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Public governance in the context of Construction 4.0

Public governance in the context of Construction 4.0: A systematic and comprehensive literature review

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1 Abstract

This whitepaper provides a comprehensive review of the academic literature on public governance in the context of Construction 4.0, focusing on eight recurring themes. The identified themes include policy and regulation, infrastructure and investment, skill development and education, digital inclusion and access, collaboration and partnerships, data governance and privacy, interactions with environmental and societal goals, and the impact of Construction 4.0 on public governance itself. Through an analysis of existing research, this review presents an overview of the current knowledge on these themes. The central insight drawn from this review is a significant disparity between the normative debates on the necessity of public governance in Construction 4.0 and the scarcity of empirical knowledge regarding its practical implementation. While scholars and policymakers emphasise the importance of public governance in addressing the challenges and harnessing the opportunities of Construction 4.0, there is a notable lack of empirical research on how public governance strategies can be effectively implemented in practice. This review contributes to the existing literature by highlighting the research gaps and emphasising the need for further empirical investigations to bridge the theoretical-practical divide in public governance within the context of Construction 4.0.

Abstract

2 Introduction

In recent years, the rise of Industry 4.0, also known as the Fourth Industrial Revolution, has brought about significant technological advancements and digital innovations that have disrupted various sectors, including construction (Lekan, Clinton, & Owolabi, 2021). This transformative paradigm combines cyber-physical systems, the Internet of Things (IoT), artificial intelligence, and big data analytics, revolutionising manufacturing, logistics, and service industries (Chen, Huang, Liu, Osmani, & Demian, 2022). Inspired by the potential benefits of Industry 4.0, the concept of Construction 4.0 has emerged (Boton, Rivest, Ghnaya, & Chouchen, 2021; Casini, 2022).

Construction 4.0 promises to revolutionise the construction industry through the seamless integration of digital technologies, automation, and connectivity. It is expected to enhance productivity, efficiency, and sustainability (Lekan et al., 2021). By leveraging innovations like Building Information Modelling (BIM), IoT devices, and advanced data analytics, Construction 4.0 aims to streamline processes, optimise resource allocation, improve collaboration, and deliver projects with greater speed, precision, and cost-effectiveness (Sawhney, Riley, & Irizarry, 2020).

Despite extensive discussions on its opportunities, the practical implementation of Construction 4.0 has been limited (Begic & Galic, 2021a; Oke & Arowoiya, 2022; Turk, 2023). Barriers to adopting Construction 4.0 include technological challenges, limited industry collaboration, resistance to change in the construction industry, cost considerations, and a skills gap (Calvetti, Magalhaes, Sujan, Goncalves, & de Sousa, 2020; Schonbeck, Lofsjogard, & Ansell, 2020). While public governance issues, such as regulation, policy, and government support, are often mentioned as both drivers and barriers to the adoption of Construction 4.0, there has been limited in-depth research on their role in shaping and regulating this phenomenon (F. S. B. Ibrahim, Esa, & Kamal, 2019; Munoz-La Rivera, Mora-Serrano, Valero, & Onate, 2021; K. Y. Wang, Guo, Zhang, & Schaefer, forthcoming; van der Heijden, 2023).

To address this research gap, this whitepaper presents a systematic and comprehensive literature review on public governance in the context of Construction 4.0. Acknowledging the scarcity of literature specifically focused on public governance in Construction 4.0, the review expands its scope to include insights from public governance in the broader context of Industry 4.0 (for a detailed discussion of the historical background of Industry 4.0, see Klingenberg, Borges, & Antunes, 2022). This approach aims to draw relevant parallels and leverage existing knowledge from the broader domain of Industry 4.0.

To ensure a systematic and rigorous selection of source material, this study follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Shamseer et al., 2015). PRISMA is a recognised framework for conducting systematic literature reviews, promoting a structured and transparent process. By analysing and synthesising existing research, this study aims to explore the opportunities, challenges, and regulatory and policy considerations that public governance encounters in the context of Construction 4.0. The findings are expected to establish a basis for further research, policy development, and practical implications for governments and public institutions involved in shaping the future of construction in the digital era.

The subsequent sections of this whitepaper provide an overview of Construction 4.0 and a conceptualisation of public governance as relevant to this study (Section 2). The methodology used for the literature review is described in Section 3. Section 4 discusses the potential influence of public governance on Construction 4.0, drawing upon evidence from the reviewed literature. Finally, Section 5 presents the conclusions.

3 Conceptualising Construction 4.0 and public governance

3.1 A brief reflection on Construction 4.0

The construction industry is often perceived as slow in adopting new technologies and innovations due to its complex nature and high-risk projects (Demirkesen & Tezel, 2022; Forcael, Ferrari, Opazo-Vega, & Pulido-Arcas, 2020). However, the emergence of Construction 4.0, characterised by digitisation and automation, presents a transformative opportunity (Manyika et al., 2017). Construction 4.0 can revolutionise building and infrastructure design, construction, and operation (Sawhney et al., 2020).

