Application and Evaluation of a Cross-Fertilization Methodology in the AEC Industry: New Technologies, Digitalization and Robotization

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Abstract. The construction industry (AEC) has been stuck in a state of lagging innovation for too long, especially when certain processes are deepened. Excluding research into innovative and high-performance materials, it is difficult to stimulate and introduce new updates in other sectors.

In this historical context - NextGenEU, Green Deal, Horizon Europe - the AEC is called upon to assimilate the advances that Industry 4.0, digitization and robotization are introducing. This will have to happen quickly and with different types of innovations: technological, in management processes and in the economic structure of companies.

The aim of this paper is to design a methodology to classify useful innovations for an established sector and to determine which ones are more difficult to adopt and implement successfully. This was done by applying the methodology of the so-called "cross-fertilization" of knowledge spheres. This methodology is based on the principle that multidisciplinary interaction of projects and technologies leads to a network of innovative ideas.

The original contribution of this paper is the definition of the characteristics arising from the cross-fertilization process and the qualitative assessment of their applicability in a stated scenario: the worksite of large-scale infrastructure projects, with a particular focus on the management and monitoring of work progress and the construction of tunnels. The analysis of the results highlights four areas of action for implanting innovations in AEC and how this is only possible through a multi-disciplinary and integrated process.

Keywords: Innovation · Industrial Cross-fertilization · Digitalization

1 Introduction

Over the years, within the AEC industry - Architecture, Engineering and Construction - a status quo in the operative approach and method has been maintained. This has highlighted the difficulty in the introduction of new technologies and innovations on a large

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scale [1], often one-off and dedicated (e.g. new materials). The latency in the introduction of new technologies in AEC can be traced back to several inhibiting factors: the small number of economies of scale within a highly fragmented sector [2]; the absence of initiatives and training of companies and employees [3]; and the multidisciplinary nature of each project and the presence of multiple teams generate difficulties in recognizing roles, responsibilities and distribution of benefits [4].

With the advent of the fourth industrial revolution, we are witness of an acceleration in the digitalization and automation of work that will have an enormous impact on the work and career experiences of individuals [5]. In the latest recovery plans and new development strategies on an International scale and promoted by the European Union, a key role is played by Digitalization. The European Green Deal identifies digital transition as one of the two pillars on which to formulate its strategies [6] to be implemented through the plans promoted by the NextGenerationEU fund [7]. Within them, a number of themes of interest are highlighted in this contribution: Research and innovation - to boost economies and competitiveness; Employment support and job creation - to support job creation and transition to new sectors and types of work; Connectivity - fast and accessible digital connectivity; Energy efficiency in buildings - investment in energy renovations and compliance with the highest energy efficiency standards [8]. The latter is conceptually extendable to the entire AEC industry.

The Cluster 4 - Digital, Industry and Space - of Horizon Europe itself emphasizes how investment in research in this sector can support Europe's technological and economic competitiveness. Some specific areas of intervention are also highlighted: a human-centered and ethical development of digital and industrial technologies; digital and emerging technologies for competitiveness and fit for the Green Deal [9]. The whole plan outlines a circle of initiatives, strategies, and guidelines at European level on the digitalization of processes and infrastructures. Indeed, the AEC and related industries are stimulating the adoption of advancements in artificial intelligence and Internet of Things (IoT) ecosystems to increase productivity and economics value [1].

This contribution attempts to answer some questions arising from the difficulty of introducing digital and robotic innovations within the AEC; an industrial cross-fertilization methodology will be developed to investigate the main innovative trends: intelligent robotics; cloud VR/AR and AIoT; Digital Twins; 4D printing and Block-chain [10].

Which industries innovate the most?

Do they prefer digital systems or the introduction of robotic systems in a given context? How can these innovations be introduced in AEC?

In order to address these questions, 125 innovations were identified within 9 target sectors. From their analysis, in relation to their possible applicability in the construction of large infrastructures and the management of complex construction sites, four possible alternatives for their classification come out.

The paper is divided into five parts: the second is useful to provide a context around which to focus the research. The concepts of Building Information Model (BIM) and Digital Twin (DT) will be introduced as well as motivating the issues that inhibit innovation within the AEC.

The third part proposes and explains the original methodology used, which cross-fertilizes critical literature analysis. In the first instance, two of the problems present in an AEC are identified: the maintenance of the Tunnel Boring Machine (TBM) head and the tracking of the progress of huge worksites.

In the remaining parts, the results will be analyzed, and conclusions will be drawn regarding the methodology used. For the development of this methodology and its application, reference is made to the activities carried out by UniWeLab, a Joint Lab of the University of Genoa, which involves volunteer students from different disciplines doing research on real problems, identified by the collaboration between the University and Webuild, a leading Italian multinational in the large infrastructure construction sector.

2 Background

Referring to digital innovation in AEC, the thought goes to the modification of operation sequences and processes, caused using digital technologies [11]. The challenge is to have a process that is able to encompass the various components around the realization of an infrastructure, in which engineering and economics aspects are no longer than only few of the branches. From this assumption, new technologies will improve and change operations and processes, requiring changes in overall security, adaptive business, and sustainability. [12–14]. Therefore, at all stages of the infrastructure life cycle, from preliminary design to execution and maintenance, they are required to adopt digital models that facilitate the project management process [15].

