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A typology of digital building technologies: Implications for policy and industry

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Abstract. Digitalization and digital technologies are buzzwords in today's building industry. Because of their promising opportunities to improve (among others) the sustainability footprint of the built environment, they have emerged as an important topic for policymakers, managers, and researchers. Yet, the debate is dominated by references to Building Information Modelling (BIM) and to the success of digital businesses in other industries; it thereby fails to consider other promising digital building technologies and ignores that—in the building industry—many digital technologies require alignment with buildings' physical components. For these reasons, it is unclear how the implications of digital transformation of the building industry for policy and business. In this paper, we develop a typology of digital building technologies, and categorize and assess 29 important building technologies. The substantive differences among different types of building technologies provide valuable insights into how digital building technologies affect the functioning, structure, and competition in the building industry and where digital building technologies offer opportunities to remedy the industry's sustainability footprint. Based on our findings, we offer recommendations to policy makers, companies, and researchers interested in digital building technologies.

1. Introduction

Until the late 1990s, digital technologies appeared as basic software or “the internet.” This “first wave” of digital technologies allowed for simple levels of automation, analytics, and digital communication improving the efficiency of processes [1]. Yet, the digital technologies that concern people nowadays are part of a “second wave” of digital technologies of which Big Data analytics, cloud computing, Artificial Intelligence (AI), or the Internet of things (IoT) are only examples [2]. Some industries, such as retail or media, have already encountered the disruptive impact of the second wave of digitalization. New market players and business models have changed prevailing industry practices [3]. As these changes suggest, this “second wave” of digital technologies is a key enabler for disruptive innovations and the creation of new business models that not merely complement but fundamentally transforms how companies create, deliver, and capture value.

The building industry, too, has benefitted from digital technologies. In the past, digital technologies, such as e-mail, simulation software, or Enterprise-Resource-Planning (ERPs) systems have helped to adjust and improve existing processes. More recently, digital technologies of the second wave are also developed and adopted across the building industry and promise to transform prevailing processes and



business models. This second digital transformation thus promises many opportunities to increase efficiency, productivity, and transparency across the building industry.

For business leaders and policymakers, understanding the digital transformation of the building industry is relevant for several reasons. The emergence of digital building technologies may change the competitive dynamics in the industry. Companies that successfully employ digital technologies may benefit from substantive efficiency gains that will allow them to offer similar services at lower prices. A company's IT capabilities may eventually determine whether it qualifies for joining building projects—digital technologies may thus emerge as the new entry barrier in the building industry. The enhanced transparency introduced by data-driven building technologies may oust companies that rely on opaque pricing and offer others opportunities to develop new business models.

The digital transformation also raises questions concerning the industry's labor market. In particular, trends in the area of prefabrication or robotics may drastically reduce the number of workplace in the building industry. Companies may need to transition from a large workforce of manual labor to a small one trained in handling IT or IT specialists. For policy, alleviating the industry's dependency on manual labor may lead to large-scale unemployment but may also offer a solution to the lack of skilled personnel—depending on the current situation of the labor market. Either way, policymakers will face questions of how to retrain the current and train the future workforce for a digital building industry.

The digital transformation of the building industry may also offer opportunities to policy makers to address sustainability and energy-related concerns associated with the building industry. Currently, the industry is one of the most energy-intensive ones with 40% of the primary energy consumption globally and about 36% of global CO₂ emissions [4]. Digital technologies offer several solutions to minimize the ecological footprint of the industry and help streamline processes across the entire building lifecycle in a more efficient, transparent, and safer way.

Yet significant barriers to digitalization remain. First, the adoption of new digital technologies in the building industry has been slower than in other industries. This is not necessarily surprising given the structural characteristics of the industry. Highly fragmented, with low margins, and low investments in R&D, building companies either have had no time (during construction booms) or no money (during building industry crises) to develop and adopt new technologies. Second, the current debate on digitalizing the building industry tends to focus on one digital technology, Building Information Modelling (BIM). A debate dominated by the promises of BIM not only risks neglecting the substantive challenges of successfully commercializing BIM solutions but, more importantly, risks neglecting other digital building technologies that may offer a more direct route to transforming the industry.

Third, the building industry differs from other industries affected by second wave digital technologies in one important aspect: the central role of the physical built environment. Successfully developing and commercializing second wave digital technologies is in itself challenging [5], integrating digital technologies with physical building components creates an additional complexity that has yet to be fully understood. A better understanding of how digital technologies will transform the building industry may thus provide important insights into other applications of digital technologies that require consideration of the physical world.

