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DIGITAL TRENDS IN THE BUILDING INDUSTRY

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Executive Summary

The rise of digital building technologies offers nearly unlimited technological opportunities; opportunities to modernize the building industry, to increase productivity levels in building projects, and to transition towards a more sustainable built environment. The variety of digital technologies designed for the built environment is astonishing, ranging from smart heating systems and software for digital planning and design, such as BIM (Building Information Modelling), to robotics and drones that facilitate construction.

But what impact will digital building technologies have on existing industry structures and dynamics? How can policymakers and industry players leverage the potential of digitalization? Are any of these technologies more favorable and promising than others? And, what implications does their rise have for investors, architects, construction companies, and other industry players?

To address these questions, we have categorized and analyzed, and—together with industry experts—evaluated 29 of the most important digital building technologies. By distinguishing software-based from cyber-physical building technologies and complementary technologies from platform ones, we develop a typology of four distinct building technologies. Our typology offers new insights into their technological features, industrial applications, and diffusion and socio-economic implications. We show that digital building technologies may change the industry in a variety of ways. For example, Building Information Modelling (BIM), the digital bundling technology that dominates the public debate, primarily raises levels of transparency throughout the planning and construction process and helps avoid planning failures. In contrast, pre-fabrication and on-site robotics directly increase productivity and resource efficiency during the construction phase, with possibly significant labor-market implications. The impact of other technologies, such as smart buildings and building automation, is less apparent and depends more strongly on the successful commercialization of other digital building technologies.

Our findings indicate that the rise of digital building technologies offers opportunities to pursue different policy objectives. Some digital building technologies may significantly increase transparency during

tendering and planning, reducing hidden costs involved in pricing and costs occurring due to information loss. In this report, we outline implications for innovation, competition, labor, and education policy, emphasizing the potential side effects of policy support measures. We also show that, while digital building technologies offer ways to address energy and sustainability objectives, the incentives for industry players to adopt such technologies are not primarily based on their sustainability impacts but driven by regulations, cost reductions, or productivity gains. Finally, as these changes in the building industry also have important implications for the various stakeholders in the industry, we have summarized the implications for five of the most important industry players in the form of *“What this means for….”* descriptions.

Our report also illustrates the opportunities of the rise of digital building technologies for established companies and for newcomers to the industry. Equipment manufacturers experiment with leasing models to finance the substantive investment costs in modern technologies, platform owners monetize access to platform users, and newcomers use the volumes of data collected by digital building technologies to design and offer new services to investors, operators, and occupants. Ultimately, as our report shows, the ability of players to design successful business models will be key for unleashing the potential of digital building technologies.

Malte Toetzke
Otto Windeck
Christina Nakhle
Dr. Johannes Meuer

For inquiries, please contact

Dr. Johannes Meuer
Group for Sustainability & Technology
ETH Zurich | Department of Management, Technology and Economics
Weinbergstrasse 56/58 | WEV J 420 | CH-8092 Zurich
Email: jmeuer@ethz.ch
Web: www.sustec.ethz.ch

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We take full responsibility for the views expressed here, as well as any inaccuracies and mistakes.

“What this means for….“

Digital building technologies are likely to fundamentally disrupt the building industry in several ways. In the following, we summarize the most important implications of the digital transformation of the building industry for policymakers, architects, building planners, construction companies, and property developers. Our ‘*What this means for…*’s are high-level summaries; if you’d like to follow up on some of the implications, we refer you to sections in the report that contain more information.

WHAT THIS MEANS FOR ARCHITECTS….

1. Digital building technologies will increase the relevance of the planning phase, shifting attention to technical and life-cycle aspects of buildings. The role of architects will shift towards earlier and closer collaboration with building planners. Architects should thus **develop expertise in digital building technologies** (in particular BIM) **and more closely align their work with that of building planners.**
2. Developers of digital platform technologies, such as BIM, compete for users and market share in a winner-takes-all market. Platform technologies offer similar functions but prevent compatibility by using different APIs and user interfaces, thereby limiting interoperability. Users, such as architects, bare the risk of lock-in effects. **Architects need to carefully select which technologies to adopt in and build skills around, possibly adopting a two-pronged strategy.**
3. Although digital building technologies result in working from the technical skeleton of a building to its architectural design (rather than the other way around), they also offer new opportunities for architectural design (e.g., pre-fabrication, lighter materials). Architects may consider to **explore new designs at the intersection of digital building technologies and architecture.**

WHAT THIS MEANS FOR BUILDING PLANNERS….

1. Decisions concerning the digital infrastructure of buildings and thus the adoption of digital building technologies throughout the lifecycle occurs during planning. Building planners should thus gain and **maintain a substantive understanding of digital building technologies** for addressing questions related to building’s digital infrastructure (e.g., type of data, level of detail, APIs, transfer protocols).
2. The rise of BIM will intensify the focus on the planning phase so that increasingly more decisions across all aspects of the building will be taken during this phase. Building planners thus not only need to develop strong competencies in handling BIM but will also **expand their competence range to evaluate planning decisions from different professional perspectives.**
3. Additional costs, time and resources will occur during the planning stage in the building lifecycle. As official tendering rules continue to favor the lowest price rather than the best price, this puts building planners using BIM at a competitive disadvantage. Until regulators and the market adopt different tendering rules, **building planners should develop models that show the profitability of using digital building technologies during construction and use of buildings**.

WHAT THIS MEANS FOR CONSTRUCTION COMPANIES…

1. Construction companies are confronted with nearly all digital building technologies (e.g., receiving data from planning, installing ‘smart’ operation technologies). Construction companies should **expand their IT competencies across a range of digital building technologies, hire employees with digital skills** and train current employees. Technology developers providing workshops and training programs for their products can facilitate this transition.
2. Cyber-physical platform technologies (e.g., pre-fabrication, drones, etc.) offer major opportunities to significantly reduce cost, improve in quality, and increase safety on building sites. These technologies may also reduce the need for traditional construction workers. In adopting **cyber-physical complementary technologies, construction companies need to develop strategies to transition towards a smaller and more IT-skilled workforce**.
3. Digital building technologies significantly increase transparency in building projects, including technical specifications, planning schedules, and cost estimations. This may require construction companies to deliver detailed information regarding their internal processes and costs structures. Construction companies need to **carefully assess the sensitivity of the information required by project partners** as it may threaten their competitive advantage.

WHAT THIS MEANS FOR PROPERTY DEVELOPERS….

1. Digital platform technologies offer nearly unlimited opportunities to create value, provide services, and increase comfort. However, they are also costly and increase maintenance requirements. For property developers to benefit from the opportunities of digitalization, they need to better **understand their own needs and the demands of their end-customers**.

2. Digital building technologies, in particular those used during the planning phase, improve transparency and thereby reduce risks and uncertainties in building projects. Property developers should benefit from these advantages by using digital building technologies to **estimate risks and develop a better understanding of the economics of building projects.**

3. Digital building technologies may boost productivity and efficiency of building projects. But they also require project partners to bring in a minimum level of IT skills necessary for digital collaboration: if one member lacks the necessary skills, the entire project may suffer. Property developers need to **understand and define the IT competencies required in a project** and **ensure that all partners have these IT competencies.**

WHAT THIS MEANS FOR POLICYMAKERS….

1. While digital building technologies will increase demand for digital talents, robotics and pre-fabrication will reduce the number of workers on construction sites. Policy makers concerned with the labor market implications of digital building technologies should **provide funding for SMEs to re-train employees** and **incorporate digital content in educational programs** for architects and craftspeople.

2. To function properly and successfully compete in the market digital platform technologies require a critical mass of users. Yet, the competition dynamics following a winner-takes-all logic may quickly lead to market power abuse. In particular, SME’s with less market power are at risk. Policymakers need to **balance the support for platforms to reach a critical mass** (e.g., through mergers, standardization) and the risk of an dominance of a single platform owner to avoid lock-in.

3. Digital building technologies will only offer indirect opportunities to increase energy-efficiency and sustainability in buildings. Policymakers interested in supporting the transition towards a more sustainable and energy-efficient built environment should primarily **support software-based platform and cyber-physical complementary technologies** and not solely devise direct energy efficient building policies.

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Abbreviations

AI	Artificial Intelligence
API	Application programming interface
AR	Augmented Reality
BFE	Swiss Federal Office of Energy (Bundesamt für Energie)
BIM	Building Information Modelling
CAD	Computer-Aided-Design
DFAB	Digital Fabrication
EMPA	Swiss Federal Laboratories for Material Sciences and Technology
ERP	Enterprise Resource Planning
IoT	Internet of Things
IT	Information Technology
R&D	Research & Development
ROI	Return-on-Investment
SME	Small and Medium-sized Enterprises
VR	Virtual Reality

1. The rise of digital building technologies

The building industry is in high demand for a transformation. Building projects take—on average—20% longer than originally planned and budgets exceed planned values by up to 80%. Compared to other industries, levels of productivity are stagnating and workplace safety is a major concern. Additionally, as the building industry accounts for 40% of primary energy consumption globally and about 36% of global CO_2 emissions [1], it's a primary target for policymakers to achieve national and global sustainability objectives.

Digital building technologies, digital technologies applied by companies involved in the activities related to residential, commercial, and industrial buildings[1], offer many promising opportunities to address these issues across the building lifecycle. In the planning phase, digital building technologies, such as Building Information Models (BIM) or simulation tools, may drastically reduce project risks and facilitate adherence to predetermined budget and time objectives. In the construction phase, robotics in prefabrication and on-site boost productivity and mitigate accidents. In the use phase, digital building technologies can connect energy consumption, conversion, and storage and coordinate energy demand and supply across building typologies (e.g., residential, commercial, industrial), all within a broader energy and services infrastructure (e.g., mobility, waste, water). And finally, during the end-of-life phase, digital building technologies may enable the recirculation of building parts and materials and thereby foster circularity and sustainable waste treatment.

In addition to transforming existing processes, digital building technologies also promise new opportunities. For example, the building industry generates an immense amount of data, data that can be used not only to improve the overall building performance (e.g., energy, convenience) but also to develop entirely new services. Furthermore, digital technologies may increase sectoral linkages with adjacent sectors such as energy, telecommunications, insurance, or mobility and thereby enable new revenue streams driven by data and digital access to customers. As the range of possible applications with high value for the building industry expands, the digital transformation increasingly turns into a game-changer for the building industry.

Until the turn of the millennium, 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 that primarily improved the efficiency of processes [2]. The building industry, too, has benefitted from these types of digital technologies, as Enterprise Resource Planning (ERP), e-mail, or design software, have helped adjust and improve existing processes. Yet, the digital technologies that concern people

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[1] The subsection "What are digital building technologies?" in the appendix explains our definition.

nowadays are part of the ‘second wave’ of digital technologies of which Big Data analytics, cloud computing, Artificial Intelligence (AI), or the Internet-of-Things (IoT) are popular examples. Digital technologies of this second wave are also adopted across the building industry and customized to the specific use cases of the industry. For example, IoT technology connecting machines and devices provides new avenues to realize a ‘smart building.’ Virtual reality (VR) glasses help planners and investors to pre-view buildings in a virtual environment and convey a sense of indoor space. These second wave digital building technologies promise immense opportunities to increase efficiency, productivity, and transparency across the industry.