The precise definition of Construction 4.0 remains elusive, and the phenomenon is often discussed within the context of Industry 4.0 and the Fourth Industrial Revolution (Kozlovska, Klosova, & Strukova, 2021). Industry 4.0 integrates digital, physical, and biological systems, leveraging advanced technologies such as AI, automation, robotics, and IoT (Bolpagni, Gavina, Ribeiro, & Arnal, 2022). Initially introduced in Germany in 2011, Industry 4.0 is a recognised framework for digital transformation across various industries (European Commission, 2017). The core of Industry 4.0 lies in integrating diverse technologies to create interconnected systems, which also applies to Construction 4.0 (Begic & Galic, 2021a).

The term' Construction 4.0' was introduced in 2016 by the consultancy firm Roland Berger GMBH in their report titled Digitization in the construction industry: Building Europe's Road to 'Construction 4.0' (Roland Berger GMBH, 2016). Since then, its usage has gained momentum. It is important to note that Construction 4.0 can be understood in both a narrow and a broad sense. In a narrow sense, Construction 4.0 refers to incorporating digital technologies, data analytics, and automation into the construction process to enhance efficiency and productivity (Casini, 2022; Chen et al., 2022; Lekan et al., 2021). This includes technologies such as BIM, IoT, robotics and automation, prefabrication and off-site construction, virtual reality and augmented reality. From this narrow perspective, Construction 4.0 is primarily seen as a technological transformation that has the potential to significantly improve the cost, time, and quality performance in construction projects (Craveiro, Duarte, Bartolo, & Bartolo, 2019).

The broader concept of Construction 4.0 encompasses social, economic, and environmental dimensions (K. Y. Wang & Guo, 2022). It recognises that adopting digital technologies and automation requires accompanying changes in organisational, legal, and cultural frameworks within the construction industry to fully unlock its potential (Sherratt, Dowsett, & Sherratt, 2020). Moreover, it acknowledges the broader impact of these technologies on the built environment and emphasises the importance of long-term sustainability and resilience (Schonbeck et al., 2020). Lastly, it highlights the need for a holistic approach, understanding that digital technology alone cannot address the challenges at hand (de Almeida Barbosa Franco, Domingues, de Almeida Africano, Mattos Deus, & Aparecida Gomes Battistelle, 2022). In summary, the broader perspective examines the societal, environmental, governance, and technological implications of Construction 4.0 (van der Heijden, 2023).

3.2 A brief reflection on public governance in the context of Construction 4.0

Despite extensive discussions on Construction 4.0, its implementation remains limited (Turk, 2023). The existing literature highlights a gap between the theoretical discourse on Construction 4.0 and its practical adoption, observed across developed and developing economies and by both large corporations and small and medium-sized enterprises (SMEs) (Begic & Galic, 2021a; Oke & Arowoiya, 2022). Previous literature reviews have identified various barriers to the adoption of Construction 4.0, including high initial costs, resistance to change within the construction industry, and the fragmented nature of the sector (F. S. Ibrahim, Esa, & Rahman, 2021; Munoz-La Rivera et al., 2021; K. Y. Wang et al., forthcoming). These reviews also emphasise the pivotal role of public governance, acting as a significant barrier when ineffective or ignored but as a crucial driver when adequately implemented (ibid).

In the context of Construction 4.0, public governance refers to the involvement of governments and public institutions in facilitating, guiding, and overseeing the transition to Construction 4.0, focusing on ensuring responsible and inclusive implementation of advanced technologies (van der Heijden, 2023). This involvement can take various forms, including direct regulation, policy frameworks, financial incentives, and collaborations with industry stakeholders (Baker, Gaspard, & Zhu, 2021; Behl, Singh, Pereira, & Laker, 2023; Rodriguez-Espindola et al., 2022). This comprehensive understanding of public governance aligns with contemporary public policy, public administration, and regulatory governance discussions, which acknowledge the diverse range of approaches, spanning from top-down government intervention to hands-off facilitation of voluntary initiatives by non-governmental actors (Rhodes, 2007).

The recognition of public governance as a significant factor influencing the adoption of Construction 4.0 is not surprising, given the historical role of governments in directing the development and implementation of new technologies (Smith, Stirling, & Berkhout, 2005). Governments are typically expected to mitigate risks associated with new technologies, ensure fair competition among stakeholders, and create favourable conditions for technology adoption (Klinke & Renn, 2021). However, in the context of Construction 4.0, the stakes are higher due to the increased complexity and interdependency of technological innovations (Klingenberg et al., 2022). Governments and public institutions must consider the potential implications of innovations across different areas of the construction industry and strive for system-level improvements beyond each technology's individual contributions. This necessitates early regulatory and policy analysis during the research and development phase rather than waiting until technologies are already in use (Kagermann, Wahlster, & Helbig, 2013).

