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Technology Innovation for Sustainability in the Building Construction Industry: An Analysis of Patents from the Yangtze River Delta, China

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Abstract: Advances in technology provides the potential to innovate sustainability in the building construction industry. Drawing on the literature and expert reviews, this research discloses the potential of 14 specific technologies in waste minimisation, energy saving, and efficiency improvement for sustainable building construction and develops a conceptual framework engaging the building life cycle (the planning, construction, use and operation, and demolition phases) and the actors for assessing technological innovation at a local level. This framework is used to identify how technologies were innovated for sustainable building construction through the selected 3017 patent invention applications from the Yangtze River Delta (YRD), one of the fastest urbanising areas and the largest market for the building industry in China. Findings unveiled that innovation is uneven amongst the 14 technologies and the degree of mixing was relatively low in the YRD. The contribution of the technological innovation to sustainability is mainly actualised through efficiency improvements in building construction (2265) and through directly reducing waste (1094) and energy consumption (642). Some general-purpose technologies (e.g., blockchain, cloud computing), which assume to fundamentally innovate the industry, are mostly absent with less than 10 records each, leaving the potential for future adaptive technological innovation. Furthermore, state-owned enterprises as the main sources of patent inventions amongst applicants in the YRD may suggest the dissimilar path of China towards technology innovation compared to its Anglo-American counterparts.

Keywords: sustainable building construction; technology innovation; full life cycle; sustainability; patent invention; China

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1. Introduction

The building and construction industry is one of the most wasteful and energy-consuming industries on Earth. In accordance with the report of global alliance for buildings and construction released by the United Nations Environment Programme, carbon emission generated by the operation of buildings reached a peak of around 10 billion tons in 2019, accounting for 28% of the total CO_2 emissions of all energy-related industries. In China, carbon emission in the building and construction industry accounted for 39% of the total emissions generated by society, where the construction of buildings alone accounted for 18%. The consumption of electricity and the reliance on traditional fossil fuels in building operations are the main factors contributing to carbon emissions, thereby calling for proactive approaches for decarbonisation, energy-saving, and environmental protection in the full life cycle of buildings to achieve sustainability [1]. Although some disruptive technologies for digitalisation or industry 4.0 are viewed as having great potential to effectuate sustainable building construction, researchers have acknowledged that the application of these state-of-the-art technologies in building construction is lagging behind other industries due to the added complexity of integrating intelligent, often virtual and digital, technologies into the physical built environment [2,3]. We explore the progress of technology innovation and application in realising sustainable building construction, and how this technological transformation can proceed at a local level. Here, disruptive technologies refer to those with the opportunities to displace established means of building construction and reshape the industry towards sustainability (primarily related to digitalisation, big data, intelligent automation, and energy saving etc.) [4]. Assimilating the advancement in technology should overcome the large and heavy characteristics of construction products, the shortage of investment in R&D, and organisational fragmentation. Clarifying how typical disruptive technologies can possibly be applied to the building industry is of great importance to enable a more sustainable physical world. Although many studies have discussed the application of disruptive technologies in the building construction industry, few have clearly and systematically indicated the possible paths to concrete sustainability objectives. Sustainability is a comprehensive concept and its original environmentalist theory underpins embracing biodiversity and ecosystem integrity [5]. As reported by the United Nations, the concept of sustainability should 'meet the needs of the present without compromising the ability of future generations to meet their own needs' [6]. This grand narrative is in need of translating to specific aims in different areas to make sustainability operational and easy to implement. In the building and construction industry, sustainability can be specified as minimising waste and negative environmental impacts, maintaining low energy and resource consumption, and maximizing safety and efficiency throughout the full life cycle—planning and design (PD), construction (C), operation and maintenance (OM), and end of use or demolition of buildings (ED) [7–9]. However, how disruptive digital or industry 4.0 technologies could possibly benefit these specific objectives when being applied to the building industry is insufficiently discussed in extant research [10–14]. Building construction is a highly localised industry, but studies examining place-based technological innovations in the building construction industry that serve sustainability purposes are rarely reported and the main contributors at the local level, which are the critical actors to disrupt the industry, are unclearly known. This study is one of the first attempts to address the issue. First, it purposefully synthesises 14 technologies' paths to sustainability objectives by reviewing the existing literature to clarify these issues and uses patents as proxy to reveal the innovation patterns of these technologies in the Yangtze River Delta (YRD), one of China's fastest urbanising areas and the largest market for the building industry. It goes beyond a simple review or forecast of the possible application of advanced technologies in this industry and contributes to a contextualised understanding towards how technologies with potential to innovative building construction for serving sustainability objectives.

2. Technologies with Innovative Potential for Sustainable Building Construction: Towards a Conceptual Framework

This research consults the Scopus and Web of Science (WoS) databases to identify technologies with innovative potential for sustainable building construction. Searches for studies published after 2018 that used keywords, such as 'digital/disruptive/technology/building/construction' in the article title and abstract, were conducted. Over 450 articles were automatically found in the WoS, and 102 articles were filtered from the core collection with irrelevant studies manually excluded. These articles were either overviews of multiple technologies [10,11] or detailed accounts of singular technology [12–14], discussing their application or potential in the building construction industry. This study further investigated highly similar or repetitive articles by looking at the contents, keeping 53 articles for this study to consider. Additionally, this study verified the representativeness of the filtered articles and revealed that the filtered articles matched well in research areas, topics, origins, and sources, and thus could be used for further review.