Besides its positive impact on macro-economic industry indicators (e.g., productivity, energy consumption, etc.) the digital transformation is likely to affect the industry in several important ways. The emergence of digital building technologies will change the competitive dynamics in the industry. Companies that successfully employ digital technologies will benefit from substantive efficiency and productivity gains that will allow them to offer similar or better services at lower prices. Digital capabilities may eventually also be a key requirement in construction tenders—digital skills may thus emerge as a new competitive factor in the building industry. Furthermore, the enhanced transparency introduced by data-driven building technologies may oust companies with business models that rely on opaque pricing and information advantages. Finally, digital building technologies offer incumbents and newcomers opportunities to develop new business models with enhanced services, new revenue models, and higher product qualities [3, 4].

The digital transformation also has important implications for policymakers. For example, the digital transformation raises questions concerning the industry’s labor market. In particular, trends in the area of prefabrication or robotics on building sites may drastically reduce the number of required workforce in the building industry. Digitalization may imply transitioning from a large workforce of manual labor to a small workforce of IT trained employees. Moreover, policymakers will have to react to new competitive dynamics, such as platform competition and lock-in effects, but also a potential disadvantage of small and medium sized enterprises (SMEs) to successfully manage the digital transformation and stay competitive.

How will digital building technologies transform the industry? What can policymakers do to facilitate this transition? And why are successful business models for digital building technologies key to this transition?

2. Understanding digital building technologies

To address these questions, we followed a four-step procedure as illustrated in Figure 1. Our process involved **scouting** for important digital building technologies, **categorizing** these along two dimensions, **describing** the various types of digital building technologies, and **evaluating** the implications of digital building technologies for policymakers and business.

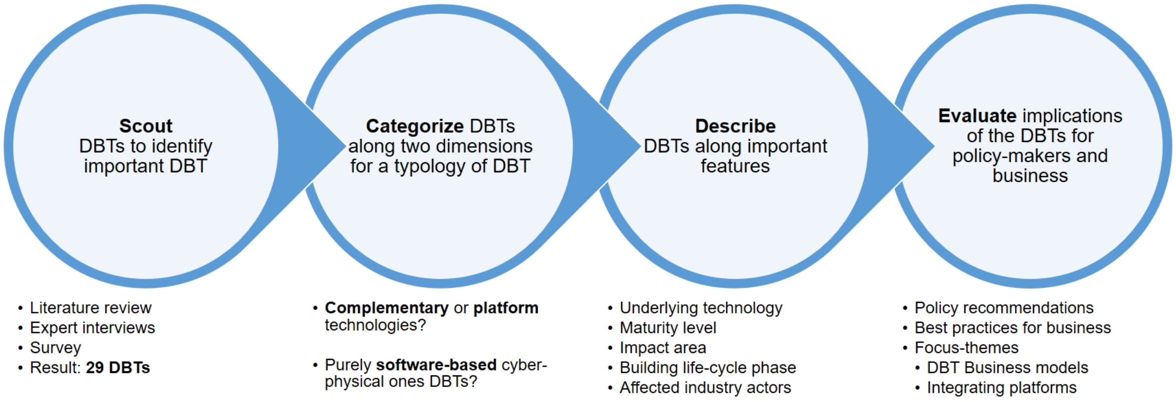


Figure 1 A four-step process for evaluating DBTs

Scouting for digital building technologies

To identify important digital building technologies we conducted an extensive literature analysis, 12 expert interviews, and a brief survey among 14 industry experts probing into their views on important digital building technologies. The subsection in the Appendix "How we identified digital building technologies" provides more details on our approach.

Cross validating the findings from these three sources allowed us to identify **29 digital building technologies** frequently discussed in both the academic and practitioner literature and considered important digital trends in the building industry. The digital building technologies that are currently emerging and are subject of debate in the industry ranges from stand-alone planning tools, digital approaches to tendering and project management, robotics, drones and other approaches to prefabrication, to smart building and building automation. Nearly all experts outline the relevance of Building Information Modelling (BIM) and, as we explain in this report, BIM certainly has the potential to systemically transform the industry. At the same time, there are many other promising digital building technologies whose emerging offers promising opportunities for policymakers and business.

Categorizing Digital Building Technologies

To capture the variety of digital building technologies, we categorized these along two dimension. On the one hand, we distinguished **complementary technologies** from **platform technologies**. Complementary technologies directly execute specific tasks without integrating other technologies. Complementary technologies are stand-alone solutions that largely operate independently. In contrast, platform technologies integrate multiple complementary technologies and peer-users via shared databases and standardized interfaces. In addition to the platform and its integrated complementary technologies, a third key component are “interface technologies” to coordinate and protocol communication between the platform and the complementary technologies [5-8].

On the other hand, we distinguished **software-based technologies** from **cyber-physical technologies**. Software-based technologies have no direct link to the physical environment. In contrast, cyber-physical technologies integrate computational with physical processes, combining ‘computing, communication and storage capabilities with monitoring and/or control of entities in the physical world’ in a secure, efficient, and real-time manner [8-12]. Cyber-physical systems thus carry out specific tasks by either using digital data as input to execute a physical task or by generating digital data as output of a physical environment [13, 14].

Table 1 distinguishes the 29 digital building technologies along these two dimensions and provides a typology of digital building technologies: (1) **software-based complementary** technologies; (2) **software-based platform** technologies; (3) **cyber-physical complementary** technologies**;** and (4) **cyber-physical platform** technologies**.** Not all digital building technologies can unequivocally be assigned to one of the four types. However, the typology provides valuable insights into the differences between digitalizing the building industry and ultimately their implications for policy and business.

Table 1 A typology of digital building technologies

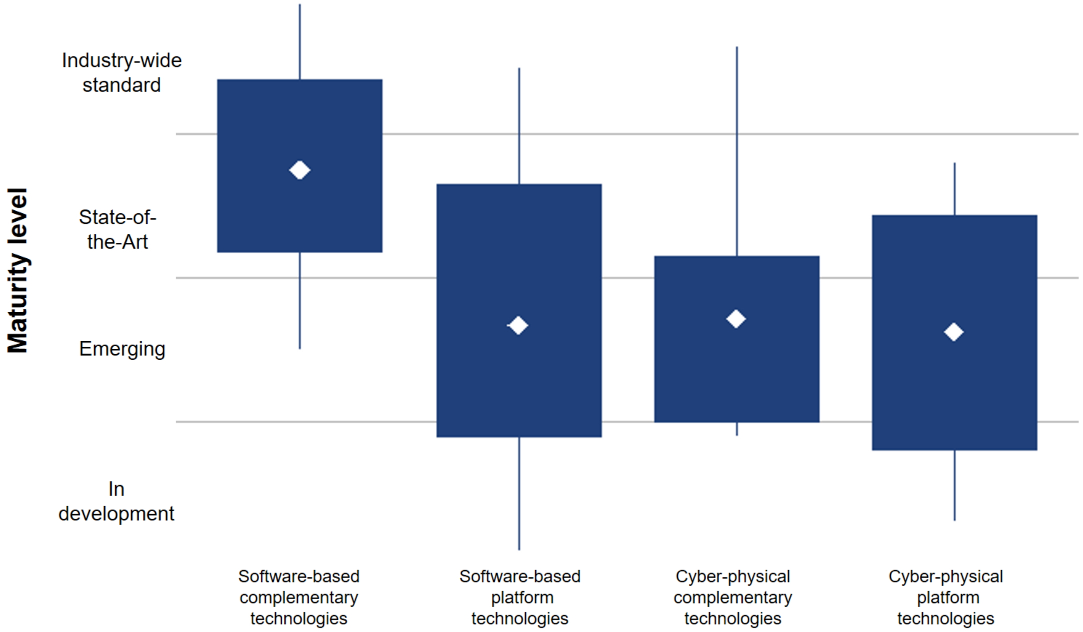
Cyber-physical technologies (#16)	**Cyber-physical complementary technologies (#9)** - Laser scanning - Automated prefabrication - RFID tracking devices in operation - On-site drones (construction) - On-site robotics (construction) - Predictive maintenance - 3D printing (on-site) - 3D printing (off-site) - Augmented reality (AR) in operations	**Cyber-physical platform technologies (#7)** - Cloud-based logistic platforms - Sensorics/ monitoring building data - Building automation - Optimization of building functions - Smart-building systems - Connectivity of building to infrastructure - Automated building condition analysis
Software-based technologies (#13)	**Software-based complementary technologies (#5)** - Computer-aided design (CAD) - Logistic management software - Parametric design - Building performance simulation - VR in design and planning	**Software-based platform technologies (#8)** - Digital documentation - Enterprise-Resource Planning (ERP) - Closed BIM 3 - E-Business and E-Tendering - Mobile technology in project coordination - Customer service automation - Block chain in project documentation - Open BIM (n-dimensional)
	Complementary technologies (#14)	Platform technologies (#15)

Describing digital building technologies

We used five criteria to describe each of the 29 digital technologies. We specified (1) the technological maturity level of each digital building technology (e.g., ‘in development’, ‘state-of-the-art’); (2) the underlying general-purpose digital technologies (e.g., AI, IoT, cloud computing); (3) the actors primarily affected by the development or introduction of a specific technology (e.g., planners, construction companies); (4) the building life-cycle phase in which a technology is primarily applied (e.g., planning, construction, use); and (5) its primary impact areas (e.g., efficiency, transparency, convenience). The subsection “Five criteria to describe digital building technologies” provides more details on the criteria to describe digital building technologies.

As Figure 2 shows, the four types of digital building technologies differ widely in their maturity levels. Software-based complementary technologies are clearly more mature than any other type of digital building technology. Complementary technologies, both software-based and cyber-physical ones, have a lower variance in maturity levels between the four types of technologies, 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.

Figure 2 Maturity levels of digital building technologies
Note: The white dots indicate the mean, the size of the boxes the variance in maturity level of each type.



As Figure 3 shows, DBTs also differ in the extent to which they draw on general-purpose technologies, their primary impact area, the affected building lifecycle phase, and the involved industry actors. In contrast, cyber-physical building technologies strongly depend on IoT to integrate the digital with the physical realms and cloud computing to centrally stored and make available data form the various physical components at that may be located in distant places.

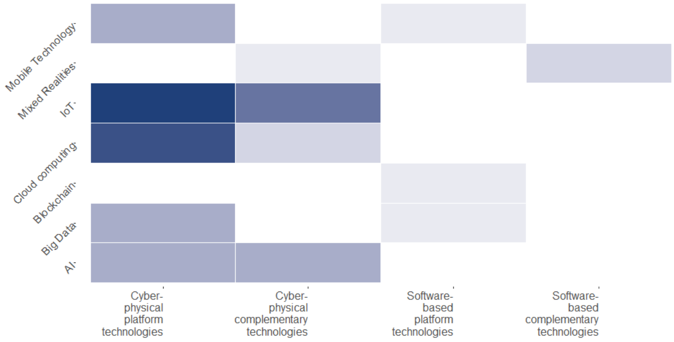


Figure 3 Underlying (general purpose) digital technologies

Note: The color scale (from white to dark-red) indicates counts of digital building technologies that belong to a specific type of digital building technologies (x-axis) and have been assigned a specific attribute of the evaluation criteria (y-axis).

Figure 4 highlights that primary impact areas of the four types of digital building technologies. Software-based building technologies usually serve rather singular areas: complementary ones primarily increase the quality of particular building components; platform ones significantly increase transparency in the built environment. In contrast, the impact of cyber-physical building technologies appears more evenly distributed, improving efficiency, productivity, safety but also convenience and the overall sustainability in the built environment.