Moreover, Construction 4.0 and its broader counterpart, Industry 4.0, are expected to offer significant opportunities for public governance itself, enabling regulatory transformation and value creation (Lohmer & Lasch, 2020). Governments and public institutions can leverage these technologies to enhance policy development, implementation, and evaluation, focusing on achieving the underlying principles of laws and regulations (Yeung & Lodge, 2019). In turn, businesses may benefit from reduced regulatory burdens by integrating compliance into their construction processes, transforming it from a mere cost to a value-added component. This improved compliance is expected to drive product and service quality, empower employees, enhance consumer satisfaction, and mitigate industry and manufacturing risks (Carpintero, Foster, Makarova, & Telpis, 2021).

3.3 A global snapshot of public governance initiatives in the context of Construction 4.0

Governments and the construction industry worldwide increasingly acknowledge the potential of Construction 4.0 and digital technologies in driving innovation, boosting productivity, and achieving broader social and environmental objectives. This recognition is driven by the projected growth of the Construction 4.0 industry. For instance, it is estimated that the United States will experience significant growth in Construction 4.0, with a value of around USD 40.5 billion by 2030 (Credence Research, 2023). Similarly, New Zealand expects Construction 4.0 adoption to contribute NZD 8 billion to its GDP between 2021 and 2026 (HERA, 2021).

To harness the potential of Construction 4.0, governments have implemented public governance initiatives worldwide. In the United States, the National Institute of Building Sciences (NIBS) promotes the adoption of Building Information Modeling (BIM) through initiatives like the General Services Administration's BIM Guide Series and the U.S. Army Corps of Engineers' BIM Standards (Lee & Borrmann, 2020). Singapore's Building Construction Authority leads the implementation of Construction 4.0 practices through the Construction Industry Transformation Map (BCA, 2022). Malaysia has developed and implemented the Construction 4.0 Strategic Plan (2021-2025) to revolutionise its construction industry and improve worker safety, sustainability, and ethical behaviour (CIDB, 2021). Likewise, China's Made in China 2025 policy, which includes the adoption of Industry 4.0, places a strong emphasis on the construction sector (J. Wang, Wu, & Chen, 2020).

In Europe, the European Commission actively supports research and development in Construction 4.0 through initiatives like the EU Horizon Call on Interactive Technologies (European Commission, 2019). Construction 4.0 is integrated into broader European programs and policies, including the European Green Deal, the New European Bauhaus, Fit for 55, and the revision of the Energy Performance Building Directive (ECTP, 2022). Regulation and legislation also play a crucial role in Europe, with most member states having rules and policies targeting the digitisation and automation of the construction industry (European Construction Observatory, 2021). Governments in Europe are setting an example by mandating BIM for public works in procurement processes, following the recommendation of the EU Directive for Public Procurement that was launched in 2014 (European Commission, 2014).

Several European countries have implemented initiatives to embrace Construction 4.0 principles. For instance, the Czech Republic introduced its Industry 4.0 Initiative (Průmysl 4.0), focusing on Construction 4.0 and the digitisation of construction processes (Lazaro, 2017). Germany launched a BIM Roadmap implementation initiative to establish digital planning and construction as standard practice in federal infrastructure projects (European Commission, 2021c). Ireland supports small and medium-sized enterprises through programs like BIM-Implement and BIM-Enable (European Commission, 2020). Portugal's Industry 4.0 National Strategy (Indústria 4.0) promotes digital transition and re-skilling efforts in the construction industry (European Commission, 2021b). France has a Digital Transition Plan for Buildings (Plan Transition Numérique dans le Bâtiment) and a Plan BIM 2022 to drive BIM adoption and standardisation (European Commission, 2022). The Netherlands has the BIM Gateway (BIM-Loket), a national portal for information and management of Open BIM Standards. The BIM Gateway helps stakeholders reduce maintenance costs and enhance productivity through BIM-bots (European Commission, 2021a).

However, despite the proliferation of public governance initiatives in the realm of Construction 4.0, there remains a lack of comprehensive understanding regarding their effectiveness and impact on adopting Construction 4.0 practices. It is unclear whether these initiatives facilitate the adoption of Construction 4.0 or potentially create barriers to its implementation. This whitepaper

will now delve into these issues and explore the performance of public governance initiatives in the context of Construction 4.0.

4 Methodology

This whitepaper builds upon a prior literature review on Construction 4.0, which involved a systematic approach to select 134 articles from an initial pool of over 300 (van der Heijden, 2023). Among these 134 articles, nine specifically addressed the topic of public governance, serving as a foundation for this systematic review and providing essential background information for introducing this whitepaper.

The information from the previous review and the baseline data guided identifying and analysing documents for the systematic evidence synthesis (Gough, Oliver, & Thomas, 2012). Following established protocols for this evidence synthesis, relevant documents were sourced from the Web of Science database, focusing on peer-reviewed journal articles, books, and book chapters to ensure their quality. The search primarily targeted English-language publications pertaining to public policy in the context of Construction 4.0 (Gough et al., 2012; Heyvaert, Hannes, & Onghena, 2017; Moher, Liberati, Tetzlaff, & Altman, 2009; van der Heijden, 2021b).