Precisely with a view to a circular economy for AEC, several studies focus on the generation, evaluation and valorization of construction and demolition waste (CDW) [16, 17]; this is mainly due to the fact that the current recycling system for these materials has a high environmental impact and a considerable level of resource waste [18, 19]. Bringing CDWs within a circular vision in the AEC industry, as well as digitization, has encountered socio-economic barriers related to resistance to cultural change and the high cost of making a profit only in the long run [16].

In recent years, much attention arose around technologies such as BIM and DT as tools to be implemented and useful for the life cycle management of infrastructure and buildings [20]. BIM is an important tool for a complete digitalization of the building process; however, this innovation process is mainly developed by the tool providers themselves [21] and the innovation itself can be classified as product or service innovation, or related to operational and management practices, methods and processes [22]. Instead, a Digital Twin is a complete simulation of a real system through which to model its behavior as parameters and operational scenarios change in order to predict how it will respond [23]. Although DTs are still in their infancy, BIM systems are already more solid. However, in the literature many researchers refer to DTs interchangeably with BIM [24]. This underlying confusion may be among the problems that prevent a "smooth" implementation of these tools.

In addition to BIM and DT, artificial intelligence (AI) is increasingly being adopted by organizations, but implementation is often done without carefully consideration of the employees who will work with it. If employees do not understand or work with AI, it is unlikely to bring value to the company [25].

Another topic of relevance is the safety of and on construction sites. Focusing on AEC, conceptual designs for safety management based on the use of AI directly on the construction site were first proposed [26]; the influence of site layouts on construction workers' perceptions of robots and how their layouts affect the smooth running of site activities was also studied [27, 28].

Furthermore, among the issues that inhibit investment in digitalization and automation in AEC, it has been noted how they can contribute to wages and careers' inequality in low and medium-skilled jobs [29, 30]. However, it has been shown that in the sectors implementing robotics, inequality in the employment/population ratio is minimal [31], especially when compared to the impact of other capital and technologies [28]. In fact, project management in the construction industry presents unique challenges, which have a clear impact on project success. This is due to the fact that each project has unique characteristics such as: location, number of personnel, specific equipment, integrated logistics, cost variations and business capabilities. These are all factors that influence the design and make up the complex space of maneuvering in management [32].

Thus, referring to the major problems in the construction sector, the following items mainly emerge: labour shortages; site safety; site management and worksite organization; optimal use and processing of materials; personnel training and updating. These are all industrial systems' issues that are responsible for the delay the introduction of new technologies.

3 Methodology

As the previous section has shown, there is neither much past expertise nor novel motivation to introduce new technologies within the AEC and this is mainly due to the specific boundary conditions that differ from project to project.

For this reason, the UniWeLab research group identified the need to introduce a new methodology that could help the development of new solutions. This is the case of a context, such as that of Genoa. The City sees numerous works being carried out, involving excavations in complicated territories and the management of construction sites that are large in terms of the number of activities, companies and workers (e.g. Terzo Valico - Cociv, Sub-port Tunnel, New Outer Dam, New Waterfront).

The methodology proposed and used by the consists of three steps (see Fig. 1): a targeted literature analysis; the identification of the main issues under study; the application of industrial cross-fertilization to identify the industries that innovate the most and their affinity with AEC. This approach investigates if and how technological and cultural cross-fertilization from other industries is possible for AEC (see Fig. 1).

All outputs contribute to the final classification of the four areas of intervention, which will be commented on in the fourth section of the paper.

3.1 Literature Analysis

The literature review is conceived as a preliminary step in the start-up of the methodology, the purpose of which is to provide basic training on the subject of investigation and its issues: in this case, it is about digitalization within the AEC industry.

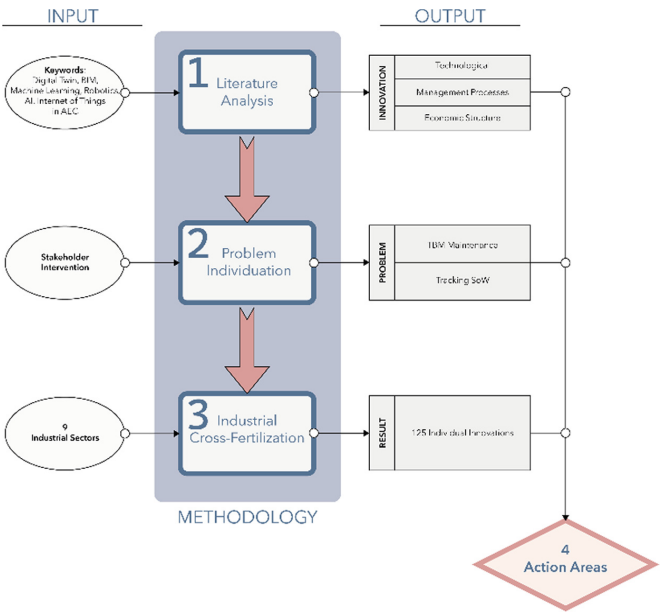

Fig. 1. Example diagram of the proposed methodology.

