

IMPACT OF 3D PRINTING TECHNOLOGY ON MEETING CONSTRUCTION 5.0 CRITERIA

Nikola Spicek¹

Svetlana Besklubova^{2*}

Miroslaw J. Skibniewski³

1 BMW Group AG, Munich, Germany, nspicek11@hotmail.com

2 The Hong Kong University of Science and Technology, Hong Kong, sbesklubova@connect.ust.hk

3 University of Maryland, College Park, USA, mirek@umd.edu

Abstract

In parallel to Construction 4.0, a new concept is also emerging, known as Construction 5.0. It combines the digital benefits of the Fourth Industrial Revolution with the Sustainable Development Goals, resilience and human welfare. Meanwhile, the adoption of 3D printing technology in construction projects can bring many benefits, such as reduced on-site labor, more reliable management of project deadlines and budgets, and more effective waste management. The question therefore arises as to whether 3D printing technology meets the characteristics of the Construction 5.0 paradigm and what the effects of 3D printing technology that meet the criteria of Construction 5.0 are. This study developed a taxonomy to assess how 3D printing technology meets the criteria of Construction 5.0. The model incorporates four main impact dimensions: Environmental Sustainability, Construction Safety, Compatibility Technology, and Resilience, to which 24 factors are assigned. Four case studies were evaluated using this modeled taxonomy. In view of these initial observations, it can be stated that 3D printing technology fulfills the Construction 5.0 criterion. 3D printing technology was found to be superior or at least slightly better than conventional construction methods in almost every respect, which is particularly evident in the impact dimension "Increased environmental sustainability (ES)". Using the prism of the human-centered approach and human-robot collaboration, humans could maximize their creative and inventive potential, while robots would take over dry, repetitive and very complicated tasks by means of automation.

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1. Introduction

The world is currently in the Fourth Industrial Revolution or Industry 4.0. Industry 4.0 is considered an innovative industrial phase in which various emerging technologies converge to provide digital solutions [1]. Technologies consider four dimensions: Smart Manufacturing, Smart Products, Smart Supply Chain, and Smart Working, while enabling technologies consider four elements: Internet of Things (IoT), Cloud Services, Big Data (BD), and Analytics [1]. Ten years after the introduction of Industry 4.0, the European Commission announced Industry 5.0. Industry 4.0 is considered technology-driven, while Industry 5.0 is value-driven. The coexistence of the two industrial revolutions raises questions and therefore requires discussion and clarification [2].

Industry 5.0, the Fifth Industrial Revolution, consists of intelligent digital information and manufacturing technologies [2]. Nahavandi [3] introduces the concept of Industry 5.0, where robots are interwoven with the human brain and work as collaborators rather than competitors. A new paradigm of Industry 5.0 involves the penetration of AI into people's everyday lives, their "collaboration" with the aim of increasing human performance and returning humans to the

"center of the universe" [4]. In other words, Industry 5.0 is characterized by an increased collaboration between humans and intelligent systems, facilitated through high-precision industrial automation that is supported by critical thinking [28]. In recent years, we have seen significant advances in robotics and AI research. While there are many studies on human-robot collaboration in simple tasks focusing on robot development, there is a lack of studies focusing on organizational issues arising from human-robot collaboration. Whether or not Industry 5.0 will mainly be about human-robot collaboration, human-robot collaboration will be a major change for organizations. Indeed, robots in our lives are likely to represent a significant change for humanity [29].

The construction industry is changing its processes and working methods, and the expansion of new technologies in recent decades [5]. The construction sector plays a key role in the economy of any country [6] and it is therefore a crucial sector for the European business, involving a wide range of stakeholders and companies as well as providing 18 million jobs [7]. According to the World Economic Forum, a 1% increase in productivity could save \$100 billion a year in construction costs worldwide, which can contribute to a country's competitiveness and sustainable development [8], [9], [10].