Initially, documents were sourced by applying the search query: (("Construction 4.0" AND (govern* OR polic* OR polit* OR regulat* OR standar*)) AND (problem OR challeng* OR concern OR constrain* OR opportun* OR benef* OR promis*)). This search query limits the search to articles on Construction 4.0 that engage with the broad public governance themes discussed earlier. The search query used wildcard characters (e.g., 'govern*') to capture variations of relevant terms (such as 'governance', 'government', and 'governing'). This search yielded 19 documents. The titles and abstracts of these 19 documents were then reviewed, and those that indicated an explicit focus on public governance in the context of Construction 4.0 were included in the review. This resulted in the inclusion of 5 documents.

Due to the limited number of articles found, the search was expanded to include literature on public governance in the broader context of Industry 4.0, which encompasses Construction 4.0. A new search query was applied: (("Industry 4.0" AND (govern* OR polic* OR polit* OR regulat* OR standar*)) AND (problem OR challeng* OR concern OR constrain* OR opportun* OR benef* OR promis*)). This search yielded 1232 documents. The titles and abstracts of these documents were reviewed, and 105 documents were found that indicate an explicit focus on public governance in the context of Industry 4.0. After removing conceptual and theoretical articles, 41 documents remained for inclusion in the review.

After removing duplicates from the initial set of five documents on Construction 4.0 and 41 on Industry 4.0, 45 unique documents were selected for further analysis. These documents were carefully read, and detailed notes were taken and recorded in a working document. To facilitate systematic data analysis, the working document was then analysed using Atlas.ti, a computer program specifically designed for handling complex data analysis (Bearfield & Eller, 2008; Sutton, Papaioannou, & Booth, 2016). The analysis aimed to identify patterns and extract unique insights from the source material. An overview of the source material and the codes utilised in the analysis are made available as appendices to this whitepaper.

The subsequent sections of this whitepaper translate relevant findings on public governance in the context of Industry 4.0 to the specific context of Construction 4.0. Additional documents were occasionally consulted to enrich this process to obtain more detailed information concerning the general observations derived from the 45 sourced documents. These additional documents were identified through a snowball sampling approach, which involved exploring references within the source material or consulting contemporary works by the same authors (Gough et al., 2012; Petticrew & Roberts, 2006). For a comprehensive overview of the source material, please refer to Appendix A, while a complete set of the utilised codes can be found in Appendix B.

5 Insights on public governance in the context of Construction 4.0

Based on the comprehensive literature review, eight main themes related to public governance emerge: (1) policy and regulation, (2) infrastructure and investment, (3) skill development and education, (4) digital inclusion and access, (5) collaboration and partnerships, (6) data governance and privacy, (7) alignment with environmental and societal goals, and (8) the impact of Construction 4.0 on public governance itself. It is essential to acknowledge that these themes are not mutually exclusive, as they often overlap and interact, as will be further explored in the subsequent sections.

5.1 Policy and regulation

Among the eight identified themes, the most prominent one in the literature is "policy and regulation," which can be attributed to its extensive overlap with the other themes. In many ways, the remaining themes (except for "the impact of Construction 4.0 on public governance") can be seen as specific applications or focused areas within the broader context of policy and regulation for Construction 4.0, as explored in academic research.

According to the reviewed literature, policy and regulation play a crucial role in shaping the adoption of Construction 4.0 by creating an environment conducive to its implementation. Governments and public entities can establish supportive policies encouraging investment in digital infrastructure, research and development, and skills training, particularly relevant for SMEs and firms in developing economies aiming to adopt Construction 4.0 (Rodriguez-Espindola et al., 2022). Incentives such as tax benefits or grants can motivate firms to embrace Construction 4.0 technologies, fostering innovation and improving competitiveness (Behl et al., 2023). Additionally, policy measures can promote collaboration, interoperability among stakeholders, and the adoption of Construction 4.0 by transforming the construction industry's culture and bringing top management up to speed with relevant developments (Findik, Tirgil, & Ozbugday, 2023). Scholars emphasise that such policies should be developed and implemented as a comprehensive package of interventions rather than in isolation (Nudurupati et al., 2022).

Developing standards and regulations is a crucial task for governments as it ensures the seamless integration of diverse Construction 4.0 technologies and systems. Common standards for data exchange, cybersecurity, and interoperability are seen as vital for effective collaboration and harnessing the full potential of Construction 4.0 (Ochella, Shafiee, & Dinmohammadi, 2022). Governments can further facilitate the adoption of Construction 4.0 by establishing regulatory sandboxes or testbeds, enabling companies to experiment with new technologies in controlled environments and iteratively refine regulatory frameworks. These public governance initiatives provide industry stakeholders with guidance and strategic direction (K. Y. Wang et al., forthcoming). Policy and regulation also have the potential to address barriers and risks associated with the adoption of Construction 4.0, including cybersecurity and resilience risks, workforce transition and skills development, and the integration of Construction 4.0 ambitions with environmental and social policy goals, as discussed in the following subsections.

