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Promoting additive construction in fast-developing areas: An analysis of policies and stakeholder perspectives

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A R T I C L E I N F O

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A B S T R A C T

Construction 3D printing (C3DP) has emerged as an important force in automation and sustainable transformation of the construction industry. Despite the implementation of numerous incentive policies, its development and application remain at a relatively slow pace in developing countries. This research employs the Q methodology to explore the perspectives of China's stakeholders on the innovation policies for the development and application of C3DP. The study reviews the development of C3DP in China and identifies statements related to C3DP promotion policy and development. Based on data from C3DP industrial experts, the results reveal four distinct policy perspectives: conservative exploration, aggressive progression, intensive investigation, and tentative stimulation. A consensus exists that provides direction for policymaking though the divergences among stakeholders highlight the complexity of implementing policy mixes. This study has theoretical and practical significance in supporting policy mixes for C3DP development and adoption in fast-growing areas.

1. Introduction

The construction industry has been instrumental in facilitating social development in fast-urbanising areas. Nevertheless, the development of construction industry has faced new challenges. Due to its significant environmental impact, the sector ranks as one of the least successful in transitioning towards sustainability (Gan et al., 2015). For example, conventional construction techniques consume a substantial amount of energy and materials, generating construction waste (Aslam et al., 2020; Guerra et al., 2019; Li et al., 2022), greenhouse gas emissions (Sandanayake et al., 2019), and air pollution (Zhang et al., 2021). Moreover, the construction sector is confronting the ageing workforce and labour shortage as additional obstacles (Kwan et al., 2019; Li et al., 2023). Despite its large scale, the construction industry is becoming less attractive to the labour market due to limited income and on-site safety risks (Chan et al., 2020).

To address these challenges, construction 3D printing (C3DP) has been considered a potential solution to the environmental and labour challenges in the construction industry (Wu et al., 2018). C3DP refers to a construction method for manufacturing components or entire buildings by printing materials layer-by-layer (El-Sayegh et al., 2020). For example, some studies, adopt off-site gantry-style printers to manufacture building components, incorporating the concept of prefabricated construction (Holt et al., 2019; Wang et al., 2018). Some cases also show the potential of on-site printing methods, which are more cost-efficient for large-scale construction projects (Buchanan and Gardner, 2019; Pons-Valladares et al., 2023). Also, Laing O'Rourke's *FreeFAB* prints formwork based on recyclable hot-melt materials and combines them with mature construction techniques (Gardiner and Janssen, 2014).

In these demonstrations, C3DP presented several advantages over traditional techniques. For instance, it reduces material and energy consumption and construction waste, thereby reducing building life-cycle carbon emissions (Alhumayani et al., 2020; Siddika et al., 2019). Besides, the C3DP process is based on highly automated printers and reduces labour requirements and on-site risks in the construction process (Besklubova et al., 2021; Wu et al., 2018). It can also achieve

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complex designs without formworks, which simplifies the construction cycle and reduces the cost (Siddika et al., 2019; Wu et al., 2018). C3DP technologies enable the digitisation of the entire construction process, which streamlines project management, facilitates prompt design rectification, and contributes to efficient budget control in the construction process (Besklubova et al., 2021).

However, despite the C3DP has received attention and support from government and the academia, the progress of C3DP implementation has been criticised for being slow. Promoting C3DP involves addressing not only technical reliability obstacles but also non-technical dimensions such as supply chain management, industry codes and standards, and customer acceptance (Furet et al., 2019; Kanyilmaz et al., 2022). Especially, the support and close cooperation of stakeholders plays a critical role in the promotion of C3DP, while obstacles from any of them can slow down this process (Zhang et al., 2019). The implementation of novel technologies, such as Concrete 3D Printing (C3DP), necessitates significant adjustments for developers and contractors (Zhang et al., 2019). These adjustments span across various aspects including material supply, manpower allocation, construction timelines, and site management. Moreover, the introduction of these technologies may also present unforeseen risks such as variations in product quality, consumer acceptance, and potential additional training requirements (El-Sayegh et al., 2020). From a design perspective, C3DP allows for a higher degree of flexibility in the construction process, potentially fostering innovation at the design level (Tuvayanond and Prasittisopin, 2023). For academics and educators, C3DP provides new R&D opportunities in areas such as building materials, construction equipment and management (Wu et al., 2018). However, the cultivation of talent with a comprehensive understanding of C3DP technology and construction processes may pose a new challenge. Given the diverse interests of stakeholders in the promotion of C3DP technology, policy demands often exhibit considerable heterogeneity. In fast-growing regions experiencing high demand for construction, it is crucial to adopt a mix of policies when formulating technology promotion strategies. This approach ensures that the needs of all stakeholders are addressed and contributes to circumventing obstacles arising from policy imbalances.