Keys to the review were to evaluate whether the application of a technology had the potential to benefit the sustainability of the building industry and how such benefits could be realised. Fourteen technologies, namely 3D printing, other 3D technologies (e.g., 3D simulation), artificial intelligence (AI), blockchain, building information modelling (BIM), cloud computing, drones, photovoltaics, Internet of Things (IoT), modular, robotics, sensor, virtual reality/augmented reality (VR/AR), and wireless, which are most often referred to in the existing literature, have been identified [15,16]. From virtual to factual, software to cyber-physical, supplementary to platform, the fourteen technologies' potential for sustainable building construction in relation to the full life cycle of buildings was purposefully synthesised and sorted alongside the three specific sustainability objectives: minimized waste, energy saving, and efficiency improvement. Critical actors, such as, technology providers, and their role in innovation were reviewed. This topic was much less concerned with previous research. Key points were refined to frame a conceptual framework for a follow up study in the context of the YRD (see Table 1).

2.1. Objectives of Technology Innovation in the Full Life Cycle of Sustainable Building Construction

2.1.1. Minimising Waste and Negative Environmental Impacts

Building and construction is one of the most wasteful industries on Earth, especially in the phases of construction and demolition [17]. The giant and weighty nature of abiotic building and construction projects produce substantial environmental concerns. Technologies capable of mitigating such negative impacts contribute to sustainability along this line. Three-dimensional (3D) printing is one of the most promising technologies to realise minimised or zero waste of production materials. It allows the potential to utilise state-of-the-art environmentally friendly materials, such as biodegradable, biocompatible, and natural polymers, and to produce sophisticated structures and architectural models with a lower cost and higher efficiency [18]. As a supplementary technology, 3D printing's function and effectiveness should rely on the degree of integration with computational modelling or algorithmic design, so that a good combination and coordination of technologies, such as BIM and AI, will be critical to actualise its potential [19,20]. Modular construction as an offsite production system is another method used to achieve less resource wastage. Researchers found that offsite modular construction, especially offsite prefabrication, enables reduced waste multiplication because the recycling system in a factory environment is much more robust than that onsite. Prefabrication can be aided by 3D printing and prefabricated modular buildings can minimise the effects of noise, transport, and disruption to the environment [21,22]. Construction waste recycling robots can help waste management [23]. In the mining industry, sensor-based sorting techniques facilitate construction and demolition waste recycling.

2.1.2. Maintaining Low Energy and Resource Consumption

The building and construction industry is also an energy and resource consuming industry generating substantial carbon emissions throughout its life cycle. The use of renewable energy is a critical step for nearly zero energy buildings (NZEBs). Solar photovoltaics are the most common technologies in NZEBs [24], which are often installed on the rooftop and sometimes on facades in high-rise buildings. To produce renewable energy and meet architectural requirements, professionals and researchers proposed building-integrated photovoltaic modules or systems to optimise a building's energy-saving performance [25]. Other renewable energy, such as wind, is occasionally applied. However, the application of these technologies alone is insufficient to guarantee sustainable renewable energy use. Cyber-physical technologies, such as the IoT and cloud computing, which offer high-performance computing and well-networked connectivity, open opportunities for the efficient use of energies by establishing smart building systems. Sensors plus wireless further improve the sensitivity to temperature, thermal comfort, humidity, and the danger of buildings in operation management, helping achieve automatic building maintenance [26,27]. Energy-saving and environmental protection materials, such as polymer nanocomposites, are indispensable for sustainable building operation. Other technologies, such as BIM, 3D simulation, VR/AR, AI, blockchain, sensor, and wireless, may lend a hand to energy management during building operation.

2.1.3. Maximising Efficiency, Accuracy, and Safety

Apart from doing subtraction throughout the life cycle of building construction to minimise waste and consumption, methods towards sustainable building construction have emerged through the improvement of efficiency and accuracy in design, construction, operation, and demolition to reconcile building–environment conflicts. BIM and AI in collaboration with 3D printing and modular, drones, blockchain, cloud computing, IoT, robotics, and even sensor help reduce building waste by enhancing efficiency or accuracy. BIM enables the improvement of design for material saving and buttresses sustainable operation and end-life plans and energy simulation [28]. A BIM 3D model can simulate the energy consumption during building maintenance and operation, thereby enhancing the design of space geometry and material use from an energy-saving perspective [29]. It can be assisted by IoT and blockchain, which make rapid information flow and sharing possible [30], and by AI, which can optimise the scenario towards sustainability through data mining and machine learning of such information. AI also provides real-time feedback and regulation based on perceived information enabled by the IoT, cloud computing, and blockchain [14,27]. An example of this is the automatic building diagnostic tools for abnormal operation monitoring and fault detection to identify the 'black holes' of energy consumption caused by unexpected man-made defects or equipment defects in heating, ventilation, and air conditioning [31]. Minimising waste by accuracy enhancement can be aided by drones (also known as unmanned aerial vehicles), which optimise the precision of onsite aerial surveying and greatly reduce carbon emission compared with traditional aerial photography [32] and by robotics, which improves automation with high accuracy on the construction site, both in the phases of construction and demolition. As one of the most hazardous industries, building construction leads to high rates of workplace injuries, illnesses, and fatalities, in which safety management systems are needed. Development of sensor technologies, wireless communication, cloud computing, AI with advanced machine learning, and BIM have created opportunities along this line [33]. These technologies are further strengthened by VR or AR, especially in remote repair and construction. The disruptive potential of blockchain technology is not limited to the four phases of building construction, but extends to bid, deliver, and secure payment by connecting different technologies, devices, and stakeholders through peer-to-peer networks to avoid work delay or redundancy. Its collaboration with BIM is named 'Blockchain of Circular BIM things' [30,34].