This article serves to develop a better understanding of the promises and pitfalls of digital trends in the building industry and is structured along two interrelated questions: What digital technologies influence the building industry and how will they transform the structure of the building industry?

2. Methodology

We focus on the intersection between digitalization and the building industry. We use the term *digitalization* to refer to the integration of digital technologies into everyday life [6]. Digital technologies are all technologies that comprise data or execute algorithms in digital form [1, 7]. The *building industry* refers to a specific segment of the construction industry, namely the one that includes all actors involved in, and activities related to, residential, commercial, and industrial buildings [8-10]. Thus, we consider digital building technologies as those applied by actors involved in activities related to, residential, commercial, and industrial buildings throughout the building's life cycle.

To address our research question we followed a three-step procedure. First, to identify digital technologies in the building industry, we conducted an exploratory literature review, complemented this review with expert interviews, and surveyed additional 20 industry experts asking them “What are the most important digital trends that have emerged in the building industry the in past years?” Through this process, we identified 29 digital building technologies frequently discussed in both the academic and practitioner literature.

Second, to understand the technological, managerial, and regulatory challenges associated with digital trends in the building industry, we distinguish *complementary* from *platform* technologies and *software-based* from *cyber-physical* digital building technologies [5, 11]. Whereas complementary technologies directly execute specific tasks without coordinating detached subsystems, platform technologies integrate multiple complementary technologies and peer-users via shared databases and standardized interfaces. Additionally, software-based technologies have no direct link to the physical infrastructure. In contrast, cyber-physical technologies [9] combine digital and physical properties and carry out specific tasks by either using digital data as input to execute a physical task, or generating digital data as output of a physical environment [11, 12].

Third, to provide insights into the technological features and implications for industry of digital trends in the building sector, we assessed each of the 29 digital technologies along five dimensions: two technology-related dimensions and three industry-related ones: (1) the maturity level of each digital building technology (i.e., technology in development, emerging technology, state-of-the art technology, or industry-wide standard); (2) the *general-purpose digital technologies* a building technology draws on (i.e., cloud computing, IoT, Big Data, AI, mobile technology, mixed reality, Blockchain); (3) the primary impact area (i.e., efficiency, productivity, safety, quality, transparency, convenience, sustainability); (4) the building life-cycle phase in which a technology is primarily applied (i.e., planning phase; construction phase; use/ operations phase, or end-of-life phase); and (5) the primary industry actors affected by a technology (i.e., investors, planning offices, architects, construction companies, suppliers, utilities, or end-customers).

To ensure the robustness of our findings we pre-tested all dimensions (including the labels and parameter values) for clarity and consistency, asked several experts to assess and code each technology along the five dimensions, and compared their answers for levels of agreement/ disagreement and discussed diverging perspectives to converge and agree on a common understanding of the dimensions.

3. Digital building technologies

Among the 29 digital building technologies, we find a variety of digital technologies currently penetrating the industry. Table 1 draws a typology of four distinct types of digital building technologies and categorizes the 29 digital building technologies. The specific digital building technologies differ markedly in technology- and industry-related aspects. We first provide an overview of the four types of digital building technologies and subsequently discuss important aspects for each type separately.

Software-based complementary technologies are apparently more mature than any other type of digital building technology. In fact, both types of complementary technologies have a lower variance in maturity levels between the technologies in each category, suggesting that technology development and commercialization of complementary technologies follows a more coherent pattern. In contrast, the high variance among platform technologies reflects the substantive challenges in developing and commercializing digital platform technologies. The four types also differ in how extensively they draw on general-purpose digital technologies. Software-based technologies only rarely draw on general-purpose digital technologies. In contrast, nearly all cyber-physical building technologies involve underlying digital technologies, in particular automation, IoT and cloud computing. These differences in technology-related factors directly translated into challenges associated with R&D and with successfully commercializing technologies. Software-based complementary technologies are comparably easy to develop and commercialize. Yet, as reflected in the reliance on general-purpose technologies, technological complexity increases with the shift from software-based technologies to cyber-physical technologies and from complementary to platform technologies.

Table 1. Types of Digital Building Technologies, incl. the number of technologies in each type.