Therefore, understanding the interests, concerns and views of stakeholders, such as enterprise managers, contractors, designers and clients, is important in policy mix development for technical transition. The construction industry requires a comprehensive policy framework that considers different perspectives from stakeholders to address the challenges in C3DP promotion. This study aims to investigate the policy needs of different stakeholders regarding the prospects and related policy functions of C3DP promotion and to identify theoretical and practical implications for policy formulation. The study reviews the development of C3DP and identifies statements related to C3DP promotion policy and development. The study employs the Q methodology to analyse the perspectives of diverse stakeholders and offers theoretical and practical recommendations. The findings of this study will assist decision-makers in understanding the current demands of different stakeholders and formulating a more effective policy mix for the promotion of C3DP development and adoption.

The remainder of this paper is structured as follows: Section 2 reviews the existing development and promotion policies of C3DP, construction innovations, and policy mixes. Section 3 describes the methodology employed in this research and the data collection process. Section 4 presents the analysis results and discusses the findings. Section 5 draws the conclusion.

2. Literature review

2.1. The development of C3DP

2.1.1. Technology development

The most commonly used C3DP techniques for construction include contour crafting (CC), concrete printing (CP), selective binder (cement) activation (SBA), selective paste intrusion (SPI), and D-Shape (Wu et al., 2018). The former two methods are based on material extrusion, and the rest employ powder-based systems (El-Sayegh et al., 2020). Extruded material systems are methods to print the structure by injecting and extruding the mixed material, for example, slurry concrete, by a nozzle. Unlike the CC and CP, which need to mix the slurry concrete in advance, in SBA and SPI, the liquid is applied in a thin layer of bulk material to solidify the target area. After layer-by-layer repetition, a 3D object can be created. The D shape shares a working principle similar to SBA and SPI, but its machine is equipped with a series of inline nozzles and is mainly used to construct larger-scale objects (Lowke et al., 2018).

Two main equipment systems are used in C3DP: gantry systems and articulated robot systems (El-Sayegh et al., 2020). The cartesian coordinate system is the basis of the gantry system's working principle, which allows the nozzle on the gantry system to move along the X, Y and Z axis (Labonnote et al., 2016). However, the limitation on acceleration restricts the system from printing sharp corners. The space-consuming and heavy steel frame required in the gantry system also makes it prohibitive to some narrow working environments (Tiryaki et al., 2019). The arm-based robot is another system to deliver 3D printing work, which is equipped with a robotic arm with 6 degrees of freedom and a nozzle on top of it, which provides more flexibility to the Printing (Zhang et al., 2018). Although its operation requires less space compared to the gantry system, the scale of work it can print and its reachable area is limited due to the moment generated by the base and kinematic singularities (Tiryaki et al., 2019).

The material used in 3D Printing must meet specific requirements to be compatible with the technologies and the equipment. The most commonly used material includes concrete, plaster, polymer, and metal (Ali et al., 2022). Concrete is the most widely used material in C3DP due to its high consumption. The material has strict printability requirements including fluidity, extrudability, buildability, and time setting. Metal is implemented to construct building elements (Buchanan and Gardner, 2019), with a variety of techniques including powder bed fusion (PBF), directed energy deposition (DED), sheet lamination as well as electrochemical additive manufacturing (ECAM). Although the PBF and DBD are relatively suitable for the construction industry because of technical maturity and feasibility (Buchanan and Gardner, 2019), the printed elements' small dimensions and the time spent bound their development and application (Buchanan and Gardner, 2019). Polymer materials serve aesthetic or structural purposes when combined with strength-enhancing materials such as thermoplastics, particle-reinforced polymer composites, and polymer matrix composites (Alghamdi et al., 2021). For instance, fibre-reinforced concrete is preferred in C3DP to avoid nozzle obstruction by steel reinforcement (El-Sayegh et al., 2020), and polyurethane foam has been used as both permanent formwork and insulation material (Furet et al., 2019).