2.2. Critical Actors in Technology Innovation for Sustainable Building Construction

Technologies applied in the building industry have different providers and users. For those often used in planning and design to help projects better fit and adapt to the environment, the key users are mostly architects, planners, designers, and sometimes construction companies. Some software-based supplementary technologies, such as 3D simulation and VR/AR, are task specific and relatively independent from the construction chain, and suppliers can be diverse in size and nature. Technology relying on software platforms to implement or operate, such as BIM, is in need of transparency, leaving opportunities to gather information and data sources for sharing. Collision between this type of technology and big data or cloud computing is likely to innovate the building construction industry. Blockchain, another technology based on software platforms in need of cyber security, can be used to record the changes to a BIM 3D model so that distributed and decentralised users, such as architects, designers, and managers, can access them [34]. These technologies enable a platform sharing building information amongst planners and designers, construction companies, governments, real estate developers, property management firms and purchasers or tenants. They are relatively friendly to small- and medium-sized companies as having the potential to attract venture capital and generate revenue from the market. Emerging providers, such as Madaster and Circularise, are small start-ups raising over a million euros with services available in Switzerland, the Netherlands, Germany, Belgium, and Norway [35,36]. For cyber-physical technologies supplementing building construction, such as 3D printing, robotics, modular prefabrication, and drones, the main users are in the front end of construction, preservation, or demolition, which include architects, surveyors, construction companies, and suppliers. The promotion of these technologies depends on adjustment to integrate them into the actual operation of the building industry, often requiring upfront money invested by users. Thus, leasing or cofinancing may be applied as a business model for the application of technology of this type. Technologies help establish a cyber-physical platform. For example, an automated smart building system normally demands sophisticated skills for the technological combination of the IoT, AI, sensors, and wireless, which have a high cost and a relatively high threshold for players within the industry. Thus, platform developers are likely to be from nonbuilding industries with experience in the IoT, keeping the ownership, and collaborating with technology providers to develop compatible technologies, such as photovoltaic technology for users. The multinational corporation Siemens is one example. Although these technologies offer the potential to innovate the building industry for sustainability, extant research on a localised innovation of these technologies and their role in sustainable building construction remains limited.

2.3. Toward a Conceptual Framework

Drawing on patent application data sources, this study discloses the localised applications or minor adjustments of these technologies in the building industry in the YRD, one of the most urbanised areas and the largest market for the building industry in China and engages with a full life cycle of building construction. The assessment is based on an objective-technology matrix (OT-matrix) developed from the review [12–14,30,32,37–55]. Patent records are derived to capture the existing technological innovations and their linkage to sustainable building construction is analysed one by one, followed by an applicant analysis to identify the possible underlying dynamics. The objectives of this research are as follows:

(1) to develop a conceptual framework for studying and evaluating the disruptive potential of digital and other new technologies in the sustainable building construction industry;
(2) to disclose the adaptive application and innovation of these technologies in building construction at a local level and their possible contributions to sustainability;
(3) to analyse the critical actors of the technological innovation and the possible development path in the forthcoming transformation.

Table 1. Conceptual framework of innovative potential and actors of technologies for sustainable building construction.

	Specific Technology	Key References	Objectives of Technology Innovation in Sustainable Building Construction and Applied Life Cycle			Actors
			Minimizing Waste	Low Energy Consumption	Efficiency Improvement	
1	3D printing	[12,54,55]	minimized or zero waste of production and construction materials; to make use of state-of-the-art environment-friendly materials	energy-saving and environmental protection materials		Planning and design: architects, planners, designers and construction companies Construction: suppliers, developers, and construction companies Operation: property owners and managers, users, and government End-life: demolition company Ownership types: private, multinational corporation
2	Other 3D technics	[38]	avoid unnecessary waste by 3D simulation during construction			
3	AI	[39,40]	assist waste reduction by decision making on complexity	assist energy management, e.g., identify the 'black holes' of energy consumption during operation	data mining and machine learning of big data to optimize scenario for sustainability; enable real-time feedback and regulation during operation	
4	Blockchain	[30,53]		avoid work delay or redundancy for saving energy	enable transparent and private information flow and share buttresses sustainable operation and end-life plans	
5	BIM	[13,52]	improvement of design for material saving	assist energy-saving by modal simulation during operation		
6	Cloud computing	[14,51]		high-performance computing enabling efficient use of energies during operation	high-performance computing for efficiency and accuracy during design and construction	
7	Drones	[32]	assist waste reduction, e.g., accuracy improvement to guide construction	aid carbon emission by simple ariel survey	optimizes the precision of onsite aerial surveying and accuracy enhancement	
8	Photovoltaics	[43,44]		building-integrated photovoltaic for nearly zero energy buildings		
9	IoT	[50]		networked connectivity enabling efficient use of energies	networked connectivity enabling rapid information flow and share	
10	Modular	[48,49]	less resource wastage especially offsite prefabrication		prefabrication for construction efficiency	
11	Robotics	[49]	waste recycling robot in the phases of construction and demolition		automation for efficiency improvement throughout full cycle	
12	Sensor	[45,47]	sensor-based sorting for material selection	sensitivity of temperature, thermal comfort, humidity, and danger of buildings during operation	improve sensitivity for safety management	
13	VR/AR	[41,42]	assist waste reduction by e.g., remote repair and construction			
14	Wireless	[45,46]		benefit energy management during operation	improve sensitivity for safety management	