The Construction 4.0 literature has not given enough attention to a specific governance challenge related to the servitisation trend in the construction industry, which is being driven by technological innovation (Peng, 2020). The distinction between construction products and services is becoming increasingly unclear, especially in the context of the circular economy (Behl et al., 2023). Yet, legal and regulatory frameworks are typically based on a differentiation between

goods and services. The adequacy of these frameworks and the regulatory capacity of governments to handle the servitisation of the construction industry are being questioned (Hanna, Larsson, Gotvall, & Bengtsson, 2022). Another obstacle is the use of technologies like BIM and artificial intelligence, which can introduce contractual uncertainties regarding ownership of digital models and data and legal responsibility for faults and accidents resulting from them (Oesterreich & Teuteberg, 2016).

Regulation may also be necessary to prevent anti-competitive behaviour by digital platforms and to ensure that early adopter companies, including technology and software providers, do not become overly dominant in the construction industry (Klingenberg et al., 2022). Therefore, governments need to understand the new dynamics of Construction 4.0. While Industry 3.0 technology (computers and information systems) played a significant role in the construction sector, Construction 4.0 involves traditional firms embracing new technologies, start-ups delivering new products and services with these technologies, and existing/new firms developing these technologies (Hoffmann & Prause, 2018). Additionally, governments may need to discourage traditional construction practices for some time. For example, using virgin materials might be cheaper than environmentally friendly alternatives enabled by Construction 4.0 technologies like 3D printing (Kumar, Raut, Aktas, Narkhede, & Gedam, 2023).

It is worth noting the repeated call for locally tailored or sub-national policies and regulations to promote the adoption of Construction 4.0 (Baker et al., 2021; Brownlow & Budd, forthcoming; Da Roit & Iannuzzi, 2022; Hervas-Oliver, Estelles-Miguel, Peris-Ortiz, & Belso-Martinez, 2022; Oesterreich & Teuteberg, 2016). This is because sub-national variations in socio-economic factors, environmental conditions, and industry characteristics may require different approaches to implementing Construction 4.0 solutions (Da Roit & Iannuzzi, 2022). Similarly, in developing economies, some scholars argue that governments should focus on realistic regulation to support the adoption of Construction 4.0 rather than overly optimistic and ambitious policies (Raj, Dwivedi, Sharma, Jabbour, & Rajak, 2020).

Policy and regulation also pose challenges in the context of Construction 4.0. One significant barrier is the rapid pace of technological advancements, which often outpace the development of regulatory frameworks, leading to a classic regulatory challenge (Van der Heijden, 2021a). To address this, governments need to adopt agile and flexible approaches to policymaking, allowing for iterative updates and collaboration with industry experts to keep pace with emerging technologies and evolving business models (Armstrong, Gorst, & Rae, 2019). Another challenge is accepting that construction products and services will constantly be 'beta testing' as producers utilise Construction 4.0 technologies like artificial intelligence, big data, and mass individualisation to continuously improve their offerings (Hoffmann & Prause, 2018).

Striking the right balance between promoting innovation and managing risks is crucial. It is essential to prevent regulation from becoming outdated or hindering innovation (Lohmer & Lasch, 2020). Governments should focus on establishing regulatory frameworks that define clear goals, outcomes, and performance standards while allowing flexibility in achieving them (Ochella et al., 2022). Embracing risk-based regulation can help identify and assess potential risks associated with Construction 4.0 technologies and develop targeted measures to mitigate those risks, ensuring a balance between innovation and risk management (Hanna et al., 2022). In this context, governments need to reevaluate their approach to uncertainties in regulatory risk management processes. Some scholars suggest adopting a regulatory approach similar to the precautionary principle, as the traditional concept of reducing risks to a level "as low as reasonably practicable" (ALARP) may no longer be justified in the context of Construction 4.0 (on the precautionary principle, see Tosun, 2013). By following this principle, governments can place the responsibility on those introducing emerging technologies to provide evidence of potential risks and uncertainties and propose ways to mitigate them (Ochella et al., 2022; Tripathi & Gupta, 2021).

5.2 Infrastructure and investment

A second recurring theme in the literature is the crucial involvement of government and other public entities in infrastructure and investment related to Construction 4.0 (Behl et al., 2023). Governments can play a pivotal role by allocating resources to develop digital infrastructure, including high-speed broadband networks and 5G connectivity (Loo & Wong, 2023). Establishing robust and reliable infrastructure is essential for effectively deploying and functioning Construction 4.0 technologies, as it enables seamless communication, data transfer, and integration across different systems. To promote private sector investments in Construction 4.0 technologies, governments can implement financial measures such as tax incentives, grants, and subsidies (Muscio & Ciffolilli, 2020). These incentives aim to alleviate the initial costs of adopting and implementing advanced technologies. Additionally, governments can support research and development initiatives by offering to fund and establishing industry clusters, innovation hubs, or centres of excellence (Baker et al., 2021). These efforts encourage collaboration between industry, academia, and research institutions, facilitating the advancement of cutting-edge technologies and solutions and sharing resources, expertise, and experiences (Findik et al., 2023).