2.1.2. Stakeholders

The accelerated advancement of C3DP has profound implications for stakeholders within the construction industry. The benefits derived from the application of C3DP in construction projects can vary among stakeholders, given the diverse roles they play within the industry (Anjum et al., 2017). However, these stakeholders also encounter distinct risks due to their specific roles (Craveiro et al., 2019). Prior research has investigated how key stakeholders might be influenced by the proliferation of C3DP, including enterprise managers, contractors, building designers/architects, and research institutions (Chang and Antwi-Afari, 2023).

For enterprise managers, while C3DP offers opportunities for swift development, it also presents unavoidable challenges (Anjum et al., 2017). Firstly, despite the rapid progress of C3DP technology, there is a dearth of large-scale application cases. Current C3DP buildings may not meet end-user expectations due to technological constraints, such as potentially rough surface quality resulting from the printing process (El-Sayegh et al., 2020). Secondly, most users have limited exposure to

C3DP technology. Given the unique nature of real estate, the acceptance of new construction technologies is considerably slower than other commodities. Consequently, it can be an inconvenient process for the market to recognise C3DP building products.

Contractors play a crucial role in the promotion of C3DP technology. Amid labour shortages in the post-COVID industry recovery (Xu et al., 2023), C3DP technology could offer a solution through automation and autonomy (Wang et al., 2018). However, the application of C3DP may introduce uncertainties. For instance, new technologies could drastically alter aspects of original project management such as labour demand expectations and on-site management. Additionally, there is a current lack of regulations and specifications for this technology, potentially exposing contractors to additional risks (El-Sayegh et al., 2020).

For architects and landscape designers, the advancement of C3DP technology bolsters the flexibility of design for buildings and structures (Tuvayanond and Prasittisopin, 2023). Although C3DP-based design is currently limited by the volume of the 3D printer chamber, the flexibility of C3DP enables architects to conceive and construct structures with unparalleled creativity and complexity. In contrast to traditional construction methods, additive construction can fabricate intricate shapes and designs that would be either unfeasible or prohibitively expensive using other techniques (Wang et al., 2018). This facilitates the production of highly customised products, tailored to the comfort and aesthetics of building users, potentially allowing users to become deeply involved in the design process. For architects, the promotion of C3DP may disrupt the conventional architectural design model and instigate a surge in personalised architectural design.

The roles of research institutions are also important. Currently, C3DP technology is undergoing a fast-developing period, with substantial potential for optimisation in areas such as materials, equipment, software, management, and economic applicability (Chang and Antwi-Afari, 2023). For instance, the printability and buildability of C3DP materials are frequently discussed within the industry. Furthermore, the promotion of C3DP necessitates a greater number of professionals to fulfil the demands of its R&D and practical application (Anjum et al., 2017). C3DP requires interdisciplinary knowledge networks, encompassing fields such as materials, structures, construction engineering, and computing. This presents new challenges for talent development.

2.1.3. Practical applications

Although China is at the forefront of research and application of C3DP (Forcael et al., 2020; Pan et al., 2021), the uptake of C3DP in China is tardy (Holt et al., 2019). Appendix 1 provides comprehensive details on recent Chinese C3DP projects. The information was gathered from Chinese newspapers, media outlets, and technology websites. It is found that the majority of projects are pilot demonstration initiatives, suggesting that the widespread adoption of C3DP in China is still limited. The technique information implied that the primary technique type for C3DP in China is extrusion type, including CC, CP and FDM (Sepasgozar et al., 2020).

Besides, the predominant choice of material in the majority of projects was cement-based. In addition to practical applications, research in China's C3DP materials direction has shown significant progress in the development of cement-based materials. The experiment conducted by Feng et al. (2015) demonstrated that the use of fibre-reinforced polymer sheets for wrapping and pasting could enhance bearing capacity and deformation resistance.