Figure 4 Primary impact areas of DBTs

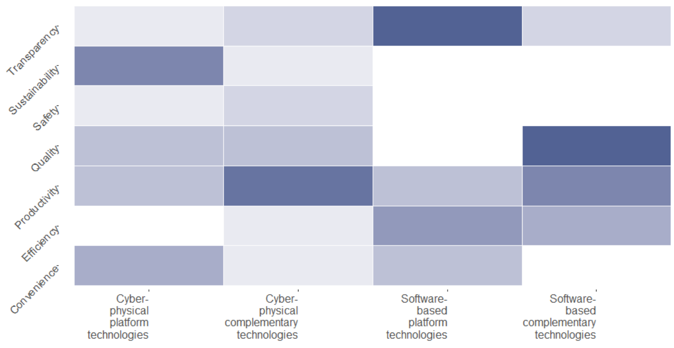
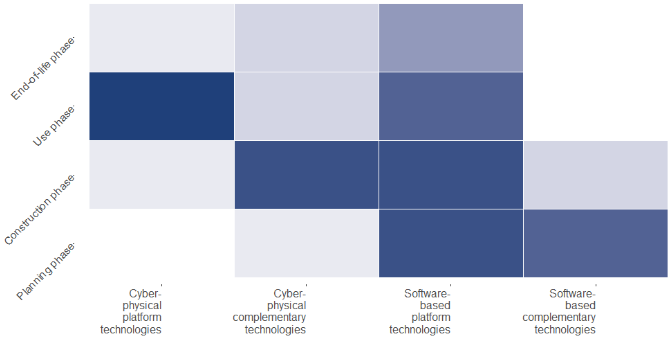


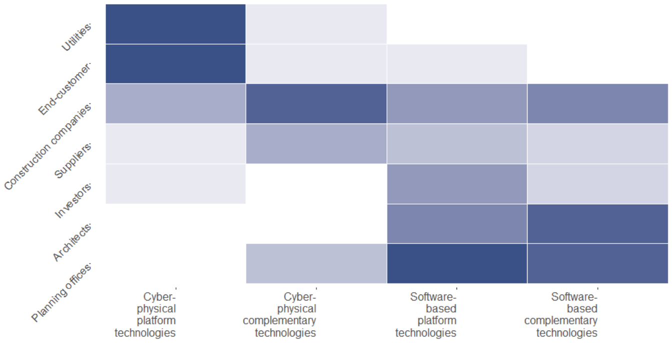
Figure 5 indicate during which lifecycle stage of the building digital technologies are primarily used. As Figure 5 shows, software-based complementary technologies are primarily used during the planning phase. In contrast, software-based platform technologies are applied across all building life-cycle phases, from planning to end-of-life. Cyber-physical technologies are used almost exclusively during construction (complementary ones) and use (platform ones) phases. Also, although some technologies may also be applied at the end of a building's life, only few technologies clearly focus on this stages.

Figure 5 Lifecycle phases affected by DBTs



Finally, Figure 6 provides an overview of the involved industry actors affected by the rise of digital building technologies. While architects mainly focus on software technologies, construction companies and planning offices deploy both software and cyber-physical technologies. Investors count to the major applicants of software-based platform technologies. End-customers and utilities both interact the most with cyber-physical platform technologies.

Figure 6 Stakeholders affected by DBTs



Overall, digital building technologies appear in a variety of forms differing in their technological complexity and the challenges associated with R&D and with successfully commercializing technologies. For example, software-based complementary technologies are comparably easy to develop and commercialize. Yet, technological complexity and R&D challenges increase with the shift from software-based technologies to cyber-physical technologies and from complementary to platform technologies.

3. Evaluating digital building technologies

Among the 29 digital building technologies that we investigated, we find a variety of digital technologies currently penetrating the industry. These technologies differ widely in their technology maturity levels, the extent to which they draw on general-purpose technologies, affected industry actors, building lifecycle phases, and primary impact areas. They also appear in very different forms and shapes. Some are small and useful for performing specific tasks (e.g., 3-D printing), others are intangible but with a wide range of applications (e.g., BIM). Digital building technologies may also appear as large, physical instruments with highly sophisticated digitalized operations (e.g., on-site robotics).

Although nearly all digital building technologies have implications for several stakeholders across a building's lifecycle, knowledge about these technologies appears highly scattered across industry actors. The only exception is BIM, a technology that overshadows the public discussion about digitalizing the building industry. Several reasons justify the heated debate about BIM as it promises levels of transparency and improvements across the building lifecycle. Yet, as our report shows, there are many other digital building technologies with significant implications for industry and policy.

To better understand the implication of digital building technologies for policymakers and business, we evaluated how the four types of digital building technologies in terms of (1) their technological features (i.e., technological complexity and development), (2) industrial applications (i.e., target group, building phase, primary value proposition), and (3) socio-economic implications (i.e., for developers and adopters, potential industry disruption).

In the following subchapters, for each type of digital building technology, we evaluate how their technological features influence the range of industrial applications and thus affect R&D and commercialization activities of both technology developers and adopters. Together the technological features and industrial application of digital building technologies determine their diffusion patterns and the socio-economic implications. Table 2 provides an overview of the technological features, industrial applications, and diffusion and socio-economic implications of each of the four types of digital building technologies.

Table 2 Features, applications, and socio-economic implications of digital building technologies

	Software-based complementary technologies	**Software-based platform technologies**	**Cyber-physical complementary technologies**	**Cyber-physical platform technologies**
Technological features				
Technological complexity	• High maturity levels • Low technological complexity	• Maturity varies/ complexity increase by size (users, data) • Big data, cloud computing	• High maturity levels • High technological complexity • Robotics, drones, IoT	• Average maturity level and technological complexity • Cloud computing, IoT, sensors
Technological development	• Incremental R&D • Links to cloud services	• Rapid and radical R&D • Links to AI & Blockchain	• Recent, new developments • AR & cloud computing	• Slow development • AI & Big data analytics
Industrial application				
Primary target groups	• Architects, planning offices, construction companies	• Investors, planners, construction companies,	• Construction companies, suppliers, new entrants	• Investors, operators, end-users
Building phase	• Planning, construction	• All life-cycle phases	• Construction	• Use phase
Primary value	• Efficiency, productivity	• Transparency, efficiency	• Productivity, quality, safety	• Convenience, data
Diffusion and socio-economic implications				
Technology developers	• Align use case with user demand • Develop high user experience & user friendly design	• Performance requirements, accessibility, add. services • Cold start & network effects • Winner-takes-all competition	• High upfront investments • User friendliness • New business models	• Constraints on growth and network effects • Incentivize external partners • Data-driven business models
Technology adopters	• Easy to implement, • Immediate benefits • Requires additional IT talent	• Platform choice (lock-in) • Network effects • Market entry barrier to profitable building projects	• High upfront investments • Integration into existing operations/ workforce	• Hidden costs of maintenance • Unclear use case • Cyber security
Current diffusion levels	• Diffusion differs by actor type and company size • Expertise/ skills limit diffusion	• Reluctance in platform choice • Fierce competition among platform developers	• Low/reluctant due unclear approaches for financial integration, labor market	• Low diffusion, mainly large/ commercial buildings • Real estate investors
Possible industry disruption	• Limited to singular improvements in efficiencies	• Competition through transparency • Industry consolidation	• New competitors • Labor market implications • New financial models	• Industrial integration • New services • Data-driven business models

Software-based complementary technologies

Technological features

Among the 29 digital building technologies in the building industry, five are software-based complementary technologies (see Table 3). Software-based complementary technologies account for the highest maturity levels among all types of digital building technologies. Most technologies either are ‘state-of-the art’ technologies or have already become a standard across the building industry. For example, Computer-Aided-Design (CAD) or parametric design solutions are already highly diffused in the industry.

Software-based complementary technologies account for a comparably low technological complexity. In most of the cases, they neither rely on large database architectures with high-level performance requirements and analytics tools nor draw on general-purpose digital technologies such as AI, IoT, and cloud computing. Although some levels of understanding of the physical properties of buildings are important, software-based complementary technologies are not tested on their accurate impact on the building.

Industrial applications

Software-based complementary technologies are primarily intended to be used by architects and planning offices during the planning phase. For many years, R&D among software-based complementary technologies has been rather incremental as technology developers have primarily focused on developing updates and adding new features and functionalities to existing software. Autodesk, for example, differentiated its flagship software product AutoCAD into Advanced Steel, Architecture, Electrical, and other versions, providing additional domain-specific details for different user requirements. In other industries, in particular in PC software development (e.g., see Microsoft 365 [15]), software-based technologies are transforming into cloud services and establishing platforms to connect different complementary technologies. A similar transformation appears to begin in the building industry, as the example of Autodesk in Box 1 illustrates.

AutoCAD for Computer Aided Design

AutoCAD is a design tool for architects, planning offices, and project managers for drawing 3D objects. AutoCAD has largely replaced paper sheet drawings, increasing efficiency and quality in the design process. The software was released in the 1980s and is widely spread around the building industry. Latest updates in the AutoCAD software include the compatibility with mobile technology and VR technology. Recently, Autodesk is transforming its products into cloud services and integrating its software in a Platform Solution and Emerging Business division. Despite these advantages, many architecture offices still develop physical models to visualize their designs.

Box 1 AutoCAD - A software-based complementary technology

Diffusion and socio-economic implications

Technology developers face only minor challenges in developing and commercializing software-based complementary technologies. Although R&D requires some programming skills, innovation tends to be incremental with continuous updates and add-ons to existing technologies rather than radical and disruptive changes to technologies. That software-based complementary technologies rely only to a small extent on complex and sophisticated general-purpose technologies also facilitates R&D efforts for technology developers.

However, they do face challenges in successfully developing and commercializing software-based complementary technologies as success largely depends on identifying relevant use cases in which technology adopters in the building industry require support by software. Thus, technology developers need to understand the needs of technology adopters and the concrete working processes in which their technology will be used. A user-friendly design, intuitive user experience, and training offers significantly facilitate the technology adoption across the industry, as most workforce is little adaptive to new software interfaces [16].

Technology adopters may quickly and easily reap the benefits of software-based complementary technologies. These technologies are rather easily implemented into their organizational processes, as illustrated in Box 2. Software-based complementary technologies are task-specific and therefore rarely require substantive changes to the overall organizational structures or processes. Thus, technology adopters, such as architects and planning offices do not need to align the choice for certain solutions and their implementation with partners, suppliers, or customers. Furthermore, the economic benefits for technology adopters are readily apparent. Incentives for technology adopters to adopt software-based complementary technology therefore outweigh organizational barriers and possible drawbacks and foster high levels of dispersion.

Parametric design by Grasshopper3D

Grasshopper3D is a parametric design software released in 2007. It offers engineers, planning offices, and architects algorithms to automatically adjust the shapes of 3D models. Architects may find optimal parameters for building shapes, such as curvatures for roof constructions, within given restrictions (e.g. height, width, material). Grasshopper3D also allows optimizing material usage and building energy consumption, improving the efficiency of the design process and the quality of the product.