In recent years, the use of 4.0 technologies in the construction industry, referred to as "Construction 4.0", has increased, mainly due to the immense potential of Industry 4.0 to improve the performance of construction projects and to structure the underlying management processes [31]. Similarly, discussing Industry 5.0 in the context of construction, the new term 'Construction 5.0' has appeared. Construction 4.0 incorporated technologies like BIM, drones, robots, AI (including BD and Augmented Reality), Industry 5.0 introduces a social dimension to digitalization, emphasizing a commitment to Sustainable Development Goals (SDGs). As a result, Construction 5.0 represents the integration of the previous Construction 4.0 and Sustainable Construction working groups [11]. Although Construction 4.0 technology is capable of improving the design, management, operation, and decision-making of construction projects, the ability to fully integrate the technologies into the construction industry is low [12]. Even before fully realizing the potential of Construction 4.0, the concept of Construction 5.0 has already come into focus. While many companies are still grappling with the digitization of their operations through the integration of AI, IoT, and Cloud Technologies, the next phase of the Industrial Revolution looms on the horizon [13].

Among the various promising technologies and applications that Industry 5.0 supports to enhance production and deliver customized products promptly [13], one key technology is 3D printing [32]. This paper primarily focuses on the application and impact of 3D printing technology. 3D printing technology could offer several advantages over traditional processes, including lower material and energy consumption [14], [15], [16], [17], on-site production with lower resource requirements and lower CO₂ emissions throughout the product life cycle [18]. It also promotes changes in work structures, including a safer work environment, and brings about changes towards more digitalized and localized supply chains [19]. From an architect's perspective, 3D printing technology could shorten design and development cycles; allow customers to co-design products that perfectly match their needs and ambitions; enable the implementation of complex designs and the rapid management of design changes [14], [19], [15], [16], [17].

The goal of the Construction 5.0 working groups is to develop concrete recommendations/action plans for the construction sector on best practices for sustainable construction and innovation (Construction 4.0). The aim is to define opportunities, mainly from the construction companies' perspective, in terms of CO₂ reduction and energy consumption reduction (e.g., recycling frameworks, investment portfolios that allow carbon emissions reduction, etc.) [11]. The question arises as to how 3D printing technology fits primarily into the concept of Industry 5.0, but also what potential impact it has on meeting the criteria of Industry 5.0, respectively the sub-concept named Construction 5.0. This leads to the following research questions:

- 1) Does 3D printing technology match the characteristics of the Construction 5.0 criteria?
- 2) Which impact dimension inherent in 3D printing technology meets the criteria of Construction 5.0?

2. Methodology

To address the specified research questions, a multi-stage research approach was developed. Initially, a comprehensive literature review was conducted to establish a foundation for developing a taxonomy for assessing 3D printing technology in the context of Construction 5.0. This taxonomy, represented as a model, includes identified dimensions and their corresponding assessment factors. Following the taxonomy development, case studies were carefully selected to demonstrate the applicability of the model. These case studies encompass four distinct projects: a staircase formwork in Leipzig, Germany; the Zhaozhou Bridge in Tianjin, China; and two projects in Zurich, Switzerland—Smart Slab and an integrated funicular roofing system. In the third stage, focus group interviews were conducted to evaluate the selected case studies using the proposed taxonomy model and its dimensions and factors. The assessments were quantitatively supported using a Likert scale, allowing for a structured and nuanced analysis of the perceived effectiveness and benefits of the methodologies discussed. Finally, a comparative analysis was undertaken to synthesize the findings from the case studies and focus group outcomes, providing a comprehensive assessment of the research questions. This methodology ensured a thorough examination of the practical applications and implications of 3D printing technology in construction, particularly within the framework of Construction 5.0.

3. Results

3.1 Taxonomy development

To assess 3D printing technology within the context of Industry 5.0, a comprehensive assessment taxonomy was developed. The development of this taxonomy began with the identification of key dimensions through a thorough review of the existing literature. Since the Construction 5.0 concept is discussed only very tentatively in the literature, because it is a rather innovative idea, similarities and implications from Industry 4.0 and Construction 4.0 are drawn. It was assumed that Construction 5.0 is an extension of Construction 4.0 and that there is no meeting the criteria of Construction 5.0 without simultaneously meeting the criteria of Construction 4.0.