Furthermore, it is found that the most widely employed C3DP equipment in China primarily consists of Gantry and arm-based systems. In 2014, Beijing HuaShang LuHai (HSLH) developed a 3D printer capable of printing villas using steel bars and cement, along with a tower crane printing system based on the gantry system (HSLH Beijing HuaShang LuHai Technology Co., Ltd, 2014). Besides that, China Construction Co., Ltd. Technology Centre introduced a large printer in 2018 capable of printing villas and low-rise houses on-site (China Construction Technology Centre, 2017). However, research on C3DP types and equipment in China is limited due to high R&D costs and space constraints (Zhang et al., 2019). To address the shortage, He et al. (2020) developed a modular 3D-printed vertical concrete green wall system that integrates various architectural functionalities.

2.2. Regulations and policies for C3DP

2.2.1. Policies

The Chinese government has recognised the significance of Additive Manufacturing since 2013 and has emphasised the acceleration of improvement of C3DP in 2015 (State Council of China, 2015b). Actively,

Table 1
China's policies for additive manufacturing.

Category	Title
Framework Policy	• The Special Action Plan for Deep Integration Between Information Technology and Industrialization (2013–2018) (Ministry of Industry and Information Technology, 2013). • Made in China (2025); (State Council of China, 2015a.). • Opinions of the State Council on Several Policies and Measures for Vigorously Advancing Popular Entrepreneurship and Innovation (State Council of China, 2015b). • The Outline for Development of Informatisation in the Construction Industry 2016–2020 (Ministry of Housing and Urban-Rural Development, 2016). • The Development Plan of National Strategic Emerging Industries 2016–2020 (State Council of China, 2016).
Specific Instruction	• The Action Plan for Remanufacturing of High-end Intelligent 2018–2019 (Ministry of Industry and Information Technology, 2017). • The Plan of Action for Accelerating and Promoting Industry Development of Additive Manufacture 2017–2020 (Ministry of Education, Ministry of Industry and Information Technology & National Development and Reform Commission, 2017). • The Plan for the Development and Promotion of the National Additive Manufacturing Industry 2015–2016 (Ministry of Industry and Information Technology, 2015). • The Smart Manufacturing Development Plan 2016–2020 (Ministry of Finance & Ministry of Industry and Information Technology, 2016). • The Catalogue of Industries under Key Support of Intellectual Property Rights (National Intellectual Property Administration, 2018). • The Guidance of Building the Standard System of National Smart Manufacturing (2018) (Ministry of Industry and Information Technology & Standardization Administration, 2018). • Opinions of Eight Departments, Including the State Administration for Market Regulation, on Implementing the Enterprise Standards "Front-Runner" System (State Administration for Market Regulation, National Development and Reform Commission, Ministry of Finance, Ministry of Industry and Information Technology, Ministry of Finance, Ministry pf Ecology and Environment … Ministry of Science and Techonology, 2018). • The Guidance of Building the Standard System of National Smart Manufacturing (2021) (Ministry of Industry and Information Technology & Standardization Administration, 2021). • Adjusting the Relevant Catalogues of the Import Tax Policies for Crucial High-Tech Equipment, as Amended 2018; (Ministry of Finance, Ministry of Industry and Information Technology & National Development and Reform Commission, 2018). • The Action Plan for Piloting Standards of Additive Manufacture (Standardisation Administration, Ministry of Industry and Information Technology, Ministry of Science and Technology, Ministry of Education, National Medical Product Administration & Academy of Engineering, 2020). • National Key R&D Program application guidelines for Advanced Structures and Composites (Ministry of Science and Technology, 2022). • Implementation of Enterprise Standards "Leader" in Key Areas (State Administration of Market Regulation, 2022).

National Development and Reform Commission the government proposed some policies to address the development of C3DP. Table 1 shows the identified 15 policies in C3DP.

The 15 policies can be classified into framework policies and specific instructions. Framework policies are guidance and set the development direction of additive manufacturing and specific instructions focus on promoting development and application through specific instructions and incentives. In detail, the policies can be divided into two functions: monetary and non-monetary incentives (as shown in Table 2). Monetary incentives include government support for R&D, talent attraction, and favourable financing and tax policies. Non-monetary policies prioritise top-management commitment, talent cultivation, resource coordination, and collaboration.