3. Data and Methods

Figure 1 shows the research steps and methods in this study. The purpose of the literature search and review was not to explicitly distinguish the 14 technologies from each other because many of them overlapped and supported each other in application. For instance, 3D simulation can be an important constituent in VR. The list of the 14 technologies was not an all-inclusive list given the fast-growing ideas and iterative upgrade of technologies. It also did not imply that the technologies not listed were insignificant. For instance, digital twin technology has demonstrated its powerful role in this industry [2] but it is more similar to a simulation-based comprehensive concept. The principle was to specify and encompass potential technologies as much as possible and simultaneously avoid repetition. The keywords for these technologies were extracted after reviewing the disruptive potential of technologies in sustainable building construction. The patent data of each technology were collected on the basis of the extracted keywords to help understand how these technologies innovate, adjust, or were being applied in a given context. The work in this step was challenging but was achievable with the assistance of a high-performance computer, in which the geocoding of patents' location and lexical identification of technological records were possible [56]. The initial collection of patents applied from the YRD by geocoding encompassed over seven million records from 2010 to 2018. Despite the wide use of patents as a proxy to indicate innovative activities, only those that passed through substantive examination, during publication or obtained grants were valid patents under the regulation of the China National Intellectual Property Administration. The number came to over one hundred thousand after filtering the valid patents in section E of building and fixed construction. Observation demonstrated that amongst the seven main classes, building alone accounted for 35% of the all the applications, followed by hydraulic engineering (19%), construction of roads, railways, or bridges (14%), earth or rock drilling or mining (11%), locks, keys, window, or door fittings (8%), doors, windows, shutters (7%) and water supply and sewerage (6%) (Figure 2). In terms of the technological classes across cities, Shanghai alone produced over 18,000 applications, and Suzhou, Nanjing, Hangzhou, and Hefei were also important contributors. This study further filtered the patent data of the reviewed 14 technologies with a keyword search and obtained raw records (Figure 3). These records contained superfluous data, which were either irrelevant to or had low relation with the identified disruptive technologies in sustainable building construction. They were useless for analysis and were manually excluded from the dataset. Around 3000 records were investigated through rounds of examinations and were used for analysing the locally adaptive innovation and the applicants of these technologies in the YRD.

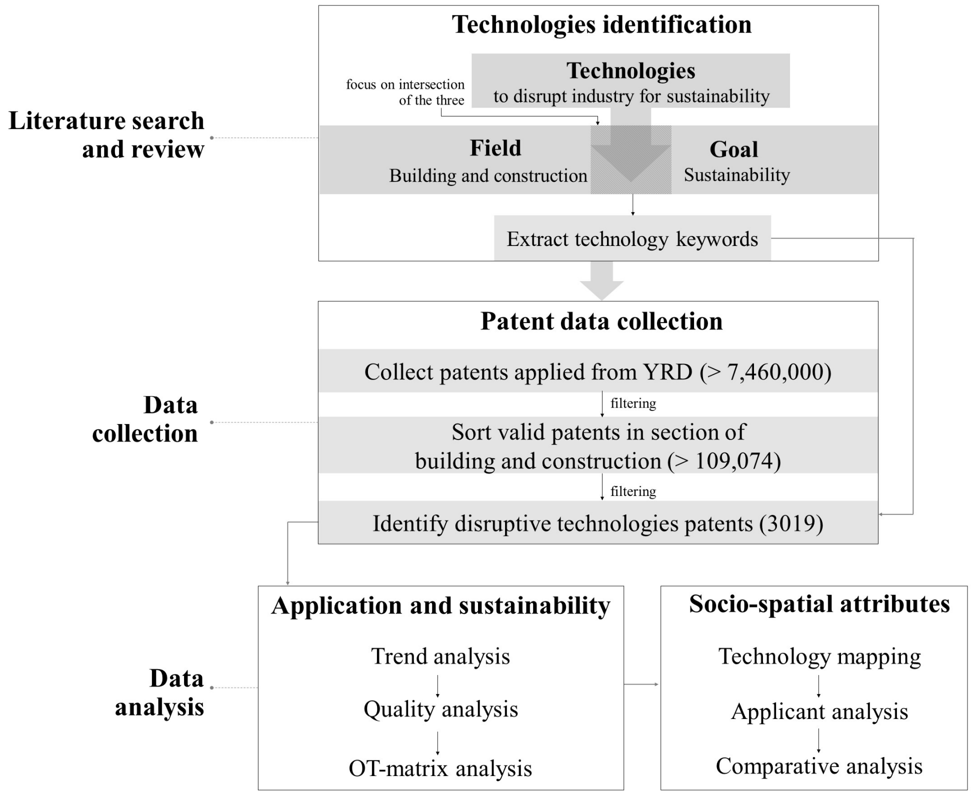

Figure 1. Research steps and methods.

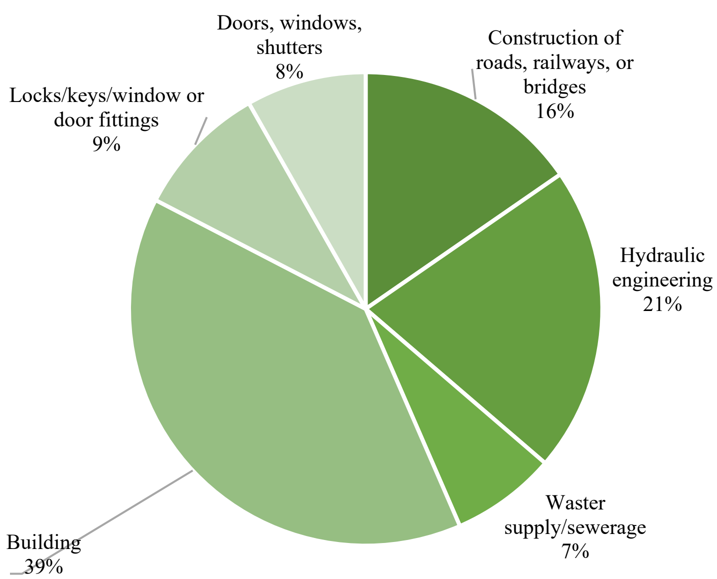

Figure 2. Composition of valid patents in the building construction industry in the YRD, China.