Environmental Sustainability (ES) dimension. Sustainability becomes one of the most important drivers in organizations and projects, which makes the relationship between project management and sustainability project management and sustainability crucial. A life cycle assessment has become an essential tool for eco-design and eco-planning, aimed at developing products and processes that are more environmentally efficient. This comprehensive evaluation measures the environmental impact of a structure throughout its entire life cycle. It encompasses a multi-parameter assessment of all significant environmental factors, such as CO₂ emissions, energy consumption, water usage, and waste generation, within a unified evaluation process [20].

Construction Safety (CS) dimension. The concept of safety culture is relatively new to the construction industry; however, it is gaining popularity because it incorporates all perceptual, psychological, behavioral and management factors [21]. There are many types of workplace hazards. These include ergonomic, chemical, biological, physical, psychological, etc., that can cause harm or adverse effects in the workplace [22]. With the increasing use of digital technologies in the design of buildings and infrastructure, questions arise about their impact on safety in construction [360].

Compatibility Technology (CT) dimension. As all Industry 4.0 technologies promise a human-centered approach, less waste and an optimized process, it is assumed that their nature should also be in line with the Sustainable Development Goals. Industry 4.0 is a reminder of the era of craft manufacturing and is accelerating the shift from mass production to mass customization. The sharing of distributed 3D printers and IoT collaboration is set to create a promising dynamic, globalized, economical and time-saving manufacturing environment for customized manufacturing products [23]. The prerequisite for this should logically mean that 3D printing technology is compatible and user-friendly with the technologies that made the Fourth Industrial Revolution possible.

Resilience (RE) dimension. With the rapid growth of information and communication-based technologies such as 3D printing, mechatronics, machine learning, Big Data and the IoT, the construction sector is experiencing a shift towards

digitalization and automation (known as Construction 4.0). Such technologies diversify the design, planning, construction, operation and maintenance of civil infrastructure systems and have a positive impact on overall project time, cost, quality as well as productivity. These new technologies mean that the industry will also become more connected, making cyber security of utmost relevance [24]. Cyber resilience covers the fields of security, monitoring and business continuity/disaster response technology. For a successful cyber resilience strategy, however, a holistic approach is required that starts with people and processes - only then does the relevant technology follow [25].

Without resilient answers to possible tech disturbances, the usefulness of 3D printing technology as a technology that can meet all the requirements of the new industrial revolution is called into question.

On the basis of the literature review as well as the concepts of Industry 4.0 and Construction 4.0 analogies, the most important impact dimensions for meeting the Construction 5.0 criteria when utilizing 3D printing technology in construction projects are determined as follows: Increased Environmental Sustainability (ES), Increased Construction Safety (CS), Increased Compatibility (Technology) (CT) and Increased Resilience (RE). Each of these dimensions has an abstract nature, making direct assessment challenging. Consequently, a list of assessment factors has been elaborated for each proposed dimension.

The dimension Increased Environmental Sustainability (ES) contains Reducing CO₂ emissions (ES1), Reducing Carbon Footprint (ES2), Reducing energy consumption (ES3), Reducing water use (ES4), Reduce construction time (ES5), Waste generation reduction (ES6) and Using local materials (ES7).

The collective named Increased Construction Safety (CS) comprises: Reduce biological hazards (CS1), Reduce chemical hazards (CS2), Reduce ergonomic hazards (CS3), Reduce ergonomic hazards (CS4), Reduce physical hazards (CS5) as well as Reduce mental fatigue of workers (CS6).

The following cluster is defined as Increased Compatibility (Technology) CT and encompasses: Compatibility with IoT (CT1), Compatibility with Big Data (CT2), Compatibility with BIM (CT3), Compatibility with Cloud Computing (CT4) and Compatibility with Artificial Intelligence (CT5).

The last impact dimensions set is named Increased Resilience (RE) and includes: Resilience for natural hazards (RE1), Resilience by Cyber security challenges and vulnerability (RE2), Robustness (RE3), Resourcefulness (RE4), Rapid recovery (RE5) and Redundancy (RE6).

All impact dimensions are graphically shown in Figure 1. An additional clarification of these can be found in Appendix as part of the answers from the case studies.