The first part of the literature analysis consists of identifying articles that make up the starting framework. This was done by asking the students in the research lab to cross-reference some keywords on Google Scholar and Scopus: Digital Twin, BIM or Building Information Model, Machine Learning, Robotics, Artificial Intelligence or AI, Internet of Things or IoT. Each of these had to be accompanied by the terms: AEC or AEC Industry or Construction Sector. Furthermore, some minimum criteria were used to refine the search: published and open access articles, in English. This first part composes the necessary input for the start of phase 1 of the methodology (as in Fig. 1).

The second part of the literature analysis consists of reading and critically reporting on the selected paper. This is done by identifying some of the main components included in each paper: thesis developed by authors, the solution they identified, analysis of the bibliography they used. Finally, the students were asked to summarize the main topic of the paper they analyzed through a guided critical analysis.

The last part is, therefore, the evaluation of results or outputs. Three types of innovation emerge from the literature review: (I) technological innovations; (II) innovations in management processes; (III) innovation in the economic structure of companies.

Technological innovations (I) include robots working autonomously [33] and alongside workers [34]; machine learning applicated to real time video capturing infrastructures progress [35, 36] or machines for laser scanning in boundary conditions [37, 38].

In management process innovations (II) there are: software for modelling the entire life-cycle of the worksite [39, 40] such as BIM [15, 22] or digital twin [41]; Decision Support System technologies [42–44]; VR and AR tools to support and simulate

design [45] or IoT and OT ecosystems - operational technologies [46]; collaborative BIM Decision Framework [47]; a multi-objective Genetic Algorithm "GA" [48]. When talking about GA in AEC, reference is made to models that aim to provide horizontal and vertical support in the organization of mega-projects. This is done through a digital system programmed to verify operations and capable of reconfiguring itself according to changing boundary conditions in order to minimize project duration and cost, optimize resource and maximize quality [49].

Innovation in economic structure of companies (III) are: digital infrastructure for effective and sustainable circular economies [49, 50]; AI integration model based on socio-technical systems theory (STS) [25], managerial business strategies of investing in innovation trends [51].

Concluding the analysis, it is the advent of Industry 4.0 itself that requires companies to reorganize themselves structurally; furthermore, another innovative aspect that emerges is the conscious use of mobile and social devices, in conjunction with specialized professionals able to facilitate the transition, by incurring minimal costs for the distribution of information and knowledge [52].

3.2 Problem Individuation

In identifying the main issues to be studied, certain notions from the previous phase were considered, but added practical and critical reflections emerged from the dialogue with the company.

The inputs from phase 1 of this methodology, it emerges that there is a little appeal in the introduction of new digital and robotic technologies in the AEC, although there is a demand and a need for them. In addition, among the major challenges faced during the tasks that make up each job order, problems emerged related to the identification of critical elements and full-time site management. In addition to these, an issue of highlighted importance by the Webuild managers of the workshop is the issue of operator safety during the most critical tasks.

From the first stated assumption, the issue of monitoring and controlling site activities emerged: tracking of statement of work (SoW). This operation is still poorly digitalized and too dependent on human judgement; SoW Tracking on the construction site is traditionally a non automated activity requiring visual inspection and dependent on human judgement and, therefore, error [35]. This activity therefore can be a primary test bed for the implementation of new technologies or digital ecosystems.

Among the most complex tasks affecting worker safety and health are those inherent in excavation operations. TBMs are widely used in hard rock tunnel excavation due to their optimal performance; however, during tunnel excavation, the rotary head is element that suffers most from wear and therefore subject to the most frequent maintenance operations [53, 54]. These critical operations occur in critical situations for the operator who, consequently, is put at risk.

Thus, in the next steps of the proposed methodology, the possibilities of introducing digital innovations in these two processes involving AEC through a process of Industrial Cross-Fertilization will be analyzed.

3.3 Cross-Fertilization Application

The last part of the proposed methodology uses an industrial cross-fertilization process to understand in which industries, outside the AEC, the major innovations occur and whether they are importable in the construction sector. Building on cross-fertilization concept, that originates in the natural sciences and accelerates the natural evolutionary process [55], various disciplines-marketing, education sciences, management-have inherited this methodology by readjusting it to their needs [56].

Thus, trying to give a definition of Cross-Fertilization as applied to the field of research and development in industry, it can be said that Cross-Fertilization is done when the combination of interdisciplinary technologies and knowledge generates new broader technological opportunities in terms of Product, Performance and Functionality [57–61]. Therefore, the purpose of interdisciplinary cross-fertilization is to avoid inventing something new that already exists; to fill gaps in a field by synthesizing knowledge dispersed across several disciplines towards a single result [62].

For this phase of the methodology, nine industrial sectors were identified in which to research new digital, robotic technologies introduced in recent times: Aeronautics and Aerospace; Agribusiness; Chemistry and Materials; Electronics and Information; Energetics; Military; Mining-Oilfield; Port; Safety and Health.