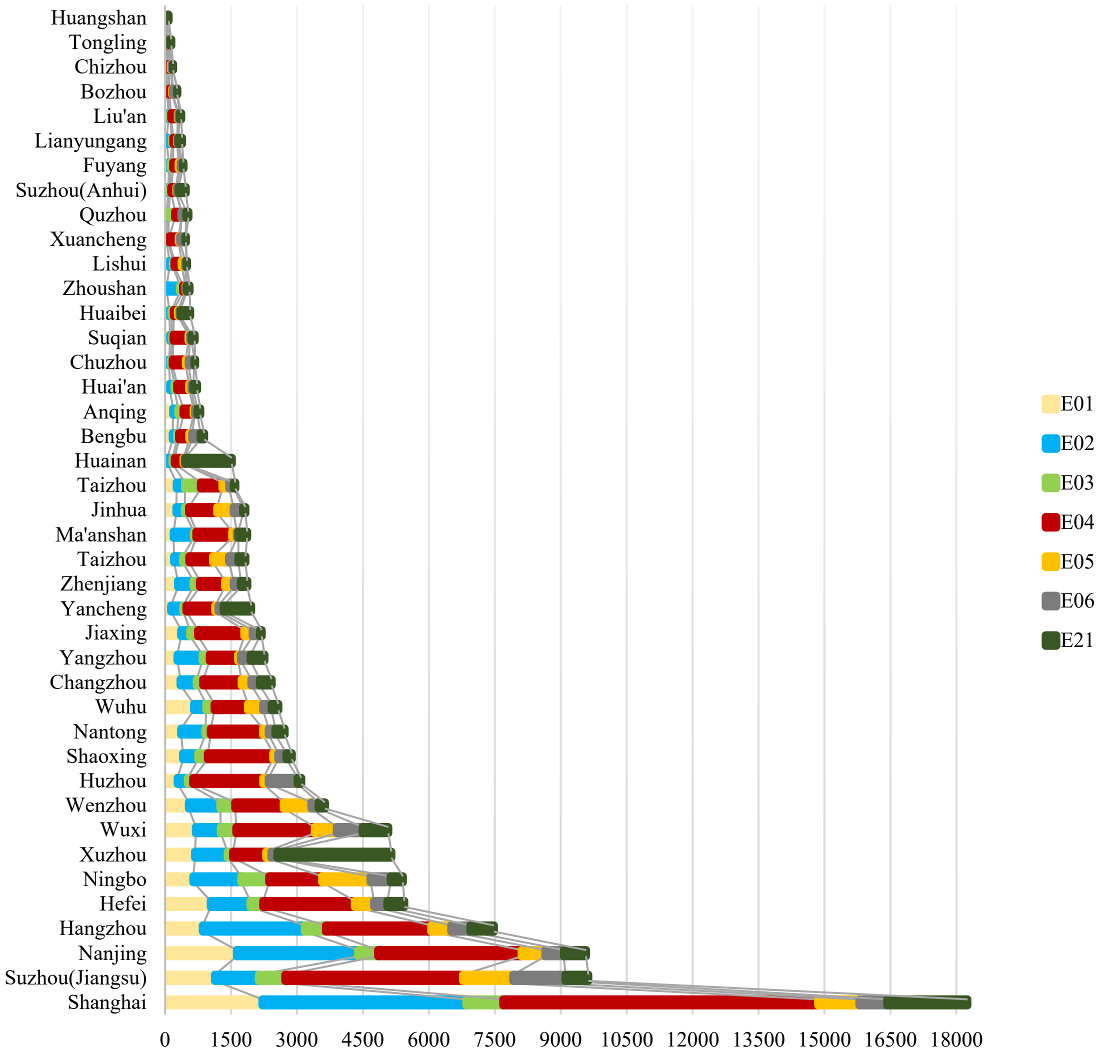

Figure 3. Composition of valid patents in the building construction industry across 41 YRD cities.

4. Identified Technology Innovation in the YRD

The 14 technologies, which have the potential to innovate the building construction industry and contribute to sustainability, were examined one by one in the context of the YRD based on the patent data. This study examined 3017 records for the 14 technologies, which can be categorised into three levels in terms of quantities. The technologies with larger numbers were modular (1021, 33.84%), robotics (502, 16.71%), photovoltaics (490, 16.24%), wireless (274, 9.08%), and sensors (263, 8.72%). Technologies with medium numbers were 3D printing (149, 4.94%), IoT (136, 4.51%), BIM (62, 2.06%), other 3D technologies (58, 1.92%), and drones (34, 1.13%). AI, cloud computing, VR/AR, and blockchain had less than 10 records each. Figure 4 reveals that an increasing trend was observed from 2010 to 2018 although the patent applications in 2016 and 2017 experienced a small drop.

4.1. Matrix Analysis of the Identified Technology Innovation in the YRD

OT-matrix analysis was conducted to reveal the sustainability objects of technologies in association with the full life cycle of building constructions, and technology-mix matrix was applied to reveal to what extent these technologies support each other in localised innovation (Figure 5). Judgement was based on the text mining of titles of specific technology, considering the possibilities informed by the review. The matrix can enlighten the future potential of technology adaptation or mix at the local level through the identification of intersections with few or no patents.