	Complementary technologies	Platform technologies
Cyber-physical technologies	Cyber-physical complementary technologies (#9) (1) Laser scanning; (2) automated prefabrication; (3) radio tracking devices in operation; (4) on-site drones (construction) (5) on-site robotics (construction); (6) predictive maintenance; (7) 3D printing (on-site); (8) 3D printing (off-site); (9) augmented reality (operations)	Cyber-physical platform technologies (#7) (1) Cloud-based logistic platforms; (2) sensors/ monitoring building data; (3) building automation; (4) optimization of building functions; (5) smart-building systems; (6) connectivity of building to infrastructure; (7) automated building condition analysis
	Software-based complementary technologies (#5) (1) Computer-aided design; (2) logistic management software; (3) parametric design; (4) building performance simulation; (5) virtual reality in design and planning	Software-based platform technologies (#8) (1) Digital documentation; (2) Enterprise-Resource Planning; (3) Closed BIM 3; (4) E-Business & tendering; (5) mobile technology in project coordination; (6) customer service automation; (7) block chain in project documentation; (8) open BIM

Regarding industry-related aspects, digital building technologies primarily improve transparency, quality, and productivity; and although their potential to improve energy- and sustainability of the built environment, these improvements occur only indirectly. Moreover, the impact of cyber-physical building technologies appears to be more evenly distributed than that of software-based building technologies. Moreover, whereas software-based platform technologies are applied across all building life-cycle phases, from planning to end-of-life, cyber-physical technologies are used almost exclusively during construction (complementary ones) and use (platform ones) phases. Relatedly, while architects mainly focus on software technologies, construction companies and planning offices deploy both software and cyber-physical technologies. Investors primarily use software-based platform technologies, while end-customers and utilities cyber-physical platform technologies.

Overall, digital trends in the building industry appear in a variety of technologies that differ in maturity levels, underlying general-purpose technologies, impact areas, building lifecycle phase and affected industry actors. As the following subchapters will show, distinguishing complementary from platform technologies and software-based from cyber physical ones helps outline important differences in the technological and managerial challenges associated with digital building technologies and understand the disruptive impact these technologies may have on the structure of the building industry.

3.1. Software-based complementary technologies

Software-based complementary technologies account for the highest maturity levels among all types of digital building technologies. Most technologies are state-of-the art technologies or have already become a standard across the industry. Software-based complementary technologies also account for a comparably low technological complexity as they do not rely on large database architectures and rarely draw on general-purpose digital technologies. For many years, R&D among software-based complementary technologies has been rather incremental as technology providers have primarily

focused on developing updates, adding new features, and have only recently drawn on cloud services and developed platforms to connect complementary technologies (e.g., see Microsoft 365 [13]).

For technology providers, key success factors are a detailed understanding of the working processes in which their technology will be used and development of intuitive user experiences and design [14]. Key users in the building industry are architects and planning offices, occasionally construction companies, to facilitate the designing of buildings (elements) and to improve the process efficiency during planning and construction (e.g., facilitating transactions, supporting design, visualizing tasks). Because software-based complementary technologies are stand-alone and task-specific, they rarely require substantive changes to the organization and are thus easily implemented and do not require alignment with partners, suppliers, or customers. Moreover, the economic benefits are readily apparent and explain why these technologies are already widely applied in the building industry.

Yet, despite the maturity of software-based complementary technologies, many industry actors still lack the expertise in handling and using them [15]. The implementation of software-based complementary technologies requires adequate training of employees. Frequently, developers offer trainings to support the transformative process of implementing software in daily working routines. Ultimately, software-based complementary technologies help actors in the building industry develop first IT capabilities and are thus an important route for companies to remain competitive in the market.

3.2. Software-based platform technologies

In contrast, the maturity of software-based platform technologies varies substantially. Whereas some digital building technologies (e.g., ERPs) are already widely dispersed, others (e.g., block chain in project documentation) remain in development. Software-based platform technologies can be found in all life-cycle phases of a building and all industry actors are potential technology users. They primarily foster transparency, thus directly addressing a major barrier for modernization in the building industry.

Platform size primarily explains differences in technological complexity, market penetration, and experimentation with new general-purpose technologies. Complexity increases with volume and heterogeneity of data and users; the more users, the more attractive for technology developers to experiment with general-purpose technologies [16]. Additionally, software-based platform technologies offer opportunities to collect valuable data to generate additional revenue streams, and thus offer substantive indirect benefits to platform owners.

Yet, successfully commercializing software-based platform technologies is subject to network effects, i.e., the value for one peer in the network increases with the number of peers. These network effects are particularly strong in market place platforms and can lead to two problems: a “cold start” problem (i.e., early adopters enjoy only few benefits and have little incentives to join) and a winner-takes-all markets that while highly beneficial to platform developers pose risks to early adopters.