The search for innovations in other industries was carried out by the students in the UniWeLab laboratory. For each sector, the search was carried out using different methods: web search, scientific articles, company reports and newsletters, trade journals… The output of this third stage of the methodology is a list of innovations to be evaluated. Each element of this list was classified according to its sector of origin and then validated as specified in Sect. 4; the ultimate goal is to determine in which sectors there are more innovations and which of them can be introduced in the AEC and in which areas.

4 Results' Analysis

Through this method, 125 technological innovations in 9 different industrial sectors were identified. Subsequently, a skimming process was introduced to identify unsuitable innovations, which reduced the list to 111; among the reasons why some were excluded were because they were too generic in relation to the contribution they could make, e.g. digital twin or robotics; or because their applicability was too far removed from the relevant sector, e.g. Synthetic Meat.

Table 1 summarizes the results of the list by breaking down the innovations by industry sector of origin at two different points in time: before and after the validation process (see Table 1). The largest digital and robotic innovations identified come from the broad sectors such as Aeronautics and Aerospace and Port (26 and 22 innovations). These are two areas where the demand for innovation is broad and urgent for the proper handling of complex tasks and activities and where precise execution is required. Also relevant is the interest in digital innovation for the Safety and Health sector, underlining how the topic of safety, which has emerged among the crucial issues for AEC, is among the most proactive.

Looking at those sectors that retained the same number of innovations after the skimming process, Mining-Oilfield and Electronics and Information stand out. This

could also be due to the affinity of the two sectors with the two issues that emerged in phase 2: TBM maintenance and SoW tracking: two works that, respectively, refer to the processes of excavation and remote verification of activities and their quantification. In the Agribusiness Sector the introduction of AI and robots that facilitate the harvesting process face some challenges attributable to SoW tracking and processing verification. Computer vision technologies are being investigated to identify fruits and vegetables in plantations and locate their position through image retrieval for algorithm operation [63, 64]; another issue concerns the study of manipulators, which must be robust enough to be able to rip the fruit from its seat, but sensitive enough to avoid compromising its integrity [64, 65].

Finally, the Chemistry and Materials sector is the industry area that has the greatest grip within the AEC, as a large part of today's construction activities include retrofitting: an activity where materials that combine high performance and cost-effectiveness are among the most popular.

Table 1. Innovations by industry sector of origin, before and after the validation process.

Industrial Sector	First List		After Validation	
	n.	%	n.	%
Aeronautics and Aerospace	26	23,4	22	19,8
Agribusiness	10	9,0	9	8,1
Chemistry and Materials	8	7,2	7	6,3
Electronics and Information	9	8,1	9	8,1
Energetics	16	14,4	15	13,5
Military	11	9,9	11	9,9
Mining-Oilfield	5	4,5	5	4,5
Port	22	19,8	18	16,2
Safety and Health	18	16,2	15	13,5
	125		111	

The last step in the analysis of the results was to verify the applicability of the innovations within the AEC. This process investigates how to classify (in a descending scale) each innovation within a reference context of the construction industry. As Table 2 shows, it was possible to identify 4 action areas which can introduce a digital and robotic innovation process: Accessory Innovation, System Innovation, Construction Site Innovation and On Operator Innovation.

4.1 Accessory Innovation

Innovations included in the Accessory Innovations are all those new technologies that do not have a possible direct application with respect to the given tasks. However, they can support of other innovations; they have collaborative value e.g. new materials or Hydrogen combustion cell. Their application is to be considered ancillary to other technologies, in order to achieve a higher level of autonomy, safety, sustainability and innovation.

Table 2. Table identifies the 4 action areas in relation to the number of innovations identified.

Classification	n
Accessory Innovation	28
System Innovation	32
Construction Site Innovation	10
On Operator Innovation	41

4.2 System Innovation

System Innovations fall mainly into process innovations, in which the pivotal goal being increased efficiency, reduced costs and time within a production process. It can be seen that, among the sectors investing the most in these technologies, there are the Port, Aerospace and Information industries e.g. Simulators or IoT ecosystem. System innovations make possible to intervene upstream of the worksite, going preventive and generating a safer and more manageable sensor and monitoring system, or platforms that can independently monitor the progress of construction projects and build a systematic strategy for collecting standardized data [66].

4.3 Construction Site Innovation

Construction Site Innovations possess a characterization such that they can act directly within the shipyard system, with possibly minor or major modifications to it. In this case we see a strong inclusion of robots within the sectors taken as examples: agribusiness, military, port and health e.g. Industrial Robots like [67]. These robots can act in three modes: Local Control; Remote Control; and full Autonomous [68]. Each level through which a robot acts indicates a different type of human-robot interface, this, means that depending on the processing at the site it is necessary to plan which robot technology is best suited. Furthermore, the results suggest that separate human-robot sites increase the perceived safety of workers in robotic tasks [10].

4.4 On Operator Innovation

On Operator Innovation means investing directly in technologies that enhance individual human potential. A worker in the construction industry performs wearisome work both physically and at stress levels, so this area includes technologies that safeguard and monitor the health of the operator e.g. mechanical prostheses. The main goal of this kind of innovation is to minimize the risk for operator - before-during-after work - directly protecting human bodies. Finally, there are innovations that utilize the direct presence of the operator on site to verify operations e.g. smart lens for constant monitoring of accessibility.