Box 2 Grasshopper3D – How software-based complementary technologies impact planning

Although software-based complementary technologies are relatively widely adopted across the industry, they still face several barriers to their diffusion as many industry actors still lack the necessary expertise and skills in handling and using them. Their adaptation strongly varies depending on the type of industry actor and company size, with larger ones focusing on planning being more likely to adopt. Implementing software-based complementary technologies does not only constitute a management decision but also requires adequate training of employees to work with software. Many potential adopters still appear to be rather rigid to technological and cultural changes with missing strategies for developing or acquiring IT talents [17] and trainings by technology developers may facilitate the transformative process of implementing software in daily working routines. Changes in the industry dynamics that will increase cost and time pressure will likely force companies to look for solutions to make their processes lean and speed up project execution. Software-based complementary technologies constitute essential tools to fulfill these requirements and the earlier companies adopt such technologies and learn to benefit from them, the stronger their competitive position.

Table 3 Five important 'Software-based complementary' technologies

Digital technology	Description	Tech. Maturity Level	Underlying digital technology	Involved actors	Life cycle phase	Impact area	Industry examples
Computer-Aided Design (CAD)	Design software that enables the sketching of computer 3D models.	Industry-wide standard	—	Planning offices, Architects, Construction companies	Planning phase	Efficiency, Quality	SketchUp
Logistics management software	Information system to determine, manage and track logistics.	Industry-wide standard	—	Suppliers, Construction companies	Construction phase	Productivity, Quality	Inform
Parametric design	Software that enables the expression of parameters and rules that define, encode and clarify the relationship between design intent and design response based on algorithms.	State-of-the-Art	—	Planning offices, Architects, Construction companies	Planning phase	Efficiency, Productivity	Grasshopper3D
Building performance simulation software	Simulating dynamic building performances such as energy consumption, air circulation or motions of flexible parts throughout digital twins.	Emerging	—	Planning offices, Architects	Planning phase	Productivity, Quality	Morrison Hershfield
VR for design and planning	Enabling observers to view digital objects in a 3-dimensional virtual environment (e.g., via VR-glasses.)	Emerging	Mixed Realities	Planning offices, Architects, Investors	Planning phase	Quality, Transparency	Hololens afca AG; Formatis AG

Software-based platform technologies

Technological features

We identified eight software-based platform technologies applied in the building industry (see Table 4). The maturity level of software-based platform technologies varies substantially. Some digital building technologies, such as ERP systems or sharepoints for digital documentation, are already widely applied throughout the industry and across the building life cycle. Other software-based platform technologies, such as project documentation via Blockchain or cloud-based logistic platforms, remain in development. Size in terms of the number and heterogeneity of users, data volumes, and variety of services are primary factor that explain differences in maturity levels. The larger the platform, the more likely it becomes a state-of-the art technology in the building industry.

Software-based platform technologies largely appear in two forms: as project management platforms (e.g., BIM) or as marketplace platforms (e.g., E-Business and E-Tender, customer service automation). BIMs create digital twins of buildings throughout a building’s life cycle. These digital twins include conditions, related processes, and transactions. Similarly, E-Business and E-Tender platforms increase transparency in market offers and biddings. The case of ‘Wolkenwerk’ in Box 3 illustrates such an e-business platform.

Technological complexity of software-based platform technologies also increases with the build up of the volume of data, number of users, and heterogeneity of users and complementary technologies. Large platforms with large data sets (e.g., BIM with 3D models of buildings [18]), multiple users and complementary services or sub-platforms that operate inter-organizationally are technologically more complex than small platforms. Moreover, technological complexity also aggravates the challenge of integrating users from different companies on one platform. At the same time, large platforms are also more attractive as they offer the opportunity for a company to achieve a long-lasting competitive advantage.

E-Business of project “Wolkenwerk”

Project “Wolkenwerk” covers the construction of four tower buildings in the centre of Zurich in Switzerland. Via a state-of-the-art E-Business platform, most apartments in the buildings already found a private buyer long before completion of the construction. The platform provides information and tools for private and commercial buyers. It enables users to view computer visualizations of the buildings, individual apartments, and office spaces. Furthermore, users can virtually furnish the apartments and visualize it via VR. This information provides increases transparency of pricing and other indicators relevant for potential buyers. For the project investor, early sales reduced financial risks and enabled early cash flows.

Box 3 E-business platforms facilitate sales and increase value

In the past years, R&D has led to radical and rapid changes in software-based platform technologies. Latest developments concern the integration of general-purpose digital technologies, such as Big Data and AI, improving interoperability (e.g., for VR glasses or mobile technology, such as smartphones and tablets), and experimenting with Blockchain applications for software-based platform technologies in the building industry.

Industrial applications

Software-based platform technologies are (or may be) used by all players in the industry (e.g., investors, planning offices, architects, construction companies, suppliers) and are found across all life-cycle phases of a building, during planning, construction, use, and end-of-life of a building. The most pertinent benefit of software-based platform technologies is that they increase transparency in building projects. For example, marketplace platform technologies facilitate access to markets, regulate and make more transparent the tendering process, and thereby facilitate matching supply and demand for building services. Likewise, project management platforms support clear communication as project partners may quickly disseminate and receive detailed and visualized information and thus mitigate misunderstandings. Through improvements in transparency, these technologies also increase the efficiency and planning reliability thereby potentially reducing costs and delays in building projects. One, thus far largely underappreciated side effect of software-based platform technologies is their accumulation of large digital datasets.

Diffusion and socio-economic implications

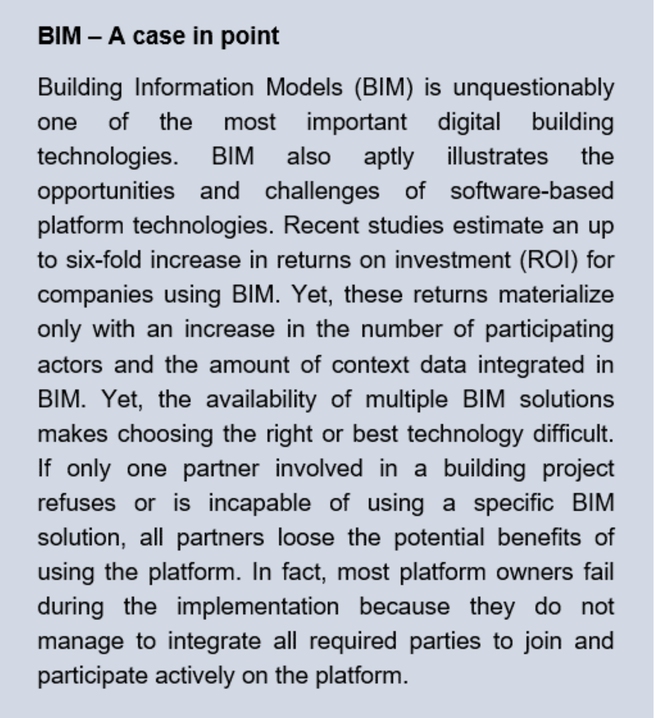
Technology developers of software-based platform technologies not only face several technological challenges but also challenging competitive dynamics. Technological challenges relate to meeting performance requirements of data traffic, enabling accessibility and seamless collaboration of users, and integrating complementary technologies and subordinate platforms. Given the extensive databases on which multiple users operate simultaneously, importing, analyzing, changing, and exporting data, developers need to develop a high performing back-end. They also have to ensure parallel operations of users on the same platform without causing contradictions and data loss. Safety copies, activity protocols, and clear governance structure help fulfil these requirements on the programming architecture. Another technological challenge pertains to implementing interfaces into their platforms to integrate complementary technologies and subordinate platforms. Open ‘Application programming interfaces’ (API) increases the attractiveness and ultimately user population of platforms but also the technological complexity for developers, as they need to handle different data types and formats.

Because the size of the platform and the associated network effects (i.e., the value for one peer in the network increases with the number of peers) are stronger in market-place platforms than in project management platforms, developers have used different strategies to compete for users and complementary services. Some offer unrestricted access via open API and expand the applicability of their platform across the building lifecycle. Others allow for only in-house complementary technologies, thereby restricting access but maintaining control over accessibility and stability of the platform.

These network effects that govern software-based platform technologies also pose three additional challenges for technology developers. First, network effects entail a ‘cold start’ problem as early adopters enjoy only few benefits and thus have little incentives to join. Second, possible winner-takes-all markets lead to fierce competition among technology developers willing to risk their survival to gain an advantage over competitors. Third, long-term lock-in effects also exists for platform developers in that ‘platform shifts,’ i.e., changing the business model underlying a software-based platform technology, are technically and economically difficult because of the tight bundling of complementary technologies and services on one platform.

Technology developers that overcome technological challenges and survive the fierce competition, enjoy substantive and attractive benefits. The more established a platform, the more attractive for users to adopt and the more difficult for them to switch to an alternative solution. Platforms thus being to grow exponentially, simultaneously reducing the marginal costs of adding complementary services. Ultimately, adopting a certain platform evolves into a necessary condition, or entry barrier, for market participation. Finally, technology developers may use the data circulating on software-based platform technologies to generate additional revenue streams, for example allowing third parties to place advertisement, contacting potential customers, or sell aggregated data to develop additional services. Thus, in addition to the direct benefits, software-based platform technologies also offer substantive indirect benefits to platform owners.

If technological complexity and market dynamics around software-based platform technologies challenge technology developers, they also do so for potential adopters. For example, improvements in transparency may require adopters to disclose valuable information (e.g., sub-contractors, technical processes). Similarly, transparency in pricing schemes, a primary objective of tender or e-business platforms that may benefit investors (e.g., insurance companies, banks, retailers) may also increase price competition and create competitive disadvantages for other companies. Moreover, established software-based platform technologies give substantive power and market control to technology developers and platform owners. In some industries, platform ownership has given severe market power to single companies. Alphabet and Amazon, for example, possess large amounts of customer data and control the provision of platform access for advertisement and contractors [19].



BIM – A case in point

Building Information Models (BIM) is unquestionably one of the most important digital building technologies. BIM also aptly illustrates the opportunities and challenges of software-based platform technologies. Recent studies estimate an up to six-fold increase in returns on investment (ROI) for companies using BIM. Yet, these returns materialize only with an increase in the number of participating actors and the amount of context data integrated in BIM. Yet, the availability of multiple BIM solutions makes choosing the right or best technology difficult. If only one partner involved in a building project refuses or is incapable of using a specific BIM solution, all partners loose the potential benefits of using the platform. In fact, most platform owners fail during the implementation because they do not manage to integrate all required parties to join and participate actively on the platform.

Box 4 BIM - Network effects challenge R&D

Finally, the competitive dynamics around software-based platform technologies also lead to a landscape of competing platform solutions that fail to achieve a necessary size and create substantive uncertainties on the side of the users. In Box 4, the case of BIM illustrates the dynamics around software-based platform technologies as the availability of multiple competing BIM solutions that do not complement each other and the development of BIM integrating software solutions show the severe competition over platform size [20].

The challenges for both technology developers and technology adopters may explain the rather reluctant and the seemingly uncoordinated adoption of software-based platform technologies. If skepticism towards digital technologies still exist in the building industry, software-based platform technologies face strong resistance as they not only require digital talents but also substantively influence existing structure, processes, and forms of collaborating. Barriers and disincentives (e.g., sharing of sensitive company data, lower profit margins due to transparency) prevent many actors from joining software-based platforms. Thus, in particular, the opportunity to increase transparency in the industry, the primary value of software-based platform technologies, may at the same time pose its major barrier to widespread adoption.