5.3 Skill development and education

A third recurring theme involves the participation of government and other public entities in skill development and education (Calvetti et al., 2020). Government interventions in these areas are considered crucial for cultivating a skilled workforce capable of effectively utilising and navigating the complexities of Construction 4.0 technologies and practices (Bolpagni et al., 2022). This requires implementing various actions and policies to promote relevant education and training, encourage lifelong learning, and address the existing skills gap (Adepoju, 2022). Governments play a critical role in shaping education systems and curricula to align with the requirements of Construction 4.0 (Chacon, 2021). This involves integrating digital literacy, computational thinking, and data analytics into school curricula from an early stage. Furthermore, governments can partner with educational institutions and industry stakeholders to develop specialised programs and courses focusing on emerging technologies such as artificial intelligence, robotics, and IoT (Nagy, Papp, & Szabo, 2021). Incentives and subsidies can be provided to individuals and organisations participating in these programs, making them more accessible and attractive (F. S. B. Ibrahim et al., 2019).

5.4 Digital inclusion and access

A fourth recurring theme in the literature is the role of government and other public entities in promoting digital inclusion and access (Balasubramanian, Shukla, Islam, & Manghat, forthcoming-b). Digital inclusion refers to ensuring equitable access and meaningful participation in the digital economy (Mervyn, Simon, & Allen, 2014), while digital access relates to the availability and affordability of digital technologies and infrastructure (Maskuriy, Selamat, Ali, Maresova, & Krejcar, 2019). Governments bear significant responsibility in creating an enabling environment that fosters digital inclusion and access for all individuals and organisations (Loo & Wong, 2023). To achieve this, as mentioned earlier, governments can invest in the development of robust digital infrastructure and connectivity and provide direct financial support to firms, particularly small and medium-sized enterprises (SMEs), which often struggle with the high upfront costs of digital technologies (Hoffmann & Prause, 2018). Additionally, governments can support initiatives that promote digital literacy and inclusion among marginalised groups, including seniors, persons with disabilities, and low-income communities (Coldwell-Neilson & Cooper, 2019). This may involve providing access to digital literacy programs, offering support for assistive technologies, and ensuring that government services, such as building permit applications and information, are

accessible online (Eirinaki et al., 2018). By addressing digital exclusion and empowering marginalised groups, including SMEs, governments can ensure that everyone can participate in the transformative journey facilitated by Construction 4.0 (Turk, 2023).

5.5 Collaboration and partnerships

A fifth recurring theme, as evident from the previous discussions, is the significance of government collaboration and partnerships with industry representatives in overcoming barriers to adopting Construction 4.0 (Weber, Gudowsky, & Aichholzer, 2019). Through public governance initiatives and interventions that foster collaboration, governments can facilitate knowledge exchange, resource sharing, and collective problem-solving, thereby promoting the seamless integration of Industry 4.0 technologies and practices (Baker et al., 2021). In addition to partnering with industry representatives, educational institutions, and academia, governments can also involve citizen representatives and non-governmental organisations (NGOs) to ensure that the adoption of Construction 4.0 aligns with societal needs and values (Sadeghizadeh, Markazi, & Shavvalpour, 2022). By engaging citizen representatives and NGOs in the policymaking process, governments can incorporate social and ethical considerations into developing and implementing Construction 4.0 initiatives. This inclusive approach can effectively address concerns related to job displacement, privacy, security, and environmental sustainability (Ghadimi, Donnelly, Sar, Wang, & Azadnia, 2022). Furthermore, governments can support initiatives that enhance digital literacy and empower citizens to actively participate in the digital economy, ensuring that the benefits of Construction 4.0 are accessible and equitably distributed (Muscio & Ciffolilli, 2020).

5.6 Data governance and privacy

A sixth recurring theme revolves around data governance and privacy. With the widespread use of digital technologies and data-driven processes in Construction 4.0, protecting data from unauthorised access and breaches while ensuring privacy becomes a crucial concern that requires government intervention (de Soto, Turk, et al., 2022). Government and public bodies play a crucial role in establishing and enforcing robust regulations and standards for data security and privacy (Bolhassan et al., 2022). This involves developing legislation and regulatory frameworks that provide clear data protection, storage, and transmission guidelines. Organisations would have specific obligations regarding data handling, including implementing security measures, data encryption, and data breach notification protocols (de Soto, Georgescu, et al., 2022). Governments can foster trust and accountability by creating a legal framework and promoting responsible and secure data use in Construction 4.0 (Sonkor & García De Soto, 2021).

Government agencies can also raise data security and privacy awareness by promoting cybersecurity awareness and launching educational programs targeting industry stakeholders (Turk, de Soto, Mantha, Maciel, & Georgescu, 2022). Collaboration with industry associations, academic institutions, and other stakeholders can facilitate the development of training initiatives to enhance cybersecurity skills and knowledge (Chang & Coppel, 2020). By raising awareness of potential threats and promoting good cybersecurity practices, governments can empower individuals and organisations to mitigate risks and adopt secure practices within the context of Construction 4.0. Additionally, governments can support international cooperation and standardisation efforts (Tripathi & Gupta, 2021). Participation in global discussions and initiatives can contribute to establishing harmonised frameworks for data security and privacy. This involves collaborating with international organisations, sharing expertise, and contributing to developing global norms and standards. Aligning efforts at the international level ensures consistent data security and privacy approaches, facilitating cross-border data flows and promoting the global adoption and securitisation of Construction 4.0 technologies (Foley, McDermott, Rosa, & Kharub, 2022).