These challenges may also explain the rather reluctant and uncoordinated adoption of software-based platform technologies. Improvements in transparency may require adopters to disclose valuable information (e.g., sub-contractors, technical processes). Moreover, the new role of the network operators may also give substantive powers to individual companies. Finally, the competitive dynamics around software-based platform technologies, as for example among BIM solutions [17], may drastically change the building industry as increased transparency may oust certain industry actors and competences in handling platforms may qualify for joining building projects. Notwithstanding these barriers, software-based platform technologies are key to a more sustainable built environment. Not only do they offer direct contributions through increased transparency. More importantly, by digitalizing processes, structures, and plans, software-based platform technologies often constitute the first step towards enabling sustainability contribution of other digital building technologies.

3.3. Cyber-physical complementary technologies

Cyber-physical complementary technologies are highly sophisticated technologies as they are designed to intervene and adapt to a building’s physical properties [7]. These technologies frequently draw on general-purpose technologies (e.g., IoT, cloud computing, AI) to connect multiple devices and recognize

their physical environment. Because of the technological complexity and the need to account for the physical built environment, developing such technologies involves substantive R&D investments.

Cyber-physical complementary technologies are mainly used during the construction phase by construction companies and suppliers. Users primarily benefit because from increasing productivity in the production and construction process, improving the quality of building components, and reducing the risk of accidents because dangerous tasks can be allocated to autonomously machines.

Yet, although many cyber-physical complementary technologies are technologically ready for the market, they still account for low market dispersion [18]. One barrier may related to the substantive upfront investment for the user. Other barriers include the challenges that users face when integrating cyber-physical complementary technologies into their operations as it requires significant adjustment to established operational processes and structures. Furthermore, overcoming the communication and skill gap between technology providers and users requires significant investments in training, re-training, and hiring efforts.

Notwithstanding these barriers, cyber-physical complementary technologies promise several opportunities for new market developments. For technology providers, they offer avenues for new business models, such as product-service systems (e.g., leasing contracts based on usage), data-driven services (e.g., analyze user behavior to improve safety and efficiency in processes), or financial models (e.g., leasing, co-financing, etc.).

Overall, although the industry has only reluctantly adopted cyber-physical complementary technologies, these technologies offer opportunities for new market players to transform the building industry through new business models. By shifting investment patterns and workforce composition, they may significantly disrupt the industry with technology developers gaining prominence while threatening small and medium sized companies. Most importantly, cyber-physical complementary technologies offer significant sustainability contributions in a, thus far, labor-intensive and error-prone life-cycle stage (i.e., construction) and thus deserve particular attention from policymakers.

3.4. Cyber-physical platform technologies

Cyber-physical platform technologies, such as smart building systems, require substantive sensor technologies in and around building to coordinate user behavior with building components. They also heavily draw on general-purpose technology, such as cloud computing, IoT, and AI. R&D in cyber-physical platform technologies faces both the challenges of cyber-physical technologies and those of platform technologies. R&D challenges pertain to the real-time processing of data to and to the level of process automation and sensors necessary for cyber-physical platforms. Possibly for these challenges, they remain in development and are nowadays mainly used in large public and commercial buildings.

Technology developers of cyber-physical platform technologies usually maintain ownership over platforms. However, because of the technological complexity and substantive development costs, they strongly incentivize external technology providers to develop complementary technologies, both software-based and cyber-physical ones, compatible with their platform ecosystem. Clearly, as developers seek to reach a critical mass of users to join their platforms and to create a lock-in effect, competition among developers intensifies.

Cyber-physical platform technologies appear particularly attractive entry technologies for new market players from adjacent industries, in particular technology engineering companies with experience in IoT. In fact, many non-traditional industry players with stronger ties to other sectors, such as Siemens or WAGO, entered the building industry with cyber-physical platform technologies. Similarly, many technology component manufacturers begin digitalizing their components by equipping these with IoT sensors, APIs, and smart metering technologies. Thus, cyber-physical platform technologies traditionally serve as an entry point for new market players into the building industry.

This merging of building industry with companies from adjacent industries also lead to changes in existing business models. Cyber-physical platforms also produce different revenue models depending on the service type over the building lifecycle and offer opportunities to monetize data through additional services (e.g., energy optimization, predictive maintenance, and customer / tenants services).

Overall, cyber-physical platform technologies appear particularly valuable for more efficiently managing buildings during their use phase. These technologies offer opportunities for cost savings and new revenue streams. Yet, given the challenges associated with R&D, the severe competition for platform leadership, and their limited potential to realize efficiency and productivity gains during the planning and construction phase, it remains unclear if, and if so how, cyber-physical platforms may transform the building industry.