Nonetheless, software-based platform technologies may drastically change the building industry. Improvements in transparency may increase competition in the industry and force actors to reduce costs or improve their quality [21]. At the same time, they offer platform owners additional revenue streams to develop and exploit new business models [22], mainly driven by remunerating aggregated platform data (e.g., to insurance companies) and giving platform access to 3rd parties (e.g., for advertisement). Ultimately, software-based platform technologies may determine which companies survive in the building industry as those failing to develop the skills and competences to operate on certain software-based platform technologies may be excluded from joining building projects and thus disappear from the market.

Table 4 Eight important ‘Software-based platform’ technologies

Digital technology	Description	Tech. maturity level	Underlying digital technology	Involved actors	Life cycle phase	Impact area	Industry examples
Digital documentation	Documentation of contracts, receipts, communication, and other project related documents in digital formats.	Industry-wide standard	-	Construction companies, Planning offices, Investors	Planning phase, Construction phase, Use phase, End-of-life phase	Transparency, Convenience,	
ERP systems for building project management	Planning, management, and documentation of resource flows (e.g., financial, material flows) via standardized information systems.	State-of-the-Art	-	Construction companies, Planning offices, Suppliers	Planning phase, Construction phase	Efficiency, Quality	SAP
Closed BIM (3-dimensional)	Digital representation of physical characteristics of a building, forming a reliable basis for decisions during a projects life cycle. Closed BIM have no standardized interfaces and are used by few actors that work on the same model.	State-of-the-Art	Big Data	Planning offices, Architects, Investors	Planning phase, Construction phase, Use phase, End-of-life phase	Productivity, Transparency	Revit
E-Business and E-Tender in construction	Conducting of procurement, bidding, and sales activities via electronic, internet-based platforms.	State-of-the-Art	-	Planning offices, Architects, Construction companies	Planning phase, Construction phase, Use phase	Efficiency, Transparency	etenders
Mobile Technology for project coordination in construction	Using smart phones or tablets to coordinate a project throughout the internet and cloud systems. Mobile Technology offers different users ubiquitous access to dynamically adjusted information throughout the project as a single source of truth (SSOT).	State-of-the-Art	Mobile Technology	Planning offices, Architects, Construction companies	Planning phase, Construction phase	Efficiency, Transparency	Capmo
Customer service automation	Coordinating the communication and automating orders between building service providers and residents via online channels.	Emerging	Mobile Technology	End customers, Suppliers, Planning offices	Use phase	Efficiency, Convenience	Allthings
Blockchain for project documentation	Documentation of project activities and related transactions throughout open and distributed ledgers in a permanent and secured way using cryptography.	Technological development	Blockchain	Planning offices, Architects, Investors	Planning phase, Construction phase, Use phase, End-of-life phase	Convenience, Transparency	
Open BIM (n-dimensional)	Digital representation of both physical and functional characteristics of a project, forming a reliable basis for decision making during a projects life cycle. Open BIM solutions offer defined interfaces that enable collaboration of different actors on the same models.	Technological development	-	Planning offices, Architects, Investors	Planning phase, Construction phase, Use phase, End-of-life phase	Productivity, Transparency	buildingsmart

Cyber-physical complementary technologies

Technological features

Among the digital building technologies, nine technologies are cyber-physical complementary technologies, technologies that interweave physical and digital properties [23] and either use data as input to execute physical tasks (e.g., smart power tools) or generate data as output of a physical environment (e.g., scanning with VR glasses, smart meters) (see Table 5). Some cyber-physical technologies, primarily related to the field of robotics, are capable to simultaneously perform both tasks.

These technologies are capable of scanning the physical environment to generate and process data for executing physical tasks. Examples of cyber-physical complementary technologies in buildings involve robotics both applied in pre-manufacturing and on building sites, sensor-equipped tools such as AR glasses or drones, and IoT enabled devices such as smart power tools.

Cyber-physical complementary technologies are highly complex, matching sophisticated materials and hardware components with advanced software solutions. Their technological complexity increases when designed to adapt to their environment (e.g., building sites) or simultaneously generate data and execute tasks. Whereas some cyber-physical complementary technologies are already mature and applied in the market, others are just emerging. They have relatively short R&D cycles and in the past five years, many new technological solutions have entered the market.

The DFAB House - Prefabrication, robotics and 3-printing technologies in construction

The DFAB house is the world's first residential building that has been predominantly built by 3D printers and robots in prefabrication and on site. The project was executed by researchers of ETH Zurich and EMPA in collaboration with industrial partners and constitutes a pioneering project. Using cyber-physical complementary technologies, the researchers could minimize the required material and let robots execute tasks that are too dangerous, unhealthy or complicated for humans. 3D printers extending the possibilities of building forms allowed new design possibilities and considerable decreases in material usage. The innovative construction process of the DFAB house could thereby enhance productivity and safety in the construction process and quality and sustainability of the building.

Box 5 The DFAB – Implementing cyber-physical technologies into construction processes

Recent developments include incremental adjustments to existing construction equipment and building technologies (e.g., heat pumps, electricity systems, appliances) to make these products usable in a digital environment. Other developments include more radical innovation, such as drones and robotics on building sites that replace or radically transform current operations, cloud computing to enable the connectivity of machines and devices, and AI for recognizing the physical environment.

Industrial applications

Cyber-physical complementary technologies are primarily used during the construction phase either during the construction of the actual building or the installation of components. Primary technology adopters thus are construction companies and suppliers, in particular in the case of prefabrication. These technologies offer three major benefits. First, they significantly increase productivity in the construction process as they not only enhance but also reorganize production and construction processes but also drastically reduce time, costs, and materials. Second, they improve the quality of building components because machines, for example in prefabrication, work more precisely. Recent technologies such as 3-D printers are capable of creating entirely new and highly accurate shapes and reduce material needs. Together, improvements in construction processes and quality of components may also drastically reduce energy and resource consumption of building projects. In the end, cyber-physical complementary technologies should thus significantly accelerate the transition towards a more sustainable built environment. Third, as illustrated in Box 5, cyber-physical complementary technologies reduce the risk of accidents to employers as dangerous tasks can be reallocated to autonomously or partly autonomously working machines.

Diffusion and socio-economic implications

The main challenges for technology developers are the substantive upfront investment necessary for developing cyber-physical building technologies and designing tools to facilitate and improve the user experience of their technologies. Many technology developers struggle with the challenge to design cyber-physical complementary technologies in such way that they are easy to control and supervise by human users. Interestingly, accomplishing both challenges requires matching capabilities of both established companies in the building industry and new market entrants. Primarily, companies new to the building industry develop cyber-physical complementary technologies (e.g., drones on building sites). Innovation thus appears in the form of push (supplied) rather than pull (demanded) innovation, as the case of eDAQRI in Box 6 illustrates. Whereas established companies have the knowledge and expertise to ensure that technologies meet the needs of the industry and to help design tools in a user-friendly manner, new comers often have easier access to the necessary financial resources and experience with R&D in such a field.

To developers, cyber-physical complementary technologies mainly offer opportunities to create new business models such as product-service systems. Instead of selling a product, developers may offer provide smart leasing contracts (performance-based) for the machine usage and add automated maintenance and overhaul services. As the cost of cyber-physical complementary technologies often exceeds the customers' budgets, such business models could become the main enabler for making such technologies affordable and boosting market dispersal. For example, smart building power tools can estimate when maintenance is needed and how the machine should be optimally operated. A technology adopters consequently only pays for the actual usage of the machine.

Augmented Reality by eDAQRI supports work on construction sites

The Augmented Reality glasses developed by eDAQRI allow workforce on site to compare construction progress with the final design. Primary users are construction companies and architects. The glasses project digital objects, such as missing construction parts, on real objects of the building. This helps workers during constructions to identify and locate subsequent tasks and provide supporting information. The glasses thereby considerably enhance the workflow on construction sites. During the use phase of a building, the glasses can be used for maintenance operations. The AR glasses by eDAQRI can be integrated into the Autodesk BIM platform. This allows integrating entire 3D models of buildings and enables full-scale walkthroughs on a cyber-physical construction site. The AR glasses enhance efficiency, productivity and transparency of construction processes.

Box 6 AR glasses for construction and maintenance processes

Technology developers on the other hand can use life-cycle data generated by cyber-physical complementary technologies to analyze user behavior and significantly improve innovation cycles by adjusting weaknesses. From a value chain perspective, such business models shift machine failure risks to those actors in the value chain that can handle them the most – from technology adopters to technology developers.

To technology adopters the benefits of cyber-physical technologies are apparent with improvements in process efficiencies, quality, and safety. However, cyber-physical technologies challenge adopters in two ways. First, cyber-physical complementary technologies are costly to develop and consequently require substantive upfront investment on the side of the adopters. New business models based on financial instruments (e.g., leasing, co-financing, etc.) may help overcome this barrier. Second, cyber-physical complementary technologies have significant implications for workplaces in the building industry as they often replace human- with machine-labor and thus reduce the workforce demand. Additionally, they require new skill sets, requiring workers to be able to operate digital technologies. Adopters thus face the challenge of managing a transition from a large, less IT-skilled workforce, to a small one with substantive IT skills and digital talents. A the same time, as the building industry in many industrialized countries is increasing under pressure because of a growing shortage of workers [24], cyber-physical complementary technologies may offer a promising solution to the labor shortage.

Despite the availability of several cyber-physical complementary technologies that are market-ready and their substantive benefits, they are far rarely used in practice and still account for low market dispersion [25]. Uncertainties in underlying financial models, the communication and skill gap between technology developers and adopters are some of the main obstacles in the commercialization of cyber-physical complementary technologies. Many potential adopters do not know how and where to implement cyber-physical complementary technologies effectively in their construction processes.

Adopting cyber-physical complementary technologies across the building industry will have substantive implications for the building industry. First, they offer an attractive entry point for new market players that may significantly disrupt the industry in changing investment patterns and workforce composition. Because investment requirements and skill levels may ultimately decide which companies may qualify for collaborating in building projects, complementary building technologies appear particularly crucial for small and medium sized companies (SMEs). Relatedly, cyber-physical complementary technologies will require entirely new business models, promising a transformation of the industry beyond its technological foundation.

Second, the primary technology adopters, construction companies, will radically transform from labor-centered construction processes towards collaborative construction processes between employees and cyber-physical complementary technologies. Third, the diffusion of cyber-physical complementary technologies will pose substantive challenges to policymakers. For transitioning towards a more sustainable built environment, cyber-physical complementary technology offer important solutions. At the same time, their diffusion will also have important implications for the labor market, requiring possibly additional programs for re-training current and new educational programs for future workers.

