P15). Alternatively, it could entail using data analysis techniques to provide targeted personalized products to users (P1, P14). “Alipay’s financial advisor feature provides customized products. Customers with over 300,000 RMB deposited in Alipay can obtain the Wealth Black Card, and users of different card levels will receive various services” (P1).

(2) New Technologies as Design Aids

Eleven (73.3%) interviewees mentioned that new technologies could serve as tools to assist in design, enhancing the efficiency and accuracy of the design process. Therefore, industrial designers should possess the corresponding capabilities.

Assisting in user analysis: New technologies can aid in user analysis. For instance, they can use eye-tracking experiments to capture users’ areas of interest (P1, P10). Data statistics, data analysis techniques, or Artificial-Intelligence-Generated Content (AIGC) can be employed to assist in surveying user needs during the product development phases (P3, P13). These technologies are also instrumental in gathering user feedback after a new product is launched, facilitating product improvements and upgrades (P1, P2).

Assisting in graph generation: New technologies can also aid in generating design solutions. During the ideation process, employing AIGC technology to generate creative design ideas can replace traditional brainstorming methods. “This is a means of assisting design and increasing productivity”, as one participant mentioned (P8). “Designers only need to input design keywords to quickly generate design solutions” (P13). Technology-assisted design generation significantly enhances work efficiency and is a vital tool in future design work. Therefore, alongside mastering traditional computer-aided design skills, acquiring proficiency in new design generation tools is necessary, as “the skill requirements are also changing” (P6).

Assisting in model fabrication: Participants also highlighted how new manufacturing processes can aid in creating product prototypes. New techniques like 3D printing, 4D printing, and additive manufacturing have improved the efficiency of model fabrication. “In the past, this work had to be done in factories” (P2). They emphasized the importance of mastering these manufacturing technologies, stating that “during the design process, when we want to visualize the model, we use 3D printing to create prototypes and examine product outcomes” (P11).

Theme 2: Industrial Design Knowledge

The Industrial Design Knowledge theme contains two sub-themes, Knowledge of Intelligent Manufacturing Systems and Interdisciplinary Knowledge.

(1) Knowledge of Intelligent Manufacturing Systems

Among the 15 interviewees, half of them emphasized that in the Industry 4.0 era, many manufacturing companies have already achieved automated production. Therefore, design professionals' understanding of smart manufacturing systems is crucial for grasping the role of industrial design in smart manufacturing systems and conducting industrial design work from a macro perspective (P2, P6, P11). Smart production lines are primarily managed by technical professionals who impose specific requirements on industrial design. Hence, industrial designers should be knowledgeable about smart factories, cloud computing, and automation-related knowledge to facilitate effective communication with technical professionals. This knowledge enables them to meet the demands of technical experts and complete industrial design tasks accordingly (P4, P6, P10). From an industrial engineering standpoint, designers should bolster their comprehension of intelligent manufacturing systems, encompassing intelligent sensors, industrial robots, adaptive manufacturing technologies, and industrial automation and control systems, alongside digital production processes. This expanded understanding enables designers to incorporate intelligent manufacturing processes into their designs, ensuring seamless integration of designed products with automated production lines and smart devices (P12). Furthermore, as designers deepen their grasp of intelligent manufacturing systems, it is essential to foster an awareness of sustainable manufacturing practices (P12). This includes embracing energy-efficient methodologies and the utilization of biodegradable materials, thereby mitigating the environmental footprint of the designed products throughout the manufacturing process (P15).

(2) Interdisciplinary Knowledge

More than half of the interviewees emphasized the interdisciplinary nature of industrial design, underscoring the requirement for industrial designers to possess interdisciplinary knowledge. When considering the entire design process, they noted that during the initial stages of user research, knowledge related to sociology and psychology is required. In the design and development phases, familiarity with subjects such as materials science, structural engineering, and data science is necessary. Once products are introduced to the market, expertise in disciplines like marketing and business studies becomes crucial.

"Design is a comprehensive discipline that interconnects various fields, including the humanities, technology, art, economics, and management. Emphasis should be placed on the breadth of knowledge." (P2, P6, P9, P13). In the era of Industry 4.0, it becomes even more crucial to supplement interdisciplinary knowledge related to new technologies (P9, P13). Precision manufacturing's high-precision quality standards necessitate designers to possess interdisciplinary expertise, particularly in addressing the specific requirements for small-sized products (P12). Proficiency in advanced manufacturing processes like laser cutting is also imperative to meet the intricate demands of precision manufacturing (P15). The correlation between materials and industrial design is intricate. Enhancing comprehension of smart materials, biomaterials, sustainable materials, and other emerging materials contributes significantly to product design innovation and sustainable development. Additionally, a nuanced understanding of how various manufacturing processes influence material properties and structures aids in making informed decisions about materials and processes during the design phase (P15).