2.2.2. Standards and regulations

Standards and regulations play a crucial role in establishing operational and management standards for the industry, thereby enhancing the development of 3D printing. As indicated by the National Standard Disclosure System website, the Chinese government has issued and implemented 25 standards, with an additional 5 sets prepared to implement. Fig. 1 shows the information on proposed regulations, revealing a predominant focus on construction materials, with 15 regulations about metal and three for plastic, while a notable lack of regulations exists concerning concrete.

However, only four industry norms have been issued to regulate the manufacture of 3D Printing products (Table 3). The absence of comprehensive regulations and codes presents challenges to the promotion and advancement of this emerging technology (Kothman and Faber, 2016). Moreover, the lack of regulations has led to liability issues, as the unclear accountability system hinders the assurance of quality in 3D printing projects (Labonnote et al., 2016).

2.3. Construction innovation and policy mixes

C3DP stands as a pivotal and emerging component within the realm of construction innovation. Investigating various factors and employing analytical frameworks within the context of construction innovation yields invaluable insights for this research endeavour.

2.3.1. Construction innovation

The construction industry, like many others, undergoes transitions driven by advanced technology. Despite the availability of sustainable and cutting-edge technologies and concepts such as BIM, MIC, and green building, the industry is often criticized for its conservative nature. The shortage performance can be attributed to various factors, including insufficient funding for R&D, limited cooperation between different research parties and a fragmented supply chain (Ali et al., 2022).

To respond to the hindrances, some studies have pinpointed a range of factors that contribute to the advancement of the construction industry. These encompass industry-driven best practices, financial backing, human expertise and transparency, governmental backing, research and development, self-reliant ethos, institutional reinforcement, and assistance from developmental agencies (Ali et al., 2022; El-Sayegh et al., 2020; Zhang et al., 2019). Besides, Chang et al. (2019) emphasised the pivotal role of government leadership and funding, industry coordination, and regulatory policies in propelling construction innovation.

Government policies have been recognised as crucial in facilitating the transformation of the construction industry and the adoption of new

Table 2
Policy functions.

Category	Sub-category	Specific context
Monetary	R&D	• Provide funding for additive manufacturing-related R&D (Ministry of Industry and Information Technology, 2015) (Ministry of Science and Technology, 2022).
	Talent	• Set up talent incentive mechanisms and policies about transmuting the research results and products into stock, stock options and other rewards to attract domestic and oversea talented personnel (Ministry of Industry and Information Technology, 2015).
	Financing	• Guide the banks and institutions to strengthen the support of credit and loans for the additive manufacturing industry (Ministry of Industry and Information Technology, 2015); • Support the financial guarantee institution provides credit guarantee for related enterprises (Ministry of Industry and Information Technology, 2015); • Encourage the enterprise to finance through the listing or issuing financial products (Ministry of Industry and Information Technology, 2015); • Selective forerunners in additive manufacturing as role models and encourage the government to give priority to cooperating with forerunners. Provide incentives, including funding and credit and fund support to the forerunner (State Administration for Market Regulation, National Development and Reform Commission, Ministry of Finance, Ministry of Industry and Information Technology, Ministry of Finance, Ministry pf Ecology and Environment … Ministry of Science and Techonology, 2018).
	Tax incentives	• Develop tax support policies for the software, design and equipment in the additive manufacturing industry; Free of tariffs and import duties for part of components for additive manufacturing components, including powder bed, powder feeding and wire feeding electron beam equipment (Ministry of Finance, Ministry of Industry and Information Technology & National Development and Reform Commission, 2018, Ministry of Industry and Information Technology, 2015); • Preferential income and import tax policies are provided for enterprises that purchase equipment, materials and components (Ministry of Finance & Ministry of Industry and Information Technology, 2016).
Non-monetary	Top-Management commitment	• Plan to construct and improve the additive manufacturing standard system and intensify its implementation (Standardisation Administration, Ministry of Industry and Information Technology, Ministry of Science and Technology, Ministry of Education, National Medical Product Administration & Academy of Engineering, 2020; Ministry of Finance & Ministry of Industry and Information Technology, 2016); • The clear guidance for setting up the standards for additive manufacturing equipment (Ministry of Industry and Information Technology & Standardization Administration, 2021; Ministry of Industry and Information Technology & Standardization Administration, 2018)(MIIT & SA, 2018; MIIT & SA, 2021); • Formulate the regulations and code with related enterprises (Ministry of Industry and Information Technology, 2015); • Establish an additive manufacturing committee of experts which focuses on the research of industry development and policy (Ministry of Industry and Information Technology, 2015).
	Talents	• Organise additive manufacturing knowledge training for the teachers and set up related disciplines (Ministry of Industry and Information Technology, 2015).
	Collaboration and resource management	• Strengthen the communication and collaboration among colleges, research institutions and enterprises (Ministry of Industry and Information Technology, 2015; Ministry of Finance & Ministry of Industry and Information Technology, 2016); • Encourage overseas enterprises to establish a research base in China and the cooperation between domestic and overseas enterprises (Ministry of Industry and Information Technology, 2015); • Encourage cooperation between enterprises and colleges to establish related disciplines in colleges (Ministry of Industry and Information Technology, 2015).