5 Discussion and Conclusion

Concluding remarks firstly concern to the analysis of the limitations of this research, mainly arising from the context of application. Referring to existent literature, it is possible to point out that, as far as the subsequent stages of the methodology are concerned, the results obtained are sufficient for the identification of the issues around which the specific case study was developed. However, for a future refinement of this methodology, an updating of the analysis through an established methodology, for instance such as PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), can be proposed. This procedure is followed for an objective evaluation of the literature, assuming that a bibliography emerging from key word searches in Scopus can be integrated for a greater accuracy of the result.

The application of this kind of methodology requires a rapid development of digitalization and cannot be done alone. Therefore, once the change due to the Industrial Revolution 4.0 is taken into account by the AEC companies, they will have to adapt to the transformation, caring not to settle for one-off solutions aimed at changing a single process, but evolving into an ecosystem architecture for which a bold, conscious and long-term vision is required [46].

Primarily, it important to highlight that AI changed job structures; for example, the use of robots in pharmacy industry reshaped the employment relations between different occupational groups and created new types of professional figures in new jobs [69]. Is this precisely the definition of new tasks that provides the incipit for the digital development of AEC? Relative to the use of AI are increasing figures such as trainers, explainers, and sustainers [70] who are responsible for the proper functioning of AI. In addition, new figures also call for new government policies to encourage and help the reducing the negative impacts of AI on future jobs [71].

This process cannot be steered by sanctions and penalization, because it is now obsolete and ineffective [22]; it is necessary to establish a collaborative and strategic process of knowledge and technology sharing among different sectors to achieve a higher level of innovation. In order to accelerate this change in a static sector like the EAC, disciplinary interaction under the intuition of individual actors is not enough; policies and initiatives from above are needed. With this in mind, the positions adopted at the European level with the aforementioned NextGenerationUE, Green Deal and Horizon Europe projects are aimed at facilitating digitisation in all sectors. Of course, it is necessary to point out that the import process, which is not present within this paper, will have to take place depending on the characteristics of the target sector, and each technology, where it is possible, will undergo more or less significant modifications. In fact, as is evident from the analysis of the results and the four fields of action identified within the AEC, it is not always the case that a new technology has the characteristics for a right implementation in a new sector, but it is the target sector itself that needs to undertake an evolution and an updating. Perhaps for a better implementation of digital within the AEC's worksites, could it be firstly necessary to rethink their configuration?

In conclusion, it emerges that digitalization is expected to create new opportunities and solve old problems, and this can also happen through an integrative process between separate disciplines, knowledge and sectors. Indeed, the cross-fertilization of knowledge

and technologies networking is an advantageous mode of operation for innovation in any sector [59, 63].

References

1. Maureira, C., Allende-Cid, H., García, J.: Optimization in AEC-AI 4.0 industry multi-level adaptive methodology for knowledge mapping. In: Yang, X.S., Sherratt, S., Dey, N., Joshi, A. (eds.) Proceedings of Seventh International Congress on Information and Communication Technology. LNNS, vol. 465, pp. 729–737. Springer, Singapore (2023). https://doi.org/10.1007/978-981-19-2397-5_65
2. Johnson, R.E., Laepple, E.S.: Digital innovation and organizational change in design practice. In: Proceedings of the 23th Annual Conference of the Association for Computer-Aided Design in Architecture (ACADIA), pp. 179–183 (2003). https://doi.org/10.52842/conf.acadia.2003.179
3. Bernstein, P.G., Pittman, J.H.: Barriers to the adoption of building information modeling in the building industry. Autodesk Building Solutions, White Paper **2004**(1), 1–14 (2004)
4. Holzer, D.: Are you talking to me? Why bim alone is not the answer. Association of Architecture Schools in Australasia, March 2007. https://doi.org/10.5130/aab.v
5. Hirschi, A.: The fourth industrial revolution: issues and implications for career research and practice. Career Dev. Q. **66**(3), 192–204 (2018). https://doi.org/10.1002/cdq.12142
6. European Green Deal Homepage. https://digital-strategy.ec.europa.eu/en/policies. Accessed 09 Mar 2023
7. NextGenerationEU Homepage. https://next-generation-eu.europa.eu. Accessed 09 Mar 2023
8. NextGenerationEU – Tematic analyses. https://ec.europa.eu/economy_finance/recovery-and-resilience-scoreboard. Accessed 09 Mar 2023
9. Horizon Europe – Cluster 4 Homepage. https://horizoneurope.apre.it/struttura-e-programmi/global-challenges-european-industrial-competitiveness/cluster-4/. Accessed 09 Mar 2023
10. Pan, Y., Zhang, L.: Roles of artificial intelligence in construction engineering and management: a critical review and future trends. Autom. Constr. **122**. Elsevier B.V (2021). https://doi.org/10.1016/j.autcon.2020.103517
11. Goger, G., Piskernik, M., Urban, H.: Studie: Potenziale der Digitalisierung im Bauwesen Empfehlungen für zukünftige Forschung und Innovationen (Study: Potentials of digitalization in the construction industry Recommendations for future research and innovation). WKO - Wirtschaftskammer Österreich (2018)
12. Kipper, L.M., Iepsen, S., Dal Forno, A.J., et al.: Scientific mapping to identify competencies required by industry 4.0. Technol. Soc. **64** (2021). https://doi.org/10.1007/978-981-19-2397-5_65
13. Gorecky, D., Khamis, M., Mura, K.: Introduction and establishment of virtual training in the factory of the future. Int. J. Comput. Integr. Manuf. **30**(1), 182–190 (2017). https://doi.org/10.1080/0951192X.2015.1067918
14. Li, X., Shen, G.Q., Wu, P., Teng, Y.: Integrating building information modeling and prefabrication housing production. Autom. Constr. **100**, 46–60 (2019). https://doi.org/10.1016/j.autcon.2018.12.024
15. Goger, G., Bisenberger, T.: Digitalization in infrastructure construction – developments in construction operations. Geomechanik Und Tunnelbau **13**(2), 165–177 (2020). https://doi.org/10.1002/geot.201900077
16. Charef, R., Morel, J.C., Rakhshan, K.: Barriers to implementing the circular economy in the construction industry: a critical review. Sustain. **13**(23), 1–18 (2021). https://doi.org/10.3390/su132312989