5.7 Integration of environmental and societal goals

The seventh recurring theme emphasises the importance of integrating environmental and social objectives in adopting Construction 4.0. Public governance plays a crucial role in ensuring that the adoption of Construction 4.0 drives economic growth and contributes to environmental sustainability and societal well-being (de Almeida Barbosa Franco et al., 2022; K. Y. Wang & Guo, 2022). Governments and public bodies are responsible for establishing policies and regulations that promote sustainability and societal goals in Construction 4.0 adoption (Behl et al., 2023). This can be achieved by developing frameworks that incentivise using environmentally friendly and socially responsible technologies and practices (Schonbeck et al., 2020). Economic incentives, such as tax incentives, subsidies, or grants, can encourage organisations to implement sustainable measures like energy-efficient manufacturing processes and resource optimisation strategies (Van der Heijden, 2019). By aligning economic incentives, governments foster the integration of Construction 4.0 adoption with environmental and societal goals (Kumar et al., 2023).

Government agencies also support research and development efforts focused on sustainable technologies and practices within the context of Construction 4.0 (Baker et al., 2021). By funding innovation and collaborating with academia and industry, governments drive the development of environmentally friendly solutions such as clean energy technologies, circular economy models, and sustainable supply chain practices (Muscio & Ciffolilli, 2020). Moreover, governments facilitate dialogue and cooperation by creating platforms for sharing knowledge, best practices, and resources on how Construction 4.0 can contribute to multiple goals (European Construction Observatory, 2021). These collaborations can lead to the development of joint initiatives that address environmental and societal challenges associated with Construction 4.0 adoption. For example, government-led programs can encourage industry-academic partnerships to develop sustainable manufacturing processes or promote social inclusivity through workforce training and upskilling programs (F. S. B. Ibrahim et al., 2019). By integrating environmental and social objectives, governments ensure that the adoption of Construction 4.0 aligns with broader sustainability and societal aspirations.

5.8 The impact of Construction 4.0 on public governance

The final theme explores the impact of technological innovations driving Construction 4.0 on public governance, specifically in policymaking, regulation development, and implementation (Lohmer & Lasch, 2020). These advancements present opportunities and challenges in developing evidence-based policies, improving regulatory effectiveness, and promoting compliance in the construction industry (for a broader discussion, see Yeung & Lodge, 2019). The availability of large amounts of data and the increasing capabilities of AI and data analytics can potentially revolutionise policymaking (Micheler & Whaley, 2020). Policymakers can utilise technologies like BIM and IoT to access and analyse extensive datasets, generating real-time evidence and insights (Nawari, 2018). This data-driven approach enables informed decision-making, identification of emerging trends, and more accurate assessment of the impact of construction policies (Braun, Kropp, & Boeva, 2022).

The combination of Construction 4.0 technologies and RegTech (technology for regulatory compliance) holds promise for developing more effective and agile regulations (European Construction Observatory, 2021). RegTech solutions can automate regulatory processes, enhance monitoring capabilities, and streamline compliance procedures (Buckley, Arner, Zetzsche, & Weber, 2019). These innovative technologies are appealing in the context of

regulation due to their immutability and security (ensuring data integrity in legal disputes), transparency (real-time and decentralised data availability), disintermediation (eliminating intermediaries and associated risks), irreversibility (tamper-proof data), and automation (automatic data transfer and payments) (Oesterreich & Teuteberg, 2016). By leveraging AI, machine learning, and automation, RegTech assists regulators in keeping up with technological developments in the construction sector, adapting to market changes, and developing relevant and forward-looking regulations (Armstrong et al., 2019). It also aids in risk assessment, compliance monitoring, and reporting, enabling efficient compliance evaluation and identifying potential violations. For instance, regulators can leverage digital platforms to access real-time data, conduct risk assessments, and detect non-compliance more effectively (Johansson et al., 2019).

Moreover, technological advancements facilitate compliance by integrating regulatory requirements into product and service design and development (McDermott, Foley, Antony, Sony, & Butler, 2022). Through digital platforms, IoT, and blockchain, compliance measures can be embedded into organisational processes and supply chains (Gozman, Liebenau, & Aste, 2020). This approach transforms compliance from a cost of doing business into a value proposition (Kagermann et al., 2013). Companies benefit from improved efficiency, reduced risks, and enhanced reputation by proactively incorporating compliance measures into their operations (Johansson et al., 2019). Furthermore, the use of Construction 4.0 technology and RegTech helps reduce non-value-added waste regarding working hours on regulatory processes and minimises human error, a significant source of non-compliance (Foley et al., 2022). Lastly, Construction 4.0 technologies can also alleviate regulatory burdens for citizens by providing targeted online access to construction regulations, building permit applications, and obtaining energy efficiency certifications for their properties (Nawari, 2018).