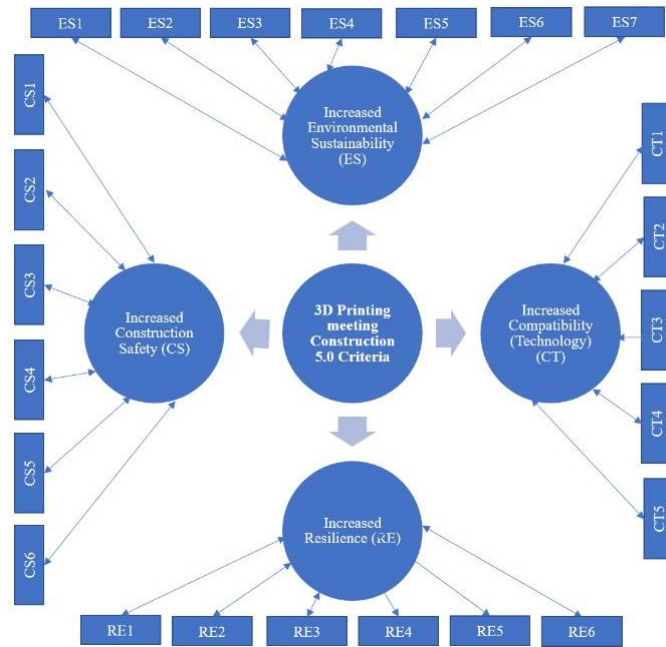


Figure 1. Proposed model of impact factors of 3D printing technology on meeting the criteria of Construction 5.0

3.2. Case studies

When selecting case studies, the intention was to find construction projects that are representative samples of the 3D printing technology utilization, from companies and universities that have proven themselves in the 3D printing community. Each of these are tangible examples of the 3D printing application, with the use of this technology as a potential alternative to traditional construction methods. Explanatory, descriptive case studies were evaluated through interviews conducted with focus groups, and these answers were later numerically / quantitatively supported by a 5point Likert scale.

Case study 1: Sächsische Aufbaubank in (Leipzig, Germany).

During building of the headquarters of the "Sächsische Aufbaubank in Leipzig", a half-spiralled staircase with transitional landing was to be assembled, which is loaded on a supporting wall (Figure 1a). High-precision concrete formwork was required to give it a smooth and homogeneous shape [26]. For this project, the project leaders placed their trust in the world-renowned formwork supplier. After an extensive analysis and definition of the formwork shape for the staircase, the surfaces were grouped by complexity. The distinctive detail of this staircase, however, was the triaxially curved surface, which reflects the concave shape of the underside of the staircase to the inside of the loadbearing wall [26].

Case study 2 - Old stone bridge rebuilt with 3D concrete printing (Tianjin, China).

Zhaozhou Bridge, a notable stone arch bridge from China's Sui Dynasty was recreated by Hebei University of Technology in Tianjin, China using 3D printing technology (Figure 1b). The 3D-printed bridge has the longest single span of 17.94m midst 3D printed bridges in the world, with a total length of 28.1m. It was printed off-site using a modular method and afterward assembled on-site to the 1:2 scale of the original antique bridge. The printed material and automated equipment were particularly planned and created for this action. This bridge has an extreme safety coefficient, as the loading of unique different bridges has been considered.