4. Discussion

The diversity of digital building technologies is immense and although most digital building technologies are still under development, they are already beginning to fundamentally change principles of the industry. Digital building technologies offer substantive opportunities to create positive impacts across the entire lifecycle of a building. Major impact areas of digital building technologies strongly vary within the four types of digital technologies, introduced in this paper. Undoubtedly, digital building technologies help address important energy and sustainability related factors in that they offer several paths to reducing energy and material consumption, increasing energy efficiency, reduce planning errors and facilitate retrofitting and demolishing of buildings and recycling or reuse of materials. However, business models of digital building technologies only rarely address energy- or sustainability-related concerns directly, as value propositions of the four types primarily tackle the areas productivity, efficiency, transparency, and convenience. Hence, most of the benefits to sustainability accrue indirectly as secondary effects. Business models that primarily promise contributions to sustainability and energy seem to struggle in succeeding. Thus, policymakers designing incentives to move towards a more sustainable built environment require an understanding of how primary (non-sustainability) benefits translate into secondary (sustainability) impacts. Thus, although digital building technologies offer several opportunities to move towards a sustainable built environment, designing policy instruments and business models to realize these opportunities remains challenging.

To better understand the promises and pitfalls of digital building technologies, we argue it is useful to distinguish four types of technologies: (1) software-based complementary technologies, (2) software-based platform technologies; (3) cyber physical complementary technologies; and (4) cyber physical platform technologies. This typology is valuable because it illustrates differences in adoption barriers, opportunities for new business models, and the transformative capacity of digital building technologies.

In particular, software-based platform technologies and cyber physical complementary technologies offer promising new business opportunities and may fundamentally disrupt the industry. Software based platform technologies do so by increasing transparency and inducing a stronger focus on the planning phase thereby shifting the traditional distribution of roles and responsibilities in the industry. By promising to reduce planning errors, software-based platform technologies offer vast secondary sustainability effects. They will also raise the entry barriers for traditional building companies while offering an attractive entry point for new industry players. Overall, software-based platform technologies may lead to a significant consolidation in the building industry.

In contrast, cyber physical complementary technologies, primarily applied during construction of buildings, promise significant improvements in productivity and safety, and, as a side-effect, reductions in resource and material consumption. Additionally, for design and aesthetic purposes, cyber physical complementary technologies offer many opportunities to provide large-scale customized buildings, thereby offering an attractive path towards a modular built environment. However, these major benefits come along with at least one major challenge for policymakers. The immediate automation of production and construction processes renders futile many traditional employments and occupations in the building industry. Prefabrication and on-site robotics may eventually replace many workplaces in the industry and shift demand for labor-intensive work to assisting, controlling, and supervising machines.

Thus, digital technologies in the building industry have important implications for business models and the industry structure. First, future business models draw more heavily on services and data analytics, especially in the case of cyber-physical technologies. Furthermore, owners of platform technologies may monetize platform-based market access for 3rd parties [19]. This shift will clearly

change the business models of companies in the industry. Moreover, the deployment of platform technologies may disrupt the underlying structure of the building industry by developing stronger linkages to other, adjacent industries (e.g., energy, mobility) and by changing the composition of the building industry. Thus, digitalization will not only lead to more digital building technologies but also, more importantly, will help integrate buildings into a broader, cross-sectoral environment.

Second, the increasing concentration in market power and the changes in the skills necessary to continue participating in building projects should lead to a strong consolidation in the building industry. Larger corporations with the ability to establish platform technologies and to invest in cyber-physical capital will have an advantage over small and medium-sized companies (SMEs) with fewer resources. As a result, SMEs might not only lose market power but also be outdistanced in terms of experience with digital technologies. Thus, digitalization poses a severe challenge in particular to SMEs.

Third, digital building technologies will have a strong influence on the employment conditions and the labor market of the building industry. Especially cyber-physical technologies significantly reduce labor intensity of construction sites. On the other hand, skill requirements for the effective deployment of digital building technologies constantly increase. Digitalization of the building industry will thus most likely lead to a substantial reduction and upskilling of labor force in the building industry. This trend will challenge companies (e.g., construction companies) to find ways to smoothly transition from a company with many employees to one with only few, highly skilled ones. Additionally, given that the building industry is major employer for low-skilled jobs, the labor market effects of digital building technologies should be more pronounced in the building industry than in other industries. Thus, policymakers should not only consider how to support the digitalization of the building industry but should also devise approaches for absorbing the negative side effects on the labor market.

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