In terms of interdisciplinary knowledge mastery, most design practitioners indicated that their familiarity with new technologies often remains confined to definitions and concepts (P1, P2, P4). As one practitioner mentioned, "We primarily focus on understanding manufacturing and processing processes; technical aspects are typically handled by specialists. Hence, improving communication frequency with technical personnel is crucial." However, two participants from different disciplines underscored the importance of designers delving deeper into understanding the principles of new technological knowledge. They emphasized that such comprehension is not solely for collaboration with engineers but is pivotal in fostering design innovation itself. Moreover, individuals should build upon their broad knowledge base and develop expertise in a specific aspect of industrial design, thus acquiring the necessary depth of knowledge. "They should be 'T-shaped' individuals with a broad knowledge base and in-depth expertise, capable of grasping the various aspects of the design process at different stages and offering unique insights within a specific domain" (P4, P8, P14).

Theme 3: Ethical Considerations in Industrial Design

Five interviewees (33.3%) pointed out that in the era of Industry 4.0, despite the improved services that new technologies can offer to users, the misuse and improper utilization of technology can also cause various issues. Technologies like big data analysis may infringe upon user privacy, as one of the participants noted: "After searching for something on a certain App, all the Apps start pushing similar content, which, to some extent, violates user privacy" (P7, P9).

In terms of social aspects and equality, elderly individuals often find themselves at a loss when faced with the constantly emerging new technologies, products, and features. As one participant pointed out: "During the peak of the COVID-19 pandemic, some regions used mobile apps for health management. However, some elderly people living alone suffered severe consequences due to their inability to use these apps" (P7). Some companies utilize big data technology to track employees' work performance. For instance, "food delivery companies keep records of the delivery drivers' performance and assign orders of varying complexity to motivate the delivery personnel to work more diligently" (P9). Designers should consider creating an accessible environment that is convenient, safe, and equitable for vulnerable groups such as people with disabilities. As one participant emphasized, "While technology is undoubtedly important, the principle should be 'no one left behind'" (P7).

When discussing solutions to the societal issues arising from the technology, the participants believed that blind misuse should be avoided (P7). Designers should incorporate ethical considerations as a restraint (P6, P11). In the discussion of the relationship between the integration of new technology with industrial design and design ethics, the participants expressed that they are overlapping, meaning that when incorporating new technology into design creativity, ethical aspects related to equality, social implications, and sustainability should also be considered to arrive at an optimal design solution (P7, P9). Design ethics serve as a crucial tool to constrain and mitigate the risks associated with the convergence of technologies and industrial design (P4).

Theme 4: Industrial Design Industry Insights

Some participants mentioned that the rapidly changing social and economic environment, as well as technological advancements, have a significant impact on the industrial design industry and the work of designers. Therefore, professionals in industrial design should possess the ability to gain insights into industry trends and maintain a forward-looking perspective. The AIGC technology, which enhances design creativity, has improved design efficiency but also has the potential to disrupt the roles of creative designers, possibly replacing their work in the future (P1). Some interviewees noted that economic fluctuations can affect the industrial design industry. The commercial nature of design means that a company's investment in design is influenced by market fluctuations (P4). Design professionals should have the ability to perceive the development trends to keep up with the times and avoid becoming obsolete.

Theme 5: Limitations Affecting Competence

Six participants (40%) emphasized potential limitations. In higher education institutions, it is difficult to access cutting-edge new materials, technologies, and products (P12, P14). This limitation can affect the feasibility of design proposals (P4, P5). In terms of interdisciplinary education, compared to engineering and science-oriented institutions, liberal arts and arts colleges encounter more significant difficulties in fostering cross-disciplinary collaborations (P6, P11, P14).

4. Discussion

4.1. Research Highlights

(1) Ethical Thinking in Mitigating Risks

This study highlights that designers integrating ethical considerations into design practices can mitigate the risks associated with the misapplication of new technologies in the Industry 4.0 era, corroborating earlier research [44,45]. Pre-Industry 4.0, ethical design focused on aspects like equality, environmental sustainability, and social morality, addressing issues such as environmental pollution and inequality. However, the rapid advancement of new technologies has introduced concerns about privacy infringements and the neglect of vulnerable groups. Research has primarily concentrated on the impacts on user privacy, security, social equality, and sustainable development [46,47]. This study identifies adverse impacts on user privacy and equality, advocating for the inclusion of ethical thinking as an additional capability in integrating new technologies into industrial design. This inclusion aims to preempt potential ethical issues during the design phase, fostering sustainable development. This finding resonates with Christoph Koch's research [45].