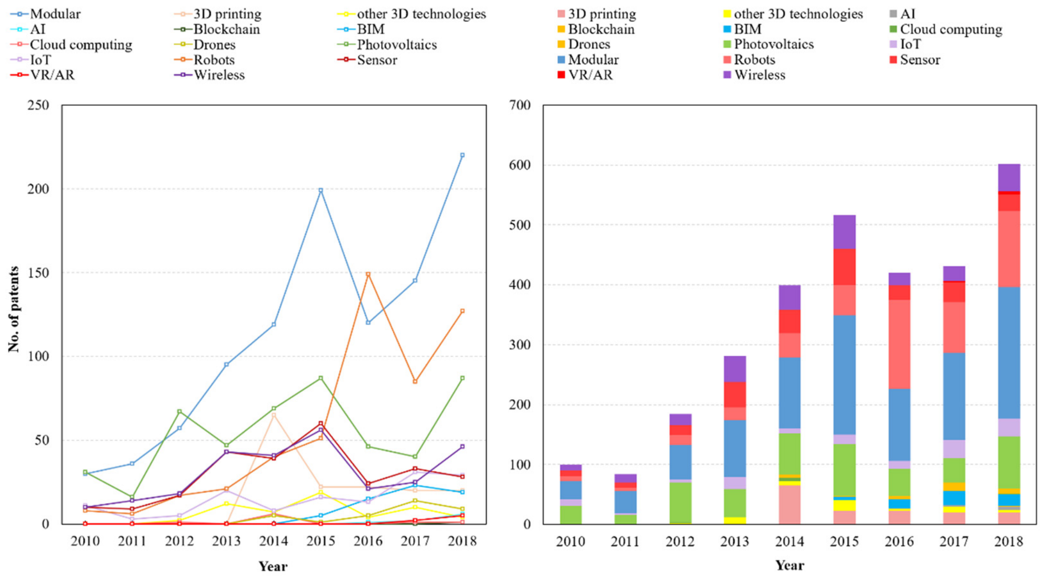

Figure 4. Trend for patent applications of the fourteen technologies during 2010–2018.

In the OT-matrix, the three objects were minimising waste and environmental impacts, maintaining low energy consumption, and maximising safety and efficiency. Technologies' contributions to these objects were examined in association with the four phases in a full life cycle of buildings. Evidenced by patents, supplementary technologies contributed more to sustainable building construction than platform technologies. Technologies with a large number of patents were the most influential on the traditional building construction industry. Modular sometimes combined photovoltaics or thermal preservation technologies for energy saving, but as a prefabricated constituent, it primarily promoted the work efficiency of building construction and reduced construction waste on site. Robotics was mainly used to substitute work once conducted by human beings, especially dangerous, environmentally unfriendly, and repetitive tasks. Automation was the main achievement of robotics, which improved precision and efficiency, thereby reducing unnecessary resource consumption. Its contribution to sustainability depended on the goals and contents of replaced jobs. Around 20% of records indicated the use of robotics to sort waste and dirty things during construction, operation, or maintenance. A few clearly indicated the integration of energy-saving ideas, methods, or technologies. Photovoltaics is often viewed as an energy-saving technology that enables the use of renewable energy. This finding was verified in the patent analysis, but a few records indicated considerations on waste reduction or construction efficiency improvement. Photovoltaics often combined modular assembly to avoid material waste onsite and accelerated installation with innovative methods. Sensors often combined wireless technology to instantly transfer data and information, thereby enhancing the efficiency of the building and construction operation. They were widely used to monitor the operation status and to respond properly for energy and resource saving and supply (especially water supply). Sensors occasionally combined photovoltaics to utilise renewable resources. Wireless technology had a similar application to sensors.

OT-matrix		No. of patents	Objectives			Applied Life cycle			
			minimizing waste and environment impacts	maintaining low energy consumption	maximizing safety and efficiency	PD	C	OM	ED
Specific technology	3D printing	149	149	10	5	-	149	2	2
	Other 3D	58	2	9	16		24	31	
	AI	9	3	1	9			9	
	Blockchain	1			1			1	
	BIM	62	10	1	60	1	62	3	
	Cloud computing	9	1	3	5	1		8	
	Drones	34	10		16	2	3	20	
	Photovoltaics	490	33	490	31	57	109	324	
	IoT	136	8	13	115		7	129	
	Modular	1021	782	60	965	10	829	56	3
	Robots	504	94	25	504	1	177	320	4
	Sensor	263	3	21	263		58	205	
	VR/AR	7		1	1	1	1	5	
	Wireless	274	2	8	274		29	250	
Total		3017	1097	642	2265	73	1448	1363	9

Technology mix-matrix		Technologies being mixed													
		3D printing	Other 3D	AI	Block-chain	BIM	Cloud computing	Drones	Photo-voltaics	IoT	Modular	Robots	Sensor	VR/AR	Wireless
Technologies for mix	3D printing	-	1					1			11	1	1		1
	Other 3D	1	-								1		4	3	
	AI			-											
	Blockchain				-										
	BIM					-		1			9		1		
	Cloud computing						-			7					
	Drones	1				1		-	1			1			
	Photovoltaics							1	-	1	33	1	3		2
	IoT						7			-	3	1	4		3
	Modular	11	2			9			33	3	-	2	3		2
	Robots	1						1	1		2	-	3		4
	Sensor	1	4			1			3	4	3	3	-		32
	VR/AR		3											-	
	Wireless	1							2	3	2	4	32		-
Total		16	7			1	7	2	40	16	64	13	51	3	44

Figure 5. Objective-technology and technology-mix matrix.

Technologies with medium numbers modestly influenced building construction industries. Three-dimensional printing was mainly applied to produce walls for architecture and then structures for infrastructure, such as bridges or tunnels, so that construction waste could be reduced. A few applications addressed energy-saving, mainly heat preservation, but seldom mentioned the use of other advanced technologies. Fewer applications improved the efficiency of 3D printing and rarely combined other advanced technologies. Most 3D printing technologies were used at the phase of construction, either onsite or offsite, but a few records showed that they were occasionally used in maintenance or renovation. Three-dimensional printing was occasionally mixed with sensors, wireless, robotics, and intelligent technology (not AI). The technology most commonly mixed with 3D printing was modular, which enabled rapid construction with minimised waste onsite. Other 3D technologies primarily deployed 3D concepts to stimulate scenes or structures, assisting construction or maintaining buildings and fixed constructions better. Three-dimensional-related technologies were mostly employed to optimise user experiences or to warn of danger through simulations. They were also used in furniture, either large or small, to reduce energy or resource consumption. In contrast to 3D printing, the role of other 3D applications in waste reduction was minimal. Other 3D technologies mix with 3D printing and modular but were more often combined with sensors and VR/AR. The IoT often served as a platform technology enabling efficient network connectivity for data sharing and information flows. However, it was still not used for main building construction on a large scale, and most of its applications were in windows or doors for antitheft purposes. The IoT also assisted intelligent construction monitoring, operation, and transportation management. The majority of BIM technologies directly benefited the accuracy and efficiency of building construction, and a small portion, which primarily integrates modular technology, was committed to helping to reduce waste and environmental impacts. BIM was also overwhelmingly used during the construction phase of large-scale buildings and sometimes bridges and other infrastructure. Drones were mostly used to improve the construction and maintenance efficiency of roads, bridges and, recently, other architecture.