17. Shooshtarian, S., Maqsood, T., Caldera, S., Ryley, T.: Transformation towards a circular economy in the Australian construction and demolition waste management system. Sustain. Prod. Consum. **30**, 89–106 (2022). https://doi.org/10.1016/j.spc.2021.11.032
18. Rose, C.M., Stegemann, J.A.: From waste management to component management in the construction industry. Sustain. **10**(1), 1–21 (2018). https://doi.org/10.3390/su10010229
19. Gruhler, K., Schiller, G.: Grey energy impact of building material recycling – a new assessment method based on process chains. Resour. Conserv. Recycl. Adv. **18**(February), 200139 (2023). https://doi.org/10.1016/j.rcradv.2023.200139
20. Naderi, H., Shojaei, A.: Digital twinning of civil infrastructures: current state of model architectures, interoperability solutions, and future prospects. Autom. Constr. **149**. Elsevier B.V (2023). https://doi.org/10.1016/j.autcon.2023.104785
21. Aminoff, A., Kaipia, R., Pihlajamaa, M., Tanskanen, K., Vuori, M., Makkonen, M.: Managing supplier innovations: a systematic literature review. Paper presented at 24th Annual IPSERA Conference, Amsterdam, Netherlands (2015)
22. Aminoff, A., Kiviniemi, M.: Driving supplier innovations towards digitalization of infrastructure projects. In: Proceedings of ISPIM Conferences, June 2016
23. Said, M.M., Pilgrim, R., Rideout, G., Butt, S.: Theoretical development of a digital-twin based automation system for oil well drilling rigs. In: Society of Petroleum Engineers - SPE Canadian Energy Technology Conference, CET (2022). https://doi.org/10.2118/208902-MS
24. Sacks, R., Brilakis, I., Pikas, E., Xie, H.S., Girolami, M.: Construction with digital twin information systems. Data-Centric Eng. **1**(6) (2020). https://doi.org/10.1017/dce.2020.16
25. Makarius, E.E., Mukherjee, D., Fox, J.D., Fox, A.K.: Rising with the machines: a sociotechnical framework for bringing artificial intelligence into the organization. J. Bus. Res. **120**(July), 262–273 (2020). https://doi.org/10.1016/j.jbusres.2020.07.045
26. Kontogiannis, T., Kossiavelou, Z.: Stress and team performance: principles and challenges for intelligent decision aids. Saf. Sci. **33**(3), 103–128 (1999). https://doi.org/10.1016/S0925-7535(99)00027-2
27. You, S., Kim, J.H., Lee, S.H., Kamat, V., Robert, L.P.: Enhancing perceived safety in human–robot collaborative construction using immersive virtual environments. Autom. Constr. **96**(March 2017), 161–170 (2018). https://doi.org/10.1016/j.autcon.2018.09.008
28. Berg, A., Buffie, E.F., Zanna, L.F.: Should we fear the robot revolution? (The correct answer is yes). J. Monet. Econ. **97**, 117–148 (2018). https://doi.org/10.1016/j.jmoneco.2018.05.014
29. Guy, M., Natraj, A., Van Reenen, J.: Has ICT polarized skill demand? Evidence from eleven countries over twenty-five years. Rev. Econ. Stat. **96**(1), 60–77 (2014). https://doi.org/10.1162/REST_a_00366
30. Goos, M., Manning, A.: Lousy and lovely jobs: the rising polarization of work in Britain. Rev. Econ. Stat. **89**(1), 118–133 (2007). https://doi.org/10.1162/rest.89.1.118
31. Acemoglu, D., Restrepo, P.: Robots and jobs: evidence from us labour markets. J. Polit. Econ. **128**(6), 2188–2244 (2020). https://doi.org/10.1086/705716
32. Rafiei, M.H., Adeli, H.: Novel machine-learning model for estimating construction costs considering economic variables and indexes. J. Constr. Eng. Manag. **144**(12), 1–9 (2018). https://doi.org/10.1061/(asce)co.1943-7862.0001570
33. Saavedra Sueldo, C., Perez Colo, I., De Paula, M., Villar, S.A., Acosta, G.G.: ROS-based architecture for fast digital twin development of smart manufacturing robotized systems. Ann. Oper. Res. **322**(1), 75–99 (2022). https://doi.org/10.1007/s10479-022-04759-4
34. Cai, J., Du, A., Liang, X., Li, S.: Prediction-based path planning for safe and efficient human-robot collaboration in construction via deep reinforcement learning. J. Comput. Civ. Eng. **37**(1), 1–10 (2023). https://doi.org/10.1061/(asce)cp.1943-5487.0001056
35. Greeshma, A.S., Edayadiyil, J.B.: Automated progress monitoring of construction projects using machine learning and image processing approach. Mater. Today Proc. **65**, 554–563 (2022). https://doi.org/10.1016/j.matpr.2022.03.137