Tu et al.'s study suggests that new technology applications can foster sustainable development. For instance, digital technology applications in wearable devices and health management have enhanced users' health management and medical efficiency, alleviating healthcare burdens [48]. The amalgamation of new or clean energy with product design reduces reliance on conventional energy sources, curbing environmental impact and promoting sustainability [49]. This evidence underscores that the application of new technologies in industrial design has dual facets: judicious use yields positive impacts on users, society, and sustainability, yet misuse poses risks. Therefore, the integration of new technologies and industrial design's potential to promote sustainability hinges on designers' ability to use these technologies sensibly. Heightened ethical awareness among industrial designers is crucial in fostering responsible technology applications, countering privacy and social inequality issues arising from recent technology misuses.

(2) Influence of Emerging Technologies on Design Tools.

The emergence of new technologies significantly influences the trajectory of design tools. Recent findings from this study underscore the positive impact of AIGC technology on designers' efficacy, aligning with prior research [50,51]. Our investigation highlights the growing significance of AIGC technology as a pivotal tool for design capabilities in the Industry 4.0 era, resonating with the insights put forth by researchers such as Yi Luo* and Le Wang, who forecasted the influential role of AIGC technology in industrial design and emphasized the imperative for a paradigm shift in design education [52]. Studies by Ziyue Guo and Dongfang Pan have also emphasized the heightened productivity achieved through AIGC in text creation and graphic design [53,54]. Our study delineates multiple facets where AIGC technology can aid industrial design, encompassing support for user research, data analysis, ideation generation, and crafting design solutions, mirroring previous research findings.

However, an alternative perspective suggests that AIGC, via algorithms and big data analysis, might autonomously generate design solutions, potentially impacting traditional designer roles [55]. This study also unveils that while AIGC bolsters design efficiency, it concurrently poses challenges to traditional design positions. This evidences the nuanced landscape wherein the collaboration between AIGC technology and designers harbors both opportunities and challenges. While AIGC technology holds immense potential, its precise implications for design roles in the future remain uncertain. Researchers should persist in exploring avenues to maximize the advantages of AIGC technology in industrial design and foster profound integration between AIGC and designers.

(3) Practical Application of New Technologies in Industrial Design

This study illuminates how new technologies drive design innovation in the Industry 4.0 era, encompassing three sub-capabilities: augmenting user experience, innovating in appearance and functionality, and meeting personalized demands. Yet, our observations reveal divergent use of new technologies among design professionals across various fields and industries. Notably, disparities exist in technology adoption between design practitioners in manufacturing and the internet industry. In physical product design, additive manufacturing, 3D printing, and Color, Material, and Finish (CMF) applications feature more prominently than in the internet industry. Conversely, the latter exhibits higher utilization frequencies for digital technologies, big data analytics, and similar tools, aligning with prior research [56–59].

Additionally, research underscores the transportation industry's emphasis on autonomous driving technology [60,61]. A survey exploring virtual reality technology's application in product design and manufacturing indicates its suitability for the automotive and gaming sectors [62]. These insights suggest industry-specific associations with the adoption of new technologies. For instance, a study examining blockchain technology adoption surveyed experts across diverse industries, proposing a conceptual framework to guide stakeholders involved in blockchain technology adoption [63].

Comparatively, these research findings provide granular industry breakdowns and in-depth explorations of technology adoption patterns. They accentuate the necessity of establishing a technology adoption framework in industrial design, aiming to clarify rationales for new technology adoption and delineate the interplay between technology adoption and specific industries.

4.2. Competency Framework

Drawing upon the outcomes of the thematic analysis, it becomes evident that a competency framework (as depicted in Figure 6) can be formulated to encapsulate the intricate interplay of diverse competencies. This competency framework is structured into three distinct components: industrial design capabilities, industrial design industry insights, and factors constraining competence.