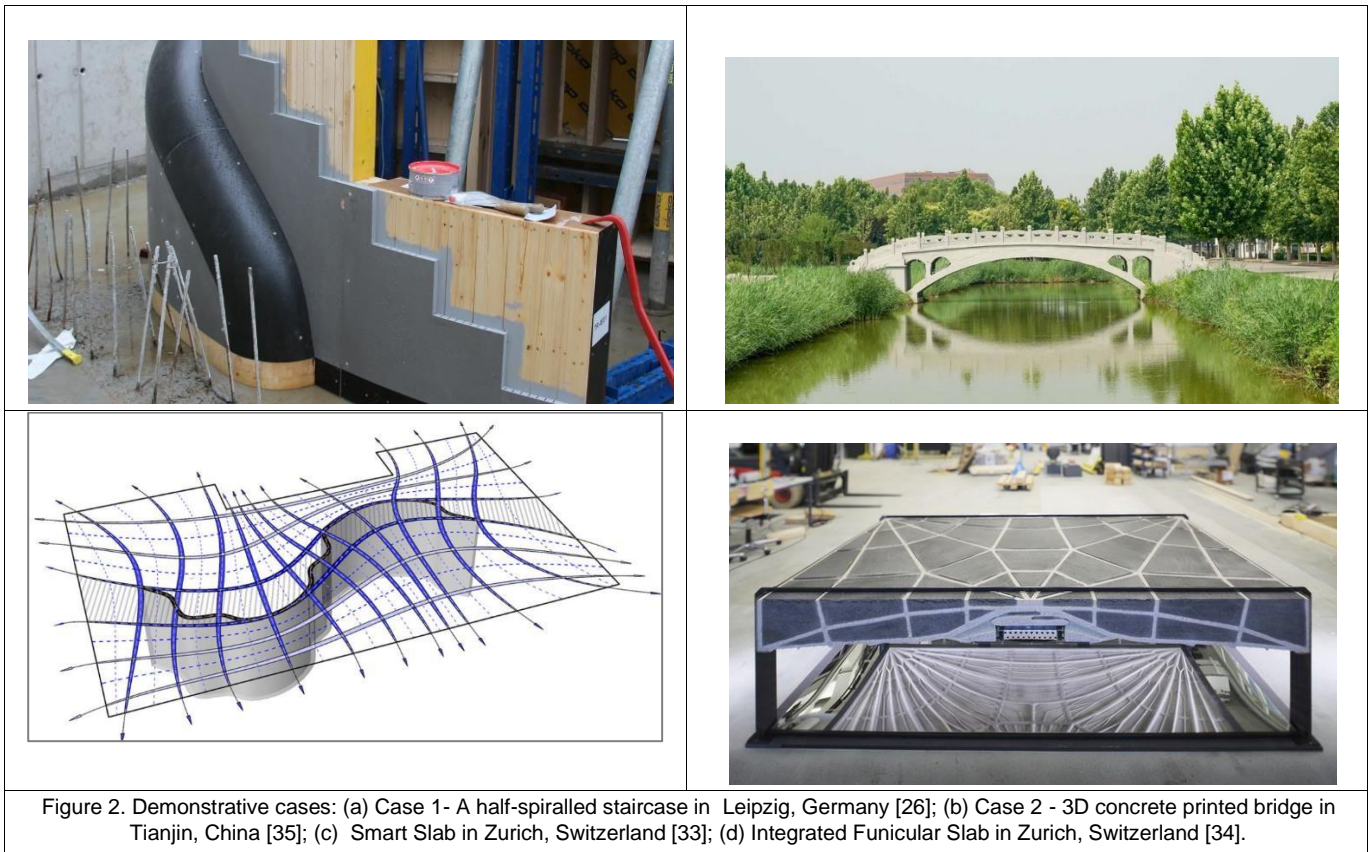
Case study 3 – Smart Slab (Zurich, Switzerland)

Smart Slab is the first load-bearing concrete slab constructed using 3D-printed formwork (Figure 1c). The lightweight concrete slab is exemplified by its three-dimensional geometric diversity on several levels. The project links great

structural properties of concrete with the geometric freedom of 3D printing technology. This construction technique allows the design of extremely improved concrete components with complex decorative structures.

Case study 4 - Integrated Funicular Slab (Zurich, Switzerland)

This case study is grounded on the state-of-the-art 3D printing technology and demonstrates how multiple layer 3D printing can be exploited to generate a tailored formwork from absolutely recyclable materials for a functional concrete slab (Figure 1d). The final product is structurally effective and only weighs 30% of a conventional solid slab. Moreover, it showcases the integration of a complex unflustered beam ventilation system within the slab's 30 cm deep construct. All these complex geometric characteristics are accomplished with an extreme-light 3D-printed formwork that weighs less than 10 kg for the complete 600 kg concrete slab.