36. Kevin, H.K., Fard, G.: Multi-sample image-based material recognition and formalized sequencing knowledge for operation-level construction progress monitoring. Comput. Civ. Build. Eng. 364–372 (2014). https://doi.org/10.1061/9780784413616.046
37. Mahmoudi, M., Vatankhahan, F., Malekahmadi, O., Goharimehr, R.: Study and performance of three-dimensional laser scanning technology in preparation industrial As-Built plans (2016)
38. Javaid, M., Haleem, A., Pratap Singh, R., Suman, R.: Industrial perspectives of 3D scanning: features, roles and it's analytical applications. Sens. Int. **2**(May), 100114 (2021). https://doi.org/10.1016/j.sintl.2021.100114
39. Hetemi, E., Ordieres-Meré, J., Nuur, C.: An institutional approach to digitalization in sustainability-oriented infrastructure projects: the limits of the building information model. Sustainability (Switzerland) **12**(9), 3893 (2020). https://doi.org/10.3390/su12093893
40. Davies, R., Harty, C.: Implementing site BIM: a case study of ICT innovation on a large hospital project. Autom. Constr. **30**, 15–24 (2013). https://doi.org/10.1016/j.autcon.2012.11.024
41. Rommetveit, R., Bjørkevoll, K.S., Halsey, G.W., et al.: eDrilling: a system for real-time drilling simulation, 3D visualization, and control. In: Society of Petroleum Engineers - Digital Energy Conference and Exhibition 2007, pp. 83–88 (2007). https://doi.org/10.2118/106903-MS
42. Smith, C.J., Wong, A.T.C.: Advancements in artificial intelligence-based decision support systems for improving construction project sustainability: a systematic literature review. Informatics **9**(2), 43 (2022). https://doi.org/10.3390/informatics9020043
43. Rao, H.R., Sridhar, R., Narain, S.: An active intelligent decision support system—architecture and simulation. Decis. Support Syst. **12**, 79–91 (1994). https://doi.org/10.1016/0167-9236(94)90075-2
44. Keen, P.G.W.: Adaptive design for decision support systems. ACM SIGMIS Database **12**(1–2), 15–25 (1980). https://doi.org/10.1145/1017654.1017659
45. Kang, L.S., Moon, H.S., Dawood, N., Kang, M.S.: Development of methodology and virtual system for optimised simulation of road design data. Autom. Constr. **19**(8), 1000–1015 (2010). https://doi.org/10.1016/j.autcon.2010.09.001
46. Woodhead, R., Stephenson, P., Morrey, D.: Digital construction: from point solutions to IoT ecosystem. Autom. Constr. **93**, 35–46 (2018). https://doi.org/10.1016/j.autcon.2018.05.004
47. Gu, N., London, K.: Understanding and facilitating BIM adoption in the AEC industry. Autom. Constr. **19**(8), 988–999 (2010). https://doi.org/10.1016/j.autcon.2010.09.002
48. Aziz, R.F., Hafez, S.M., Abuel-Magd, Y.R.: Smart optimization for mega construction projects using artificial intelligence. Alex. Eng. J. **53**(3), 591–606 (2014). https://doi.org/10.1016/j.aej.2014.05.003
49. Allen, S.D., Sarkis, J.: How can the circular economy-digitalization infrastructure support transformation to strong sustainability? Environ. Res. Infrastruct. Sustain. **1**(3) (2021). https://doi.org/10.1088/2634-4505/ac2784
50. Schröder, P., Bengtsson, M., Cohen, M., et al.: Degrowth within – aligning circular economy and strong sustainability narratives. Resour. Conserv. Recycl. **146**(April), 190–191 (2019). https://doi.org/10.1016/j.resconrec.2019.03.038
51. Gebauer, H., Fleisch, E.: An investigation of the relationship between behavioral processes, motivation, investments in the service business and service revenue. Ind. Mark. Manag. **36**(3), 337–348 (2007). https://doi.org/10.1016/j.indmarman.2005.09.005
52. Bauer, W., Hämmerle, M., Schlund, S., Vocke, C.: Transforming to a hyper-connected society and economy – towards an industry 4.0. Procedia Manuf. **3**(Ahfe), 417–424 (2015). https://doi.org/10.1016/j.promfg.2015.07.200
53. He, J.: Reasonable application, damage causes analysis, and optimization techniques of tunnel boring machine disc cutters in bid 2 project of Lanzhou water source. Tunnel Constr. **42**(S1), 500–507 (2022). https://doi.org/10.3973/j.issn.2096-4498.2022.S1.059