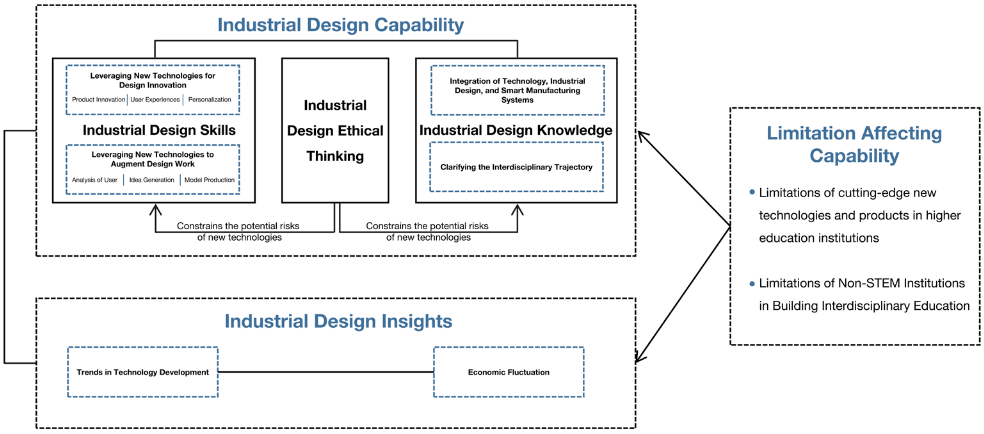

Figure 6. Competency framework for technology-integrated industrial design in the era of Industry 4.0.

4.2.1. Industrial Design Capability

(1) Industrial Design Skills and Industrial Design Knowledge

Leveraging new technologies for design innovation: Technology stands as the catalyst for innovation in industrial design [64]. Designers can propel design innovation by harnessing new technologies from three vantage points: enhancing user experiences, ushering in innovation in product aesthetics or functionality, and enabling personalization. Delivering superlative experiences and services caters to user expectations, a pivotal factor in design gaining recognition among users [65]. Product innovation encompasses the use of new technologies to drive design enhancements in functionality, usage patterns, and aesthetic dimensions. Personalization is a prominent trend that has emerged in response to shifts in production methods and the burgeoning demands of consumers.

Leveraging new technologies to augment design work: Technological progress contributes to the development of design-supportive tools, bolstering industrial designers in enhancing their work efficiency [66]. The use of new technologies can assist in various phases of the design process: during the user research stage, it can aid in the analysis of user requirements, thus facilitating a nuanced comprehension of user preferences; during the conceptualization stage, it can stimulate idea generation, lending efficient support to brainstorming sessions; and during the implementation phase, it can expedite model production, effectively realizing design solutions.

Integration of technology, industrial design, and smart manufacturing systems: Seamlessly integrating new technology with intelligent manufacturing systems through industrial design is a pivotal approach to unlocking the potential of technology and fostering the evolution of intelligent manufacturing [67]. Design professionals must wield the ability and consciousness to seamlessly amalgamate industrial design, new technology, and intelligent manufacturing systems, fostering collaboration with technical experts to proffer meticulously crafted design solutions.

Clarifying the interdisciplinary trajectory: To meet the multifaceted demands of design, industrial designers must amalgamate knowledge from a spectrum of disciplinary fields [68]. The increasing infusion of technology into design presents challenges to designers' interdisciplinary capabilities. The adeptness of designers in mastering interdisciplinary knowledge significantly influences the alignment of design solutions with smart production lines [69]. This study highlights that designers often possess a conceptual understanding of interdisciplinary knowledge, while the technical intricacies are predominantly handled by engineers. Engineers prioritize a deeper grasp of new technologies' operational principles for rationalizing design solution implementation, a viewpoint supported by some studies [70]. The dynamics of technological integration in the Industry 4.0 era require designers to bolster their interdisciplinary competencies. Moving forward, achieving a balanced proficiency in interdisciplinary skills between designers and engineers is imperative. This balance will contribute to delineating the trajectory of interdisciplinary capabilities.

(2) Industrial Design Ethical Thinking

Ethical thinking intersects with industrial design skills and industrial design knowledge. New technologies may pose challenges and risks to users and society, underscoring the role of industrial design ethics as a safeguard, working in tandem with industrial design skills and knowledge to address issues stemming from the misuse and unwarranted use of new technologies in the design process.

4.2.2. Industrial Design Insights

The advent of new technologies, such as AI, has not only facilitated design innovation and enhanced efficiency but has also presented some obstacles to design roles. The worldwide economic deceleration, precipitated by factors such as the COVID-19 pandemic, has the potential to exert negative repercussions on the industrial design sector. Professionals in the field of design should possess not just proficient design skills, but also a comprehensive understanding of the industrial design business. This knowledge is crucial to effectively foresee the potential effects of emerging technological advancements and economic fluctuations on the practice of design.

4.2.3. Limitations Affecting Competency

Higher education institutions are confronted by limitations chiefly stemming from two fundamental aspects:

(1) The inability to access cutting-edge new technologies and products.

(2) Non-STEM institutions grapple with difficulties in establishing interdisciplinary education programs.