AI, blockchain, cloud computing, and VR were the least applied technologies, as evidenced by the patents, and their influence on the building industry was relatively minimal in the study period. Cloud computing contributed most to efficiency improvements but remained not widely used in architecture. Records show that most of the applications were in sewerage and mining. These technologies mainly contributed to the efficiency improvement of construction operation and maintenance, but the combination of AI, blockchain, and other technologies was still inadequate. Numerous records served multiple goals, and the methods to achieve sustainable building construction were often overlapping. Most technologies were designed to be as intelligent as possible, but few were fused with AI.

4.2. Applicant Analysis of the Identified Technology Innovation in YRD

Table 2 presents the copatents and the top five applicants in each technology. The ratios of patents from the top five applicants varied amongst technologies, excluding AI, cloud computing, VR/AR, and blockchain with less than 10 applications. Three-dimensional printing and BIM showed highly concentrated patent sources. Around 75.17% and 64.52% of applications came from the top five applicants, and over half were from state-owned enterprises (SOEs), including the central SOEs of China State Construction Engineering Group Co., Ltd., China Metallurgical Group Corporation (MCC), Shanghai Construction Group Co., Ltd., and their subsidiaries. In contrast, the top five applicants contributing to blockchain, VR/AR, AI, other 3D technologies, wireless, and photovoltaics were mainly domestic private companies, accounting for 100%, 85.71%, 66.67%, 41.38%, 13.14%, and 8.37%, respectively. Universities mostly dominated the top five applicants in sensor technology and for the IoT, and individuals played a major role amongst the top five contributors.

Table 2. Copatents and the top five applicants in each technology.

No.	Specific Technology	Copatent	Top Five Applicants			
			Applicant Name	Application No.	Ownership	Ratio to Total
1	3D printing	18 (12.08%)	China Construction Eighth Engineering Division. Corp. Ltd.	55	SOE	75.17%
			Shanghai Construction Group Co., Ltd.	29	SOE	
			Ma **	18	personal	
			Hohai University	5	university	
			MCC	5	SOE	
2	Other 3D technology	1 (1.72%)	Suzhou Lzy Technology Co., Ltd.	10	private	41.38%
			Burgeree New Tech Jiangsu Co., Ltd.	7	private	
			Jiangsu Kaluoka International Cartoon & Comic Co., Ltd.	5	private	
			Shanghai Jianwei Cultural Heritage Conservation Tech. Co., Ltd.	3	private	
			Hefei Minxin Software Technology Co., Ltd.	2	SOE	
3	AI	-	Quzhou Yanhang Machinery Technology Co., Ltd.	2	private	66.67%
			Zhejiang Jiayuan Household Products Co., Ltd.	2	private	
			Liang **	2	personal	
			Hangzhou Leshou Technology Co., Ltd.	1	private	
			Yancheng Shengfang Machinery Co., Ltd.	1	private	
4	Blockchain	-	Huayi Ecological Landscape Architecture Co., Ltd.	1	private	100%
5	BIM	14 (22.58%)	MCC	19	SOE	64.52%
			Shanghai Civil Engineering Co., Ltd. of CREC	10	SOE	
			Tongji University	4	university	
			Yi **	4	personal	
			Nantong Si Jian Construction Group Co., Ltd.	3	SOE	
6	Cloud computing	-	Suzhou Institute of Trade & Commerce	2	university	77.78%
			China University of Mining and Technology	2	university	
			Huaxin Post and Telecommunications Consulting Co., Ltd.	1	SOE	
			Maanshan Xinqiao Industrial Design Co., Ltd.	1	private	
			Nanjing Zhichuang Intellectual Property Service Co., Ltd.	1	private	
7	Drones	2 (5.88%)	Jinling Institute of Technology	4	university	44.12%
			Suzhou Lianglei Intellectual Property Operation Co., Ltd.	4	private	
			Anhui Yixun Flight Safety Technology Co., Ltd.	3	private	
			MCC	2	SOE	
			Zhao **	2	personal	
8	Photovoltaics	24 (4.90%)	Jieshou Shaoen Precision Machinery Co., Ltd.	16	private	8.37%
			Zhejiang HEDA SOLAR Technology Co., Ltd.	16	private	
			Tongji University	12	university	
			MCC	12	SOE	
			Wuxi Aoyute New Technology Development Co., Ltd.	9	private	
9	IoT	3 (2.21%)	Zhao **	12	personal	22.79%
			Zheng **	9	personal	
			Changzhou Love Learning Education Technology Co., Ltd.	4	private	
			Guodong Group Co., Ltd.	3	private	
			Lu **	3	personal	