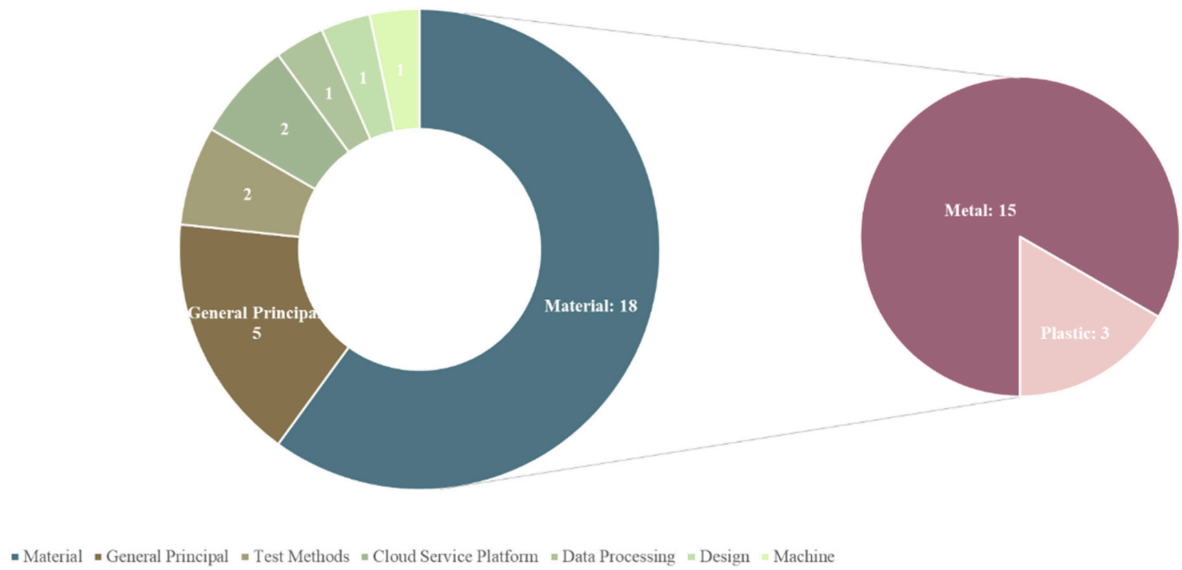

Fig. 1. The focus of 3D Printing regulations in China.

Table 3
3D printing-related regulations in the construction industry.

Year	Items	Department
2020	Technical specifications for concrete 3D Printing	CECS
2022	Test methods for basic mechanical properties of 3D-printed concrete	CCPA/ CBMF
2022	Test method for printability of 3D printing fresh concrete	CCPA/ CBMF
2022	Standard polymer composites large-scale 3D-printing	CECS

Abbreviations: CCES-China Association for Engineering Construction Standardization; CCPA-China Concrete and Cement-based Products Association; CBMF-China Building Material Federation.

technologies to address challenges (Kwan et al., 2019). Regulatory and standard policies stimulate market demand and provide guidance for innovation direction (Chang et al., 2019). However, Zhang et al. (2019) argue that these policies have not been effectively implemented, highlighting the need for a comprehensive understanding of their effectiveness and feasibility. Therefore, a holistic understanding of different practitioners' and experts' perspectives regarding effective supporting policies is necessary.