As a result, higher education institutions should proactively forge partnerships with businesses to expand students' horizons. Non-STEM institutions ought to explore measures such as recruiting external educators, engaging corporate lecturers, and fortifying collaborations with industries to counterbalance the constraints imposed by the prevailing environmental circumstances.

4.3. Limitation and Future Research

This study, however, still exhibits certain limitations. The present study has successfully identified four capabilities and one restriction. Nevertheless, a limitation arises from the sample size constraints, which prevented an in-depth analysis of these technologies in relation to design stages and specific industries, thus limiting targeted recommendations for technology adoption. Future research endeavors will encompass expansive surveys encompassing industrial designers across diverse industries, aiming to uncover variations in the adoption of new technologies within distinct sectors. Additionally, our aim is to develop a bespoke technology adoption framework tailored to the realm of industrial design in the Industry 4.0 era. This framework will illuminate the intricate interplay in technology adoption, providing invaluable guidance for practitioners within the industrial design domain. Furthermore, it is important to note that while the semi-structured interviews encompassed a diverse range of countries and areas, the predominant source of data originated from Chinese firms or universities. This bias towards Chinese entities can be attributed to objective limitations. Future study should aim to enhance the attainment of a well-rounded representation of data sources. Furthermore, this study did not establish the validity and practicality of the research findings.

Future studies should aim to conduct a more comprehensive investigation into the correlation between the four skills and the different phases of industrial design. This research should focus on developing a theoretical framework that outlines the capabilities required for technology-integrated industrial design in the context of Industry 4.0. Furthermore, it is crucial to validate the practicality and effectiveness of this framework through empirical studies.

5. Conclusions

This study aimed to investigate the essential technological competencies that industrial designers should possess in the context of Industry 4.0. It adopted a mixed research approach, combining bibliometric analysis with semi-structured interviews. Initially, a comprehensive collection of literature was gathered, using key terms like "Industry 4.0", "industrial design", "technology", and "capabilities". Subsequently, co-word analysis and cluster analysis were conducted to identify the new technologies and technology categories closely associated with Industry 4.0 and industrial design. Following this, semi-structured interviews were carried out with industrial design professionals from the United States, Europe, South Korea, and China, guided by the findings from the previous analyses. The collected data were then subject to coding and thematic analysis to ascertain the necessary technological integration capabilities in the field of industrial design during the Industry 4.0 era.

The study's findings reveal the following:

(1) In the context of Industry 4.0, there are 80 new technologies closely linked to industrial design, including big data analysis, digital twins, CPS, IoT, and more. These technologies exert their influence on industrial design in four key domains: Digital Technology and Service Experience, Intelligent Manufacturing and Personalization, Additive Manufacturing and Material Processes, and Data Analysis and Artificial Intelligence.

(2) The technological integration capabilities required in the Industry 4.0 era encompass four primary dimensions: Industrial Design Skills (comprising New Technologies as Design Innovation Methods and New Technologies as Design Aids), Industrial Design

Knowledge (encompassing knowledge of intelligent manufacturing systems and interdisciplinary knowledge), Ethical Considerations in Industrial Design, and Industrial Design Industry Insight. The study also identifies a limitation that impacts industrial design capabilities. Furthermore, it proposes a framework for design capabilities.

In the context of industrial design, the application of ethical principles proves advantageous in harnessing the benefits of new technologies, mitigating their challenges in the Industry 4.0 era, and fostering sustainable development. While leveraging AIGC technology enhances designers' work, cautious consideration is vital to address potential associated threats. Moreover, the adoption of new technologies in industrial design varies among industries, warranting deeper exploration of these industry-specific disparities in technology adoption. Furthermore, the ongoing exploration and enhancement of interdisciplinary competencies are pivotal for achieving equilibrium between design and other disciplines.

This study pioneers the integration of Industry 4.0 era new technologies within the industrial design domain, establishing a cohesive framework that intertwines these technologies with design capabilities. It delves into the correlation between new technologies of the Industry 4.0 era and industrial design capabilities, expanding the existing landscape of industrial design. By delineating the trajectory of technology-infused industrial design capabilities in this era, this study serves as a catalyst for advancing the design acumen of practitioners, ensuring their alignment with contemporary demands. Simultaneously, it furnishes design educators with a framework for nurturing design talent in the era of Industry 4.0, thereby enhancing the standard of design education. Elevating the capabilities of design practitioners and augmenting the level of design education fosters strides in industrial design and smart manufacturing, fostering beneficial outcomes for the sustainable development of society. The proposed framework for integrating technology into industrial design capabilities within the Industry 4.0 era serves as a theoretical bedrock for evolving models that encapsulate the fusion of new technologies during this epoch.

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