3.3. Case studies Taxonomy Assessment

Focus group interviews were conducted based on four distinct case studies to gather qualitative insights. Following the discussions, responses were quantitatively supported using a 5-point Likert scale to compare the outcomes with those of traditional construction methods. The scale was designed to measure perceptions of improvement or degradation, where a rating of 1 indicates "much worse," 2 signifies "worse," 3 denotes "no difference or not recognized," 4 represents "better," and 5 suggests "much better."

Figure 4.a) shows the dominance of 3D printing technology over traditional construction in area of Increased Environmental Sustainability, according to the scores collected on the Likert scale. Although to a lesser extent, this superiority is also visible in the figures 4.b (Increased Construction Safety), 4.c (Increased Compatibility (Technology)) and 4.d (Increased Resilience). Each column shows the number of points scored according to the classification from “much worse” (1) to “much better” (5), always in comparison to the traditional construction.

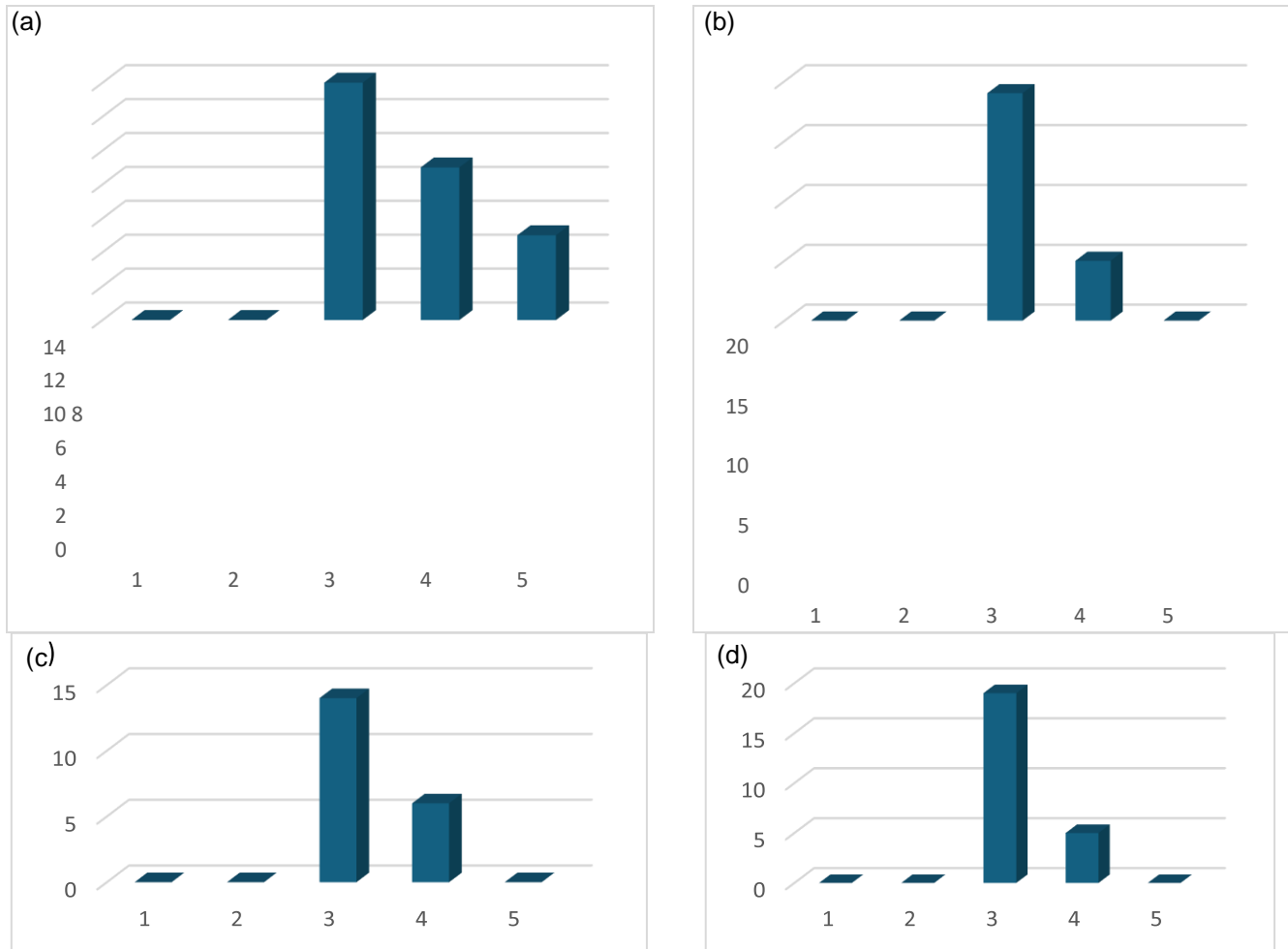


Figure 3. Category assessment: (a) Increased Environmental Sustainability; (b) Increased Construction Safety; (c) Increased Compatibility (Technology); (d) Increased Resilience

4. Discussion and Conclusion

Alongside the term Industry 4.0, we are already confronted with the concept of Industry 5.0. By contrast, while Industry 4.0 is considered technology-oriented, Industry 5.0 focuses on value. This defines Industry 5.0 as increased collaboration between people and intelligent systems through high-precision factory automation, enabled by critical thinking. It has also been noted that Construction 5.0 aims to promote the alignment of technological and digital innovation in the construction sector from a societal perspective.

This study once again highlighted the gap between Industry 5.0 and Construction 5.0, with the construction sector lagging behind in all areas, both scientifically and practically. In addition, the need for a holistic approach to managing the sustainability of projects is evident, as is the need to more consistent application of lean management principles with the aim of achieving better overall project success.

Based on analogies and conclusions from Industry 4.0, Construction 4.0 and Industry 5.0, an initial model of the impact dimensions of 3D printing technology on the fulfillment of the criteria of Construction 5.0 was presented. The

model presented in this study comprises a large number of impact components, which were narrowed down to 4 impact dimensions in order to enable a straightforward grouping and/or a consistent analysis organization. Namely: “Increased environmental sustainability”, “Increased construction safety”, “Increased compatibility (technology)” and “Increased resilience”.