2.3.2. Policy mixes

The imperative of addressing environmental challenges necessitates the transition of industries towards sustainable innovation. However, a multitude of challenges arise in the specific context of C3DP industry, including R&D imbalances, limited cooperation, and inadequate and ineffective policies. Consequently, the development of this industry necessitates the guidance of well-constructed and proactive policies.

As societies evolve to become increasingly dynamic, decentralized, and intricate, the policy mix assumes a critical function in fostering innovation through interactions among stakeholders, tools, and institutions (Flanagan et al., 2011). The design of a policy mix is a complex task, requiring careful consideration of instrument interplay and compatibility, with an emphasis on cohesion and coherence within the mix itself (Flanagan et al., 2011). Hao et al. (2020) showed that combined policies can generate cumulative impacts exceeding individual measures, driven by their synergistic effects, while inconsistent policy mixes may hinder specific objective attainment. The pivotal role of actors and institutions driving societal shifts is often underestimated, despite their critical preferences, making it imperative to comprehend stakeholders' inclinations towards policy blends for proficient strategy formulation (Kern et al., 2019). Designing policy mixes for sustainability transitions is challenging due to the requirement for cross-sector policies and the presence of uncertainties (Kern et al., 2019). To tackle this challenge, Kivimaa and Kern (2016) have introduced an analytical framework known as "creative destruction" for crafting innovative policy mixes in sustainability transitions. This framework encompasses two key dimensions: "creativity", which fosters niche market innovation and expansion, and "disruption", which involves the dismantling of existing institutions to pave the way for sustainable innovation. In the realm of innovation policy, government and public organizations initiate actions to influence the innovation process.

The aforementioned research emphasises the pivotal role of policy mixes and underscores essential considerations for their development. While previous research has explored the diversity of policies and their impacts on organizational practices in different contexts, there is limited empirical evidence on how complex policy mixes influence the implementation of radical innovations like C3DP (Rogge and Reichardt, 2016). Therefore, this study investigates stakeholder perceptions of policy mixes in the C3DP field in China, using the "creative destruction" framework. By gaining insights into stakeholder perspectives, this research contributes to a better understanding of policy implications for C3DP implementation.

3. Research methodology

3.1. Q methodology

This study employs the Q methodology to obtain the individual perspectives of stakeholders on C3DP-related policies. Q methodology is a research technique that combines qualitative and quantitative methods to study subjectivity (Duncan Millar et al., 2022). The process involves participants rank ordering a set of opinion statements onto a grid, followed by a factor analysis to identify clusters of shared viewpoints. The method can be divided into three steps including Q-set development, Q-sorting and data analysis. It blends the advantages of both qualitative and quantitative research, allowing the exploration of individual concerns and different stakeholder discourses (Boom et al., 2020; Chang et al., 2019). It was initially applied in psychology subject, and it has been exploited in other fields, including environment (Webler et al., 2009), social sciences (Wu and Forbes, 2022) as well as policy research (Boom et al., 2020; Chang et al., 2019; Sneegas et al., 2021).

3.1.1. Developing Q-Set

Identifying Q-samples and generating the Q-set are critical procedures in the Q methodology. It involves gathering a diverse set of statements related to the target topics and then screening to create a representative pool of concourses (Wu and Forbes, 2022). Various print media sources such as news articles, websites, and public records can be utilised to collect the concourses, (Webler et al., 2009). For this study, the prospects and opinions regarding C3DP policies have been identified by conducting a literature review and library research using keywords such as “3D printing for construction” and “Policies".

The study employed a structured Q set and an analytical framework rooted in potential innovation-influencing policy instruments, known as “creative destruction,” to categorise concourses (Kivimaa and Kern, 2016), with this framework originally devised for policy mixes in sustainability innovation transitions. This research only evaluated the “creation” dimension due to the nascent stage of C3DP and its limited implementation. Table 4 presents seven elements under the “Creative” dimension and related interpretations and Table 5 shows the Q sample.

3.1.2. Q-sorting

In this stage, participants were invited to sort their perspectives for a set of stimuli (statements) by using a quasi-normal distribution table (Fig. 2). Subsequent to this, focused interviews were conducted to further explore stakeholders’ viewpoints on statements with which they hold strong disagreement or agreement.