Table 5 Nine important 'Cyber-physical complementary' technologies

Digital technology	**Description**	**Tech. Maturity Level**	**Underlying digital technology**	**Involved actors**	**Life cycle phase**	**Impact area**	**Industry examples**
Laser Scanning	Using laser scanning technologies to generate data regarding shapes of objects, landscape, and other geometries.	Industry-wide standard	-	Planning offices, Construction companies	Planning offices, Construction companies	Quality, Productivity	
Automated prefabrication of parts	Automated fabrication of customized building parts and components by robotics according technical drawing files.	State-of-the-Art	-	Suppliers, Construction companies	Suppliers, Construction companies	Productivity, Quality	Modspace Katerra
RFID tracking devices in operations	RFID tracking devices allow real-time tracking of products, materials, parts, equipment, and machinery in logistics.	State-of-the-Art	IoT	Construction companies, Suppliers	Construction companies, Suppliers	Productivity, Transparency	North American Construction Group
Drones on building site	Drones that measure and scan geographic details and landscapes of building sites and that track construction progress during operations.	Emerging	IoT, AI	Planning offices, Construction companies	Planning offices, Construction companies	Transparency, Convenience	Siteaware
Automated brick building robotics	Construction robots that build structures by placing bricks with limited or without human intervention.	Emerging	IoT, AI	Construction companies	Construction companies	Productivity, Safety	SAM by Construction Robotics Hadrian X
Predictive maintenance of building power tools	Determining the condition of building power tools by collecting and analyzing real-time data via algorithms and AI. Prediction of critical machine statues and optimal maintenance dates.	Emerging	Cloud computing, AI	End customers, Utilities, Suppliers	End customers, Utilities, Suppliers	Safety, Sustainability	'Smart guard' by Meier Tobler
AR in operations	Projection of virtual objects and information in 2D on real building objects on building site via AR-glasses.	Emerging	Mixed Realities	Planning offices, Construction companies	Planning offices, Construction companies	Convenience, Sustainability	eDAQRI
3D printing on building site	Mobile 3D printers for automated layer printing of building elements and structures (e.g., cement base).	Technological development	IoT, AI	Construction companies	Construction companies	Productivity, Efficiency	MIT Digital Construction Platform
3D printing in prefabrication of parts	Using digital layer printing based on technical drawing files to fabricate customized building parts	Technological development		Suppliers, Construction companies	Suppliers, Construction companies	Productivity, Quality	

Cyber-physical platform technologies

Technological features

Among the 29 digital building technologies, seven technologies are cyber-physical platform technologies (see Table 6). Examples of cyber-physical platform technologies are smart building systems, integration systems that connect buildings to the infrastructure, and building condition analysis tools evaluating a set of building-related sensors. They often appear as integrated systems that connect different cyber-physical parts of the building with a control system (e.g., automated heating) or with the building's environment (e.g., the electricity grid, security systems, maintenance companies).

The maturity level of cyber-physical platforms primarily depends on the level of automation that allows users to conveniently control over building devices. Those cyber-physical platform technologies with lower levels of automation are already state-of-the art industry, those with higher levels of building automation are in development. For example, because building automation systems (i.e., systems that allow users to regulate building devices) require relatively little self-automation technologies compared to smart building systems (i.e., systems that additionally include technologies to allow for real-time optimization of building devices), they appear in a higher maturity stage.

The technological complexity of cyber-physical platform technologies resembles that of both cyber-physical systems and platform technologies. Most draw on several general-purpose digital technologies (i.e., IoT, cloud computing) to facilitate communication between physical objects. A central technological feature of cyber-physical platform technologies is their extensive use and demand of sensor technology (e.g., to track logistic streams, building temperatures, energy consumption). The more fine-grained and re-active the platform, the more extensive and complex the sensors. Some cyber-physical platform technologies comprise multiple different sensors that collect different types of data (e.g., smart meters, motion recognition, cameras) often in vast amounts (up to petabytes).

Recent technological development primarily occurs in two areas. In the context of building maintenance and optimization, developers increasingly integrate and upgrade general-purpose technologies (e.g., AI, Big Data, cloud computing) to improve the generation and evaluation of the substantive amounts of information [26]. Thereby, owners can identify maintenance requirements and optimize consumptions and conditions of buildings. In the context of smart buildings, as developers continue to struggle successfully commercializing their solutions, technological developments focus on increasing user-friendliness through language recognition (e.g., Amazon Alexa) and unifying interfaces.

Industrial applications

Most cyber-physical platform technologies are developed for the use phase of buildings. More recently, with improvements in Big data analytics and the potential of cyber-physical platform technologies, this creates implications for the construction phase, in particular concerning the installation of the appropriate sensor technology and building devices capable of ‘communicating’ with the system. Primary target groups for cyber-physical platform technologies are owners, operators, and building inhabitants.

Given their ability to regulate buildings and districts in varying levels of sophistication, cyber-physical platform technologies offer several benefits. Most importantly, they serve to enhance living standards by improvements in convenience for end-users. Additionally, through the collection of large amounts of user-related data and thus an increased transparency of the physical environment and the activities of the physical building system, cyber-physical platform technologies offer several indirect benefits. As such, predictive maintenance helps building operators to impede machine failures and help utilities improve buildings’ energy performance.

Diffusion and socio-economic implications

Although cyber-physical platform technologies seem to combine the technological complexity challenges associated with both platform technologies and cyber-physical ones, they pose different challenges to developers and adopters. These challenges differ from other platform and cyber-physical technologies in two ways. First, cyber-physical platform technologies do not merely connect users. Instead these platforms rather connect an ecosystem of complementary technologies that may interact with each other and be controlled by users in a holistic fashion (e.g., by defining routines or optimizing specific building functions). Second, cyber-physical platform technologies in the building environment are physically restrained to complementary technologies, buildings, or districts, a factor that complicates both the transferability and growth of cyber-physical platform technologies.

Technology developers face several challenges in developing and commercializing cyber-physical platform technologies. Because many seek to maintain ownership over their platform, the technological complexity and development costs force developers to incentivize external technology developers to contribute complementary cyber-physical technologies to their platform ecosystem and to allow them to quickly scale up platform usage. Incentivizing external partners also poses additional challenges in defining interfaces (e.g., APIs) that facilitate complementary developers to integrate their technologies into the ecosystem. As it is characteristic for platforms, cyber-physical platform technologies comprise network effects. Incentives for complementary technology developers to contribute to the platform ecosystem increase with the number of users and vice versa.

Growth of cyber-physical platforms also differs from that of purely software-based ones. Growth is linked directly to installing platforms and complementary technologies in buildings and units. In contrast to software-based technologies, the marginal costs of cyber-physical platform technologies are much higher than zero, thus strongly affecting their scalability. Scalability is further limited to the number of flats, houses, and other buildings in a given market. These differences appear to alter the role of ‘network effects' as platforms do not directly but merely indirectly and less pronounced benefit from network effects. Specifically, it appears network effects depend on two factors: (1) incentives for developers of complementary technologies to contribute to the platform ecosystem (e.g., monetary incentives, higher user base) and (2) incentives for users to adopt a cyber-physical platform technology and to prefer one brand to another (e.g., availability of large ecosystem of complementary technologies, good user interface, strong performance). Cleary, together these factors evoke a chicken-and-egg problem between having a strong user base to attract third party developers and having a strong base of complementary technologies to attract users.

Additionally, as interaction is less relevant between platforms than within a given network, the actual 'network effect' in cyber-physical platform technologies is indirect and less pronounced. Having a critical mass of users is a strong competitive advantage but is not as essential as on software-based platform technologies.

If challenges to technology developers differ from those of software-based platform technologies, the benefits are similar. Once cyber-physical platform technologies have accumulated a critical mass of users, it provides valuable information not only directly for the platform operator but also indirectly to companies outside the building industry. Direct benefits accrue from information such as specific energy consumption or capacity usage of building functions. For example, operators may use this information to optimize energy consumption of specific buildings or groups of buildings. As the case of Efergy in Box 7 illustrates, the same information may also be used for other purposes as it may help utilities to better understand patterns of energy consumption or other technology developers to offer predictive maintenance services.

Several emerging business models are structured to take advantage of these platform effects, offering benefits for users in return for gaining access to data [27]. For example, large IT companies entering the building industry appear primarily interested in opportunities for targeted advertisements and access to customers to sell directly products via their smart home platform. Thus, the price for installing cyber-physical platforms may be relatively low but platform owners will monetize building data by charging for access to the data from third parties (e.g., insurance companies, retail deliveries) or for offering additional services (e.g., maintenance).

For adopters, cyber-physical platform technology also offer several potential. In buildings, cyber-physical platform technologies facilitate the control of building functions and provide transparency for a building user via aggregated sensor data. This allows operators and investors to maintain buildings in a more secure, sustainable, and functional form. Cyber-physical complementary technologies that address end-customer needs also increase attractiveness (and thus property value) making them particularly attractive to investors. Many platforms for end-users also offer additional functions that facilitate social interaction among tenants, adding value to both tenants and investors. Finally, depending on who ultimately owns the data generated and stored by cyber-physical platform technologies, the volumes of use-related data promise many opportunities to develop new business concepts.

At the same time, the data and technological complexity of cyber-physical platform technologies pose several risks. First, given the physical installation of sensors and the necessity of other components to communicate with each other, choosing the platform is challenging, as adopters need to balance their own needs with the size and costs of a given system. From a technical perspective, it is less problematic to install and design a highly flexible and adjustable system. More challenging for adopters is to understand their own use case, in particular given the long life cycles of buildings and the potential changes in demands in the future.

The choice of a specific platform technology also raises a potential dependency on complementary services (e.g., predictive maintenance), establishing a lock-in effect as switching becomes increasingly difficult. Second, many adopters underestimate the substantive energy and maintenance costs of cyber-physical platform technologies. Third, cyber-security is a major issue as IoT technology remains vulnerable and technology networks and devices prone to be hacked.

Efergy montors energy consumption

Efergy is an international company that developed a cyber-physical platform for energy monitoring. The platform of efergy tracks electricity consumption in buildings in real-time. Efergy represents the platform owner. Main customers and users of the platform are private building inhabitants or commercial or public building users. Via portable devices, they can track their current electricity consumption, room temperatures and related energy prices. Furthermore, they can analyze past energy consumption, costs, and carbon emissions via an app. Additional customers of efergy are utilities. Utilities can install sensor devices of efergy in buildings of their customers. Thereby they gain access to customer data and have the possibility to provide incentives for customers to shift electricity consumption from peak hours to off-peak hours. Efergy's platform substantially improves the transparency for building inhabitants regarding their electricity consumption and fosters sustainable consumption behavior.

Box 7 Efergy provides transparency on energy consumption

Overall, cyber-physical platform technologies remain rather lowly diffused, those applications including low levels or simple automation diffusing faster in the market. Real estate companies with many properties are quickly adopting cyber-physical platform technologies to increase the market value of their portfolio, offer additional services to tenants, and more effectively operate and maintain buildings and districts. Large-scale use cases, however, are primarily restricted to industrial buildings, high-end segments in the market, and to new built constructions.

The potential of cyber-physical building technologies to reduce energy consumption or improve energy-efficiency of buildings remains unclear. In industrial applications, cyber-physical platforms may facilitate operations and maintenance and help identify energy saving potentials. It appears that tenants have little incentives to save energy, even if their energy consumption is made transparent. Similarly, the energy optimization potential during operations of automated energy systems is unclear although the more complex and interdependent the various energy vectors, the higher the potential for using automated platform technologies.

Likewise, it is unclear how disruptive cyber-physical platform technologies may become. Clearly, they strongly foster the merging of the building industry with adjacent industries, a shift that may generate new revenue sources for the industry. Additional revenues may be generated during the use phase of a building that constitutes by far the longest period of building life-cycle phases. Services and data driven business that can be executed throughout the ecosystems of cyber-physical platform technologies promise high profit margins. In fact, it appears that the interest of many global tech companies, such as Apple and Google, primarily stems from developing a strong presence inside people’s homes to monetize their services and to collect data. Ultimately, cyber-physical platform systems could substantially enhance large infrastructure systems such as energy grids or traffic. Nonetheless, to date, cyber-physical platform technologies are mainly integrated in large public and commercial buildings and slowly pervading into private housing so that their ultimate impact on the industry remains to be seen.