54. Liu, Y., Huang, S., Wang, D., Zhu, G., Zhang, D.: Prediction model of tunnel boring machine disc cutter replacement using kernel support vector machine. Appl. Sci. (Switzerland) **12**(5) (2022). https://doi.org/10.3390/app12052267
55. Hine, R.: A Dictionary of Biology, 8th ed. Oxford University Press, Oxford (2019). https://doi.org/10.1093/acref/9780198821489.001.0001
56. Corazza, L.: Cross-fertilization tra mondo profit e imprese sociali (Cross-fertilisation between the for-profit world and social enterprises). Impresa Sociale **3**(4), 47–60 (2014)
57. Björkdahl, J.: Technology cross-fertilization and the business model: the case of integrating ICTs in mechanical engineering products. Res. Policy **38**(9), 1468–1477 (2009). https://doi.org/10.1016/j.respol.2009.07.006
58. Bogers, M., Horst, W.: Collaborative prototyping: cross-fertilization of knowledge in prototype-driven problem solving. J. Prod. Innov. Manag. **31**(4), 744–764 (2014). https://doi.org/10.1111/jpim.12121
59. González-Piñero, M., Páez-Avilés, C., Juanola-Feliu, E., Samitier, J.: Cross-fertilization of knowledge and technologies in collaborative research projects. J. Knowl. Manag. **25**(11), 34–59 (2021). https://doi.org/10.1108/JKM-04-2020-0270
60. Aparicio, G., Maseda, A., Iturralde, T., Zorrilla, P.: The family business brand: cross-fertilization between fields. Manag. Decis. (2023). https://doi.org/10.1108/md-04-2022-0445
61. Fusco, F., Marsilio, M., Guglielmetti, C.: Co-creation in healthcare: framing the outcomes and their determinants. J. Serv. Manag. **34**(6), 1–26 (2023). https://doi.org/10.1108/josm-06-2021-0212
62. Pan, Y., Froese, F.J.: An interdisciplinary review of AI and HRM: challenges and future directions. Hum. Resour. Manag. Rev (2022).https://doi.org/10.1016/j.hrmr.2022.100924
63. Harvey, J.F.H., Cohendet, P., Simon, L., Borzillo, F.: Knowing communities in the front end of innovation. Res. Technol. Manag. **58**(1), 46–54 (2015). https://doi.org/10.5437/08956308X5801198
64. Boatswain Jacques, A.A., Adamchuk, V.I., Park, J., et al.: Towards a machine vision-based yield monitor for the counting and quality mapping of shallots. Front. Robot. AI **8**(April), 1–12 (2021). https://doi.org/10.3389/frobt.2021.627067
65. Hobbs, J., Khachatryan, V., Barathwaj, S., et al.: Broad dataset and methods for counting and localization of on-ear corn kernels. Front. Robot. AI **8**(May), 1–11 (2021). https://doi.org/10.3389/frobt.2021.627009
66. Alzadjali, A., Alali, M.H., Veeranampalayam Sivakumar, A.N., et al.: Maize tassel detection from UAV imagery using deep learning. Front. Robot. AI **8**(June), 1–15 (2021). https://doi.org/10.3389/frobt.2021.600410
67. Greeshma, A.S., Edayadiyil, J.B.: Automated progress monitoring of construction projects using machine learning and image processing approach. Mater. Today Proc. **65**(2022), 554–563 (2022). https://doi.org/10.1016/j.matpr.2022.03.137
68. Wetzel, E.M., Liu, J., Leathem,T., Sattineni, A.: The Use of Boston Dynamics SPOT in Support of LiDAR Scanning on Active Construction Sites. Paper presented at the Proceedings of the International Symposium on Automation and Robotics in Construction, 2022-July 86–92 (2022). doi: https://doi.org/10.22260/ISARC2022/0014
69. Barrett, M., Oborn, E., Orlikowski, W.J., Yates, J.A.: Reconfiguring boundary relations: robotic innovations in pharmacy work. Organ. Sci. **23**(5), 1448–1466 (2012). https://doi.org/10.1287/orsc.1100.0639
70. Wilson, H.J., Daugherty, P., Bianzino, N.: The jobs that artificial intelligence will create. MIT Sloan Manag. Rev. **58**(4), 14–16 (2017)
71. Waring, P., Bali, A., Vas, C.: The fourth industrial revolution and labour market regulation in Singapore. Econ. Labour Relat. Rev. **31**(3), 347–363 (2020). https://doi.org/10.1177/1035304620941272