To put this preliminary model to the test, 4 different, in-depth, case studies were conducted. Focus group interviews were conducted, and respondents' answers were further quantified in numerical form using a 5-point Likert scale.

The large number of responses within this small sample indicates that the aforementioned aspects are either not identified or that no differentiation is made between construction projects using 3D printing technology and more traditional construction methods. Of the aspects considered, nevertheless, 3D printing technology was certified as being superior, or at least moderately superior, to conventional construction methods in practically all respects, which is particularly evident in the impact dimension called “Increased environmental sustainability (ES)”. Considering these initial observations, it can be stated that 3D printing technology fulfills the Construction 5.0 criterion.

All of these impact factors contribute to defining the criteria of the Construction 5.0 concept in their respective manner. It can be argued that 3D printing technology fulfills the criteria of Construction 5.0 in each of these impact dimensions (in which impacts are being addressed) thereby helping to shape the desired more sustainable future of construction sector. Especially through the prism of the human-centric approach and human-robot collaboration, humans would be able to maximize their creative and inventive potential, while robots will perform dry, repetitive and very complicated tasks through automation.

Given the small number of case studies carried out and their limitations in terms of stage of implementation and level of complexity, it is proposed to extend the test sample for further studies on this topic. This is also the biggest limitation of this study. The fact that they were collected in only four cases where 3D printing was applied in the part stage of the whole building context, where these projects can be freely described as pilot projects. Furthermore, conclusions are largely limited to conclusions drawn from the larger concept called “Industry 5.0”.

The contribution of this study is in creation of “Information base” on phenomenon connecting Construction 5.0 and 3D printing technology. By taking these factors into account, it is also possible to make adjustment of risk evaluation procedures when managing construction projects implemented by use of 3D printing technology.

There is also a need to create more definable targets for the Construction 5.0 concept and to establish mechanisms for measuring the successful application of this concept in construction projects that utilize 3D printing technology. Both future research directions should help standardize the process and confirm the importance of technology adaptational critical success factors in selecting a construction method for potential investors.

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