Table 6 Seven important 'Cyber-physical platform' technologies

Digital technology	Description	Tech. Maturity Level	Underlying digital technology	Involved actors	Life cycle phase	Impact area	Industry examples
Sensorics and monitoring of building data	Visualization and monitoring of dynamic building performance data (e.g., energy consumption) generated by sensors.	State-of-the-Art	Cloud computing, IoT, Mobile Technology	End customers, Utilities, Investors	Use phase	Transparency, Sustainability	ACR Systems
Building automation	Control of building functions (e.g., via smartphone APPs or other digital interfaces).	State-of-the-Art	Cloud computing, IoT, AI	End customers, Utilities	Use phase	Quality, Convenience	Efergy
Optimization of building functions	Algorithm based optimization and control of building functions such as heat and energy consumption.	Emerging	Cloud computing	End customers, Utilities	Use phase	Convenience, Sustainability	GridSense
Smart Building Systems	Integration of digital technologies into building systems to strike the trade-off between comfort maximization and energy minimization. Smart building systems offer an integrated view on different functionalities and technologies within the building system based on vast amounts of generated data.	Technological development	IoT, Big Data, AI	End customers, Utilities	Use phase	Convenience, Sustainability	Siemens Building Technology
Cloud based logistics platforms	Planning and tracking of all flows via cloud systems and IoT devices (e.g., RFID) in real time.	Technological development	Cloud computing, IoT	Suppliers, Construction companies,	Construction phase	Productivity, Safety	
Connectivity of buildings to infrastructure	Integration of buildings into infrastructure to optimize infrastructure performance such as energy generation and consumption (e.g., via smart grids.)	Technological development	Cloud computing, IoT, Big Data	End customers, Utilities, Investors	Use phase	Productivity, Sustainability	e-can
Automated building condition analysis	Analyzing building conditions based on data generated by sensors and life-cycle models based on algorithms.	Technological development	IoT, Big Data, AI	End customers, Utilities, Construction companies	Use phase	Safety, Quality	

4. The impact of digital building technologies

The diversity of digital building technologies is immense and although most are still in development, they are already beginning to fundamentally change the principles of the industry. 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, the transformative capacity and opportunities for new business models of digital building technologies.

Digital building technologies offer substantive opportunities to create positive impacts across the entire building lifecycle. Major impact areas of digital building technologies strongly vary within the four types of digital technologies, primarily improving levels of productivity, efficiency, transparency, and convenience. Digital building technologies may also help address energy and sustainability related aspects (e.g., energy and material consumption, energy efficiency, recycling or reuse of materials). However, only a few digital building technologies directly address energy- or sustainability-related concerns. Given the differences in their focus on the building lifecycle, the affected actors and the primary value propositions, the four types of digital building technologies may transform the building industry in very different ways. Recognizing these differences is important for policymakers and business alike to reap the opportunities of digital building technologies.

Software-based platform technologies, such as BIM, increase transparencies and eliminate inefficiencies primarily during the planning phase. More importantly, they constitute necessary building blocks for the efficient application of other digital building technologies throughout a building's lifecycle. Moreover, as soon as software-based platform technologies become the key digital infrastructure of the building industry, they will likely change the competitive dynamics across the industry by eliminating business models based on information asymmetries and raising entry barriers in the industry. Clearly, **the changes induced by digital building technologies during the planning phase have important ramifications across the entire building lifecycle** because they generate data and information that are valuable across all lifecycle stages.

In contrast, cyber-physical complementary technologies, such as pre-fabrication technologies or on-site robotics, improve productivity, primarily increase safety and reduce resource requirements during construction. This type of digital building technology offers major resource- and time-savings during the construction (and possibly) demolition phase. At the same time, **cyber-physical complementary technologies may trigger major disruptions among the labor market of the building industry**, potentially replacing many traditional jobs increasing digital skill requirements on construction sites. Additionally, the mismatch between the substantive investment requirements involved in cyber-physical complementary technologies and the scarcity of capital among incumbent building companies suggests that newcomers—with financial resources and technological expertise—are likely to drive the diffusion of cyber-physical complementary technologies.

Finally, the implications of the rise of software-based complementary technologies and cyber-physical platform technologies are rather unclear. Software-based complementary technologies may either be applied as stand-alone solutions or may become complements to platform technologies. Both scenarios suggest that their impact on the industry will be limited. Instead, cyber-physical platform technologies, such as smart building systems, primarily improve convenience and quality of the building experience. Optimization during the use phase may also help to reduce energy consumption and increase efficiency. Yet, the business case for the traditional building industry remains rather unclear and, to date, cyber-physical platform technologies have failed to widely diffuse across the industry. The main reason why policymakers and business may keep an eye on the development of **cyber-physical platform technologies is that they are the prime entry point into the building industry for many global technology giants** (e.g., Apple, Google, Amazon). These newcomers seek direct access to tenants (i.e., consumers) to collect data, monetize services, and implement data-driven consumer business models.

The transformative capacity of digital building technologies

Based on these insights, we argue that digital building technologies have distinct disruptive effects that will transform the underlying structure of the building industry in three major ways.

First, **digital building technologies may lead to important changes in the labor market**. Their rise will significantly increase the demand for digital talents and partly replace demand for manual work. Most routine work will cease to be manual and instead be conducted in the interaction between employees and digital building technologies. Given that the building industry is a major employer for low-skilled jobs, the labor market effects of digital technologies should be more pronounced in the building industry than in other industries. At the same time, demand for digital talents and IT skills should significantly increase. Increasing skill demands might translate into the need to either retrain remaining employees or hire new—and differently educated—employees. Digitalization of the building industry will thus most likely lead to a substantial reduction of employment in the building industry, a trend that will challenge companies (e.g., construction companies) to find ways to smoothly transition from a company with many employees to one with a few, highly skilled ones [28].

Second, the ability to handle and operate digital bundling technologies will soon determine who will be able to participate in innovative and profitable building projects. **Digital building technologies may become a new and important entry barrier for companies to new projects in the building industry**. Because large companies with more resources should more rapidly adjust to a more digitalized building industry than SMEs with fewer resources to invest in developing the necessary IT support activities, digitalization poses a particular challenge to SMEs. The building industry, highly fragmented with a large number of SMEs, may thus in the long run experience a radical consolidation caused by digital building technologies. At the same time, assuming that a large share of the building stock remains a viable market for the traditional building industry (e.g., private house-ownership of individual buildings), **the building industry is likely to experience a polarization with an innovative (digitalized) segment and a traditional (non-digitalized) one**.

Third, the building industry is likely to develop stronger linkages to other, adjacent industries, such as energy, mobility, retail, insurance, and waste. In particular in the context of the idea of a ‘Smart City’, digital building technologies are important components to allow integrating buildings in a broader environment. In particular cyber-physical platform technologies that connect devices and agents using automation and control and bilateral information flow are important integrative technologies [29]. With increasing sectoral linkages, the composition of the building industry will likely change in that established companies will discontinue traditional capabilities in favor of new capabilities and new companies will enter the industry along with novel skills and capabilities. Thus, **digital building technologies will offer more and new cooperation opportunities between the building industry and adjacent sectors,** driving the connectivity between building inhabitants, physical building, their broader environment (e.g., energy system), and interested third parties.

Implications for policymakers

The possible influence of digital building technologies on the industry has important implications for policymakers, in particular for innovation, competition, and education and labor market policies.

Our findings suggest that **innovation policy should** thus primarily **incentivize** R&D and encourage the use of **software-based platform technologies** (e.g., BIM) **and cyber-physical complementary technologies** (e.g., prefabrication). Innovation policy helps stimulate the development and commercialization of technologies that serve the public interest. As we have shown here, some digital building technologies rather serve private benefits (e.g., convenience, quality, and luxury services). Other digital building technologies, however, promise significant public benefits (e.g., transparency, energy- and resource efficiency, and sustainability in the built environment). For example, software-based platform technologies significantly reduce information asymmetry among project partners and are systemically important to enable interconnections with other sectors, centrally important for the development of more integrated systems (e.g., Smart Cities). Instead, cyber-physical complementary technologies significantly increase resource-efficiency and safety on construction sites. For these reasons, innovation policy should primarily support these two types of building technologies.

Our report also suggests that **competition policy** should **address the growing dominance of platform organizations** and **the impact of new market players** in the building industry**.** Platforms in general pose a dilemma to competition policy: to provide benefits they need to be large enough; to avoid lock-in effects they should not become a monopoly. In the built environment, given the long investment horizons and lifecycles of buildings, the dynamics of this dilemma are more pronounced. The important role of software-based platform technologies comes along with challenging competitive dynamics, as their rise creates clear benefits but also risks, most notably that single companies may achieve and potentially abuse their dominant position in the market. Moreover, the possible consolidation in the building industry (through closures, acquisitions, mergers, etc.) and the entrance of new market players may require competition policy to pay attention to the changes in the underlying economic structure of the industry. In particular, SMEs seem unlikely to develop platforms and thus vulnerable to dominant market players. Overall, we argue that competition policy should ensure a certain level of control and influence over platforms, in particular software-based platforms in the planning phase. Moreover, competition policy should seek to protect SMEs from growing competition, in particular if they have particular digital skillsets and capabilities.

Finally, to facilitate the transition towards a digital built environment with respect to labor market implications, we argue that **labor market and education policy should offer retraining programs and digital content in curricula across the entire education system to develop digital talents for the building industry.** The emergence of digital building technologies will lead to two important labor market effects: the increasing demand for digital talents and the decreasing demand for traditional employment. Depending on national labor market conditions, these changes may either lead to increased numbers of unemployed or help companies deal with a lack of skilled workers. Thus, policymakers need to find ways to develop digital skills among current and future employees in the building industry in professional education. To support skill development among the current workforce, policymakers may consider offering retraining programs and encourage industry associations to offer more digital trainings. Moreover, to develop digital talents as future employees, policymakers should encourage digital content at the university level and, in particular, at the level of the vocational education and training schools. Clearly, labor market and education policies that support the development of digital talents will significantly accelerate and smoothen the impact of digital building technologies on the industry.

Strategies and policies for business model innovation

Digital building technologies are increasingly entering the building industry and have the potential to change the industry towards a more sustainable built environment. As we argue, these changes have important policy implications, in particular for innovation, competition, labor market, and education policies. Yet, as this report has also shown, whether or not digital building technologies will widely diffuse across the industry requires a better understanding of the opportunities of companies to design functioning business models.

Companies are already experimenting with new business models. For example, new value propositions appear with platforms offering convenience while creating value through monetizing data. This shift towards services will also offer technology suppliers new differentiation opportunities, a trend that has already been observed in other industries [30]. Other companies are considering new avenues for creating value. To overcome investment requirements, technology developers may shift from merely selling a product to using a product for acquiring subsequent services using leasing, performance-based contracts, or sharing models to overcome potential investment requirements [31]. And platform owners are adopting new ways for capturing value by monetizing market access to platforms or by generating revenues, for example, by charging fees from suppliers or taking commission for transactions. **The extent to which digital building technologies will widely diffuse largely depends on the success of companies to design successful business models**.