Table 2. *Cont.*

No.	Specific Technology	Copatent	Top Five Applicants			
			Applicant Name	Application No.	Ownership	Ratio to Total
10	Modular	91 (8.91%)	MCC	40	SOE	13.91%
			Tongji University	33	university	
			Shanghai Construction Group Co., Ltd.	33	SOE	
			Zhejiang Yasha Decoration Co., Ltd.	23	private	
			China National Nuclear Corporation	13	SOE	
11	Robotics	14 (2.78%)	Wenzhou Suiren Intelligent Technology Co., Ltd.	32	private	15.87%
			Ningbo Polytechnic	16	university	
			Ma'anshan Zhicheng Technology Co., Ltd.	11	private	
			Nanjing University of Posts and Telecommunications	11	university	
			Anqing Dandelion Hydropower Installation Engineering Co., Ltd.	10	private	
12	Sensor	38 (14.44%)	Hohai University	13	university	18.63%
			China University of Mining and Technology	12	university	
			Southeast University	9	university	
			Tongji University	8	university	
			Wolong Electric Group Co., Ltd.	7	private	
13	VR/AR	-	Nanjing Yatai Jiayuan Decoration Design Engineering Co., Ltd.	2	private	85.71%
			Ma'anshan Shengdeli Intelligent Technology Co., Ltd.	1	private	
			Nanjing Gallop-Sky Electronic Technology Co., Ltd.	1	private	
			Shanghai Kaiquan Pump (Group) Co., Ltd.	1	private	
			Suzhou Taogesi Information Technology Co., Ltd.	1	private	
14	wireless	22 (8.03%)	WULIAN	14	private	13.14%
			China University of Mining and Technology	10	university	
			Leimeng Machinery Equipment Co., Ltd.	8	private	
			Beiziwei Instrument (Suzhou) Co., Ltd.	7	Foreign/USA	
			Jiangsu Shine Technology Co., Ltd.	7	private	

Table 3 lists the top 15 applicants according to their contributions to all the 14 technologies, involving 564 records, which account for 18.69% of the total applications. SOEs contributed most in terms of quantities, three central SOEs—MCC, China State Construction Engineering Group Co., Ltd., and China Railway Group Limited, and one municipal SOE—Shanghai Construction Group Co., Ltd. generate 238 records. A total of 189 patent application records were obtained from universities, including Tongji University (70), China University of Mining and Technology (41), Hohai University (32), and Southeast University (30). Domestic private companies are active contributors, especially Wenzhou Suiren Intelligent Technology Co., Ltd. (32) and Zhejiang Yasha Decoration Co., Ltd. (23), but the quantities of their applications among the top 15 contributors were not substantial, and they only generated 101 records. Individuals contributed a total of 36 records.

Table 3. Main applicants in the identified fourteen technologies.

No.	Applicant Name	No. of Patents	Applicant Type
1	China Metallurgical Group Corporation,	78	Enterprise -SOE
2	Tongji University	70	University
	China State Construction Engineering Group Co., Ltd.	70	Enterprise -SOE
3	Shanghai Construction Group Co., Ltd.	69	Enterprise -SOE
4	China University of Mining and Technology	41	University
5	Hohai University	32	University
6	Wenzhou Suiren Intelligent Technology Co., Ltd.	32	Enterprise—Private
7	Southeast University	30	University
8	Zhejiang Yasha Decoration Co., Ltd.	23	Enterprise—Private
9	China Railway Group Limited	21	Enterprise -SOE
10	Ma **	19	Personal
11	Zhang **	17	Personal
12	Jieshou Shaoen Precision Machinery Co., Ltd.	16	Enterprise—Private
13	Ningbo Polytechnic	16	University
14	Zhejiang Heda Solar Technology Co., Ltd.	16	Enterprise—Private
15	Nanjing IOT Sensor Technology Co., Ltd.	14	Enterprise—Private

5. Conclusions

This research identified the 14 technologies with disruptive potential for the building construction industry to realise more sustainable planning, construction, operation, and demolition through a literature search and review and examined their adaptive innovation in the context of the YRD through patent analysis. This review suggests that the potential benefits of the 14 technologies towards sustainable building construction can be actualised through three subobjectives: minimising waste and negative environmental impacts, maintaining low energy and resource consumption, and maximising safety and efficiency in the full life cycle of building construction. The path to the third sustainability objective is relatively indirect through safety and efficiency improvement to avoid unnecessary waste and consumption. Empirical analysis unveils that in the YRD, the contribution of advances in technologies to sustainability is essentially indirect and secondary, mostly to safety management and efficiency improvement, thereby preventing unnecessary loss or redundancy. Modular, robotics, wireless and sensors are the representative technologies on this track. Contributions to maintaining low energy and resource consumption are mainly from the photovoltaic technology, whereas 3D printing and modular benefit waste minimisation the most. The analysis also reveals that these technologies are mainly used at the phases of construction, operation, and maintenance. Technologies assumed to be applied in the phase of planning and design are not protruding, photovoltaics probably are most often involved at the design stage, followed by modular, BIM, cloud computing, drones, robotics, and VR/AR, but the records of the latter are extremely limited. Technologies assisting demolition or destruction are rare, and only 3D printing, modular and robotics have sporadically indicated the possible application at the end-life stage. Technology mix analysis indicates that the existing fusion of technologies remains insufficient, limited to those previously developed, matured technologies, such as modular and photovoltaics, sensors and wireless, 3D printing and modular. This finding implies that the mix of these immature, undeveloped technologies may have great potential in sustainable building construction in the future.

Compared with other industries, building and construction is a conservative sector that has slower adoption of state-of-the-art technologies. The high-fragmented structure and high threshold for R&D investment in the building industry has set barriers for swift technological innovation and application as short-term economic returns seem uncertain. The analysis of critical actors of the identified patents in China uncovers a possible path, taking advantage of state-owned agencies, to high-threshold technology innovation in the building industry. As identified in this study, substantial adaptive innovations come from

SOEs and the central SOEs, although they are relatively few, were a large portion of the applications. Indeed, emergent research has found that the patents from SOEs are often less valuable, in terms of economic gains, than those from private-owned enterprises. In other words, profit-making motivations are predictably stronger among private actors, thus a healthy, sustained, and energetic innovative ecosystem should call for diversified actors and inputs. Given the high investment in the R&D of the building industry, future policies can be made to encourage more genuine and spontaneously developed high-tech enterprises, especially those that are small and medium sized, in collaboration with universities and individuals to improve the economic outputs and balance the cost benefits of the R&D investment. Innovative adaption of the 14 technologies is still in the initial stage, and their sustainability potential and actual implementation and utilisation in the building industry must be further investigated.

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