6 Discussion and conclusion

This whitepaper provides a systematic and comprehensive review of the academic literature on public governance in the context of Construction 4.0 and its broader counterpart, Industry 4.0. The review covers the period from 2016, when the term Construction 4.0 emerged, to June 2023. A total of 45 source documents, including peer-reviewed journal articles, books, and book chapters, were carefully selected using a systematic approach outlined in Section 3. Additional documents were also included to offer further insights and expand on the initial set of sources. The following sections present the key findings derived from this review.

The literature consistently emphasises a significant gap between the normative discussions on the importance of public governance in Construction 4.0 and the lack of empirical knowledge regarding its practical implementation. This gap is not specific to public governance in Construction 4.0 but is prevalent in the broader implementation of Construction 4.0. The literature frequently expresses the aspiration to transition to Construction 4.0; however, in practice, the construction industry is still in its early stages of embracing Construction 4.0, and most published works primarily propose conceptual solutions rather than practical and proven applications (Baduge et al., 2022; Balasubramanian, Shukla, Islam, & Manghat, forthcoming-a; Begic & Galic, 2021b; Elghaish et al., 2022; Karmakar & Delhi, 2021; Marinelli, 2023; Oke & Arowoiya, 2022; Ozturk, 2021; Rachmawati & Kim, 2022; Schonbeck et al., 2020; Tjandra, Irawan, Nugraha, & Sunindijo, 2022).

Despite the limited knowledge about implementing public governance in Construction 4.0, both normative and empirical literature discuss the emergence of "new governance" concepts that have gained attention since the early 2000s. This governance approach is characterised by two key trends that distinguish it from previous approaches (e.g., Eberlein & Kerwer, 2004; Lobel, 2004; Rhodes, 2007). Firstly, there is a shift away from exclusive state authority in addressing societal issues, with increasing involvement of networks comprising public and private sector stakeholders in the governance process. Secondly, there is a focus on employing governance instruments that facilitate self-organisation, promote market-based solutions, or combine both approaches as alternatives or complements to traditional mandatory command-and-control strategies. The literature indicates that governments and public bodies recognise the need to (1) engage and involve the stakeholders they aim to govern in developing and implementing Construction 4.0 governance instruments and initiatives, and (2) utilise a diverse range of governance instruments and initiatives, including regulations, subsidies, education programs, and leading-by-example approaches, to effectively accelerate the adoption of Construction 4.0.

The literature on public governance in Construction 4.0 and Industry 4.0 identifies several unique challenges governments and public entities face. One challenge is ensuring workers receive adequate re-skilling and education to facilitate a smooth transition to Construction 4.0, addressing skill gaps and preventing unemployment. Another challenge is making the benefits of Construction 4.0 accessible to all, considering issues like digital illiteracy and limited access to technology. A third challenge involves managing the new data, cybersecurity, and privacy risks associated with Construction 4.0 for organisations and individuals. It is important to note that concerns are frequently raised about the capacity, knowledge, and capability of governments and public entities to effectively address these challenges (e.g., Feldman, 2012; Peng, 2020; Raj et al., 2020).

The lack of empirical knowledge about public governance in Construction 4.0 underscores the need for further research in this emerging field. However, the limited practical application of Construction 4.0 and its public governance currently restricts our ability to draw comprehensive lessons, particularly regarding interventions and initiatives in various contexts. Overcoming this

limitation requires researchers to adopt a forward-looking research agenda that goes beyond generating hypothetical opportunities and barriers. Instead, they should explore related developments that shape the future of public governance in Construction 4.0 and its potential achievements. For example, the ongoing technologisation and automation of regulation, referred to as 'Regulation 4.0' (Brennan & Dobra-Kiel, 2019), can inspire scholars. They can examine the interaction between regulation and the technologisation and automation of the construction sector, as well as the impact of these advancements on regulation itself. These avenues of inquiry offer promising opportunities for scholarly exploration and understanding, benefiting governments and public bodies seeking to govern the adoption of Construction 4.0.

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Appendix A - Overview of source material (45 articles)

Please note, this is an overview of the 45 articles that are at the base of the systematic review presented in this whitepaper. The full bibliography is available in Section 7 (References).

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Appendix B - Overview of codes used in Atlas.ti

The following set of codes was used to analyse the source documents in Atlas.ti:

- Active government support
- Address industry leadership
- Adoption I4.0 technology
- Clash pre and post I4.0
- Collaboration
- Conceptual/theoretical
- Construction industry
- Contra (finding) to typical narrative
- Covid
- Cross jurisdiction(s)
- Developing economies
- Example
- Financial support
- Good vs service
- Improved regulatory governance
- Legal/laws
- Limited government capacity/capability
- Link I4.0 and environment/ecology
- Paradigm shift
- Policy/policies
- Precautionary principle (implicit)
- Public governance finding (novel)
- Quote
- Regulation
- Regulatory burden (reduced)
- Regulatory performance (improved)
- Regulatory stop to/challenge of I4.0 technology
- Regulatory uncertainty
- Relevant though not directly related
- Security/safety of (use of) I4.0 technology
- Standards
- Sub-national preference
- Upfront costs of I4.0

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