In sum, digital building technologies create unprecedented changes—changes that may fundamentally disrupt the industry and offer new business opportunities. The transition triggered by the rise of digital building technologies is already on its way. Rather than hesitating, policymakers and company leaders need to proactively engage with digitalization. For policymakers, the rise of digital building technologies means designing policies and regulations that create public benefits while accounting for the potential side-effects of policy support measures. For companies, it means rapidly adopting those technologies that increase productivity and quality while pushing frontiers in their digital environment. Companies failing to manage a timely and effective transition to a digital building industry may likely disappear from the market in the next decade. It is hard to imagine a non-digital future of the building industry. The earlier the industry embraces digital building technologies, the more the industry and society may benefit from their opportunities. Ultimately, successfully deploying digital building technologies will require a transformational change of the industry, a change that may lead to intense competition and power struggles among established companies and newcomers, and the development of new business models.

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Appendix

What are digital building technologies?

We define digital building technologies at the intersection between digitalization and the building industry. Digitalization refers to the integration of digital technologies into everyday life [32]. Digital technologies are technologies that comprise data or execute algorithms in digital form [2, 23]. Following Schwab (2017) [2], we distinguish between (1) the first wave of digital technologies (e.g., Enterprise-Resource-Planning software) that have emerged approximately in the late 1960s and (2) the second wave of digital technologies that have emerged approximately after the mid-2000s (e.g., AI, IoT, cloud computing). These technologies are often referred to as general-purpose digital technologies because they are applied across different sectors and constitute underlying technologies for specific industrial applications (e.g., AI enabling image recognition for automated driving in the automotive industry).

The term 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 [33-35]. We thus exclude other sections of the construction industry, most notably infrastructure (e.g., highways, bridges, or energy infrastructure) because these sections differ markedly in the type of projects, involved companies, industry structure, and regulatory environment. Thus, the term digital building technologies refers to digital technologies applied by companies involved in activities related to residential, commercial, and industrial buildings.

How we identified important digital building technologies

To identify digital technologies in the building industry, we used three sources. First, we conducted an exploratory literature analysis focusing on specific applications of digital technologies in the building industry but also more generic applications of digital innovations across other industries. Second, we complemented this review with twelve expert interviews in parallel that commented on digital trends in the building industry and hinted at additional technologies to investigate. Based on these findings, we compiled a preliminary list of most important digital building technologies. Third, we surveyed additional 20 experts in the industry asking them one simple question: “In your opinion, what are the 3-5 most important digital trends that have emerged in the building industry the in past years?” We cross-validated the answers from this survey with our preliminary list of digital building technologies to check if our list contains dispensable technologies that can be dropped and if survey answers state important technologies that are omitted in our list. Through this process, we identified 29 digital building technologies frequently discussed in both the academic and practitioner literature and considered important digital trends in the building industry. During the last cross-validation step, the selection of digital building technologies of our preliminary list remained unchanged, but each technology was confirmed. Because the technologies both appear in the literature and are considered relevant by industry experts, we consider these digital building technologies as important drivers for the digital transformation of the building industry.

Five criteria to describe digital building technologies

We assessed each of the 29 digital building technologies along five criteria. This was motivated to generate comparable attributes for each of the technologies. Based on these attributes, the 29 digital building technologies can be compared regarding socio-technological features and managerial implications. Table 7 provides a brief overview of these five criteria. To provide insights into the socio-technological complexity and into the R&D challenges associated with digital building technologies, we specified the maturity level of each digital building technology (e.g., “in development,” “state-of-the-art”) and the general-purpose digital technologies (e.g., AI, IoT, cloud computing) a digital building technology uses. Furthermore, to gain insights into the potential managerial implications for companies and the industry as a whole we evaluated the primary impact area (e.g., productivity, transparency) for which a technology creates benefits, the building life-cycle phase in which a technology is primarily applied, and the primary actors developing, implementing, or employing a certain technology. We distinguish four phases in the life-cycle of a building: the planning phase (i.e., strategic planning, feasibility, design), the construction phase (i.e., bidding, building planning, construction), the use phase (i.e., operation, management), and the end-of-life phase (i.e., demolition, recycling, reuse) [33, 34]. All possible attribute values (characteristics) provided by each evaluation criterion can be reviewed in Table 7.

Table 7 Five criteria for describing digital building technologies

Maturity level Digital building technologies differ in how much the technology is developed and the extent to which companies in the building industry have adopted a technology.	
In development	The system still constitutes a prototype in the development stage. The system and its underlying technology has yet not been proven successful under mission operation.
Emerging	The system has been successfully tested under mission operation. First early adopters start to implement it into their working processes. The system and its new technology does not necessarily outperform prevalent systems as the technology is still refined throughout usage and experience.
State-of-the art	The system has been adopted by the broad majority of industry players. It represents the highest performance regarding competitive technology.
Industry wide standard	The system has been adopted by nearly all industry players. Its implementation is required by either customers, project-partners or legal entities.
General-purpose technology Digital building technologies may build on several general-purpose digital technology that provide generic functionalities with applications across multiple industries [2].	
Mobile Technology	Mobile technology refers to mobile computers such as smart phones or tablet PCs. These computers are portable and can connect to the internet via WIFI or mobile networks such as 3G, 4G and soon 5G (“5th Generation”).
Mixed Reality (MR)	Mixed Reality (MR) describes the combination of real objects with virtual objects visual for an observer. It comprises a large range of subclasses on the reality-virtuality continuum to which Augmented Reality (AR) and Virtual Reality (VR) can be assigned. AR refers to the projection of virtual objects and information in 2D on real objects. VR represents an extreme on the reality-virtuality continuum in which the observer can only view digital objects in a 3-dimensional virtual environment.
Internet of Things (IoT)	IoT comprises all kinds of devices and objects which can send and receive data, and whose state can be altered via the Internet. Many IoT devices also include sensors to transform information of the physical world into the virtual data. IoT is closely related to technology trends of big data and cloud computing.
Cloud computing	Cloud computing enables remote access to distant databases or computers via internet. Users can access a shared pool of data location-independently from devices connected to a Cloud and manipulate the data. Cloud computing provides huge potential for location-independent collaboration, ubiquity of information and territorial inclusiveness.
Blockchain	A blockchain is a digital chain of transaction records that is secured via cryptography. Every block is connected to a previous block and cannot be altered. Verification of transactions are secured decentral on a peer-to-peer basis. To change parts of the blockchain one needs to exceed fifty percent of computing power of all blockchain users. Blockchain bares huge potential for security and transparency regarding any kind of transaction and legal agreement.
Big data	Big data is the storage of data in a quantity so high that it overstrains the abilities of traditional analytic tools to operate properly. The term usually also refers to different tasks such as storage, editing, analytics and transfer of the data.

	Characteristics of Big Data are volume, velocity, variety, and veracity of the data (4V).
Artificial Intelligence (AI)	AI refers to the ability of machines and systems to perform cognitive functions that are associated with the human brain, e.g. sensing, processing oral language, reasoning, learning, and making decisions. Very broadly spoken it implies that machines carry out intelligent behaviour and connect given information and data to knowledge that can be applied to operate tasks that are non-formalized. AI machines and systems have the capacity to learn and build new knowledge bases by contextualizing input data generated by different sources.

Impact areas

Digital building technologies differ in how much the technology is developed and the extent to which companies in the building industry have adopted a technology.

Transparency	Transparency indicates the degree to which information and data regarding a certain object or process are available and visible. Higher transparency enables increases in communication, coordination, and accountability.
Sustainability	Improvements in sustainability refers to a change of a process in such way that the strains on ecological ecosystems due to waste, emissions, or the exploitation of natural resources is decreased.
Safety	A high level of safety indicates a low level of risk to which the health of a worker and consumer is exposed.
Quality	Quality is defined as the degree to which a product or service is able to fulfil a purpose. This shows that the measure of quality depends on the perspective. Quality of a product or service goes together with the perceived satisfaction of a consumer. Dimensions can include higher endurance, functionality, or any other indicators.
Productivity	The concept of productivity is closely related to the concept of efficiency. In contrast to efficiency, productivity indicators are used to evaluate a given output to the input units of workforce, physical capital, or time used throughout a production process. This shows that the concepts of efficiency and productivity do not necessarily coincide. Ideally, an optimization of a process would increase both productivity and efficiency.
Efficiency	Efficiency refers to the relation between output and input (usually measured in units of costs or material) of a process. Efficiency is generally used to compare input output relations of similar processes or of one process to an ideal state. For example, efficiency can be used as a measure of driven miles of a car per liter of gas as input unit. It indicates thereby how well certain input units are used to create an output.
Convenience	Higher convenience enables a user to achieve a goal with less effort or difficulty. This can refer to the execution of a task or the consumption of a product or service.

Industry stakeholders (affected actors)

Digital building technologies can be applied at different life-cycle stages of a building [35].

Planning phase	The planning phase comprises measures in which a larger group of potential contractors draft different realizations of the building project. This stage is prior to the physical construction process and comprises strategic planning, feasibility studies, and design.
Construction phase	The construction phase includes the determination of a certain design and project composition and the execution of the physical construction of the building. Involved stages namely are bidding, detail planning, production of materials and parts, and building.
Use phase	The use phase applies to the utilization of the building and its functionalities by private or public entities. The stages comprise both operation of the building's functions and maintenance of its conditions. The use phase represents by far the longest life cycle phase of a building.
End-of-life phase	End-of-life phase begins after the utilization of a building is abandoned. It includes its demolition as well as the subsequent waste treatment.

Industry stakeholders (affected actors)

Digital building technologies can be relevant for different actors across the building industry [35].

We distinguish seven primary actors

We distinguish seven primary actors:

1. Investors
2. Planning offices
3. Architects
4. Construction companies
5. Suppliers
6. Utilities
7. End-customers

Ensuring robustness of findings

We implemented several measures to ensure the robustness of our findings. For the collection of the most important digital building technologies, we consider the survey a proof of robustness, as we did not add any new technologies afterwards. For the evaluations of the 29 digital building technologies, we improved robustness as follows: First, we pre-tested all of the five evaluation criteria (including the labels and parameter values) for clarity and consistency with the experts from the interviews. Second, we asked several experts to classify and define attribute values to each technology along the evaluation criteria. Were multiple answers possible, we asked experts to identify the three most important categories (e.g., only the three most important actors relevant for a digital building technology). Third, after the experts' evaluations, we compared their answers. In case of disagreement, we discussed the diverging answers with the experts to understand different views and, if possible, to converge and agree on a common evaluation.

At the last stages of finalizing this report, we organized an expert workshop where a diverse group of industry experts discussed the framework and findings of the report. Those participants came from academia, industry and policy, all related to the building industry. As a general consensus, the expert group considered digital building technologies to produce substantial changes in the building industry—both on the micro-level for projects and on the macro-level for industry dynamics and industry composition. The group also observed strong uncertainties of industry actors regarding two aspects: First, industry actors are searching for successful approaches on how to design and effectively deploy digital building technologies and related business models. Second, they are unsure how their business will be impacted and forced to adapt to new trends of digital building technologies. Third, policymakers need insights on how policies and regulations can influence outcomes of the digital transformation that promote a more sustainable, more productive, and safer building industry.

The presented typology of this report was perceived as a valuable tool for both practitioners and policymakers by the expert group. Moreover, the challenges and opportunities of digital building technologies stated in the report were shared by the experts of the related fields. The expert group also approved our recommendations for technology developers, technology users and specific industry actors to be useful guidelines for decision making in the context of the digital transformation of the building industry.