3.1.3. Data collection

According to Webler et al. (2009), respondents in a Q study should possess pertinent knowledge and a well-defined perspective. The sample size is guided by two general principles: The upper limit typically constitutes one-third of the total number of statements, whereas the lower limit is contingent on the number of perspectives under investigation, with an aim of approximately three participants per perspective. As a result, this study aimed to include over 10 experts well-acquainted with the knowledge of C3DP. Snowball sampling was used to recruit participants, resulting in a final sample of 15 participants, including three designers, three enterprise managers, four engineers, and five researchers. Table 6 shows the respondents’ profiles.

3.2. Data analysis

In order to extract factors representing groups of respondents with similar perspectives for further analysis, The study uses PQMethod (version 2.35) to analyse the collected results from the Q-sorting process. Principal component factor analysis (PCA) is initially conducted to extract eight unrotated factors, with factors having eigenvalues <1.0

Table 4
Functions of policy instrument under “creative”.

Creative (Niche Support) Functions of policy instrument	Interpretation
(C1) Knowledge creation, development and diffusion	The promotion and innovation of knowledge in the whole industry, as well as their dissemination, include the R&D, education
(C2) Establishing market niches/ market formation	The formation of the niche market through demand creation
(C3) Price-performance improvements	Improvement in market competitiveness through price advantage
(C4) Entrepreneurial experimentation	The increasing adoption of innovative technologies in enterprises to expand markets and networks
(C5) Resource mobilisation	The coordination of human and financial resources as well as network infrastructure etc.
(C6) Support from powerful groups/legitimation	Legitimacy and support from the authorities, including government departments with distinct functions
(C7) Influence on the direction of search	The future development direction and vision stipulated by the authority

Table 5
Q samples.

No.	Statements
Prospects of 3D Printing in Mainland China	
1	3D Printing will be widely available in the construction market in the future.
2	C3DP (Additive Manufacturing in Construction) will gradually supersede the conventional construction method in China in the next 10–20 years.
3	3D Printing is a complementary technology in the construction sector and will not supplant the conventional construction method.
4	The transition of C3DP should be progressed in a gradual way; otherwise, widespread scepticism from society and other negative results will be caused.
5	The extensive application of C3DP is necessary to comply with the sustainable development of China.
(C1) Knowledge Creation, Development and Diffusion	
6	There is still a wide gap in the R&D of C3DP between China and other developed counties (e.g., the USA and Europe).
7	Systematically quantifying the benefits (such as life-cycle costs) of 3D-printed buildings will allow the industry to understand the technology’s advantages.
8	The research is constrained by high R&D costs.
9	There still exists problems of instability of skills and products, and it need to wait for further improvement and upgrading before they can be widely used.
10	The government should focus on the results of the R&D when encouraging R&D and avoid egalitarianism in incentive policy.
11	The breakthrough in printing material is the foundation of the development of C3DP.
12	Many studies have been performed to develop technical aspects, but nontechnical fields are overlooked (e.g., cost and management).
13	The cross-countries communication regarding AM should be intensified by the government.
14	The establishment of C3DP-related disciplines, subjects and degrees should be encouraged to reserve talent resources.
15	Cross-disciplines research should be encouraged in the R&D of C3DP.
(C2) Establishing Market Niches/Market Formation	
16	3D printing buildings have great market potential because of their design flexibility.
17	Materials and labour that can reduce the construction process make C3DP more attractive.
18	China’s green building evaluation standards should add extra points for 3D-printed buildings to enhance the technology’s market appeal.
19	The question of the safety and quality of the C3DP from the Chinese public will hinder its development.
20	The development of C3DP largely depends on the degree of customisation requirements in the construction industry.
21	The standard for the whole production process of C3DP, including design, construction, and acceptance inspection, should be formulated to guarantee its quality and safety.
22	The C3DP is supposed to enter the market from the edge areas first, like villas, small-scale buildings and pilot buildings, and improve before entering the mainstream market.
23	Technology should be first applied in major and landmark projects to build a demonstration effect.
24	The application of C3DP should be started by building components to form a demonstration effect.
(C3) Price-performance Improvements	
25	The production cost of C3DP is high due to small-scale production and expensive equipment and materials.
26	At the initial stage of application, the global supply chain can be utilised to import equipment and materials and improve product cost performance.
27	Cost is not the main problem for the application of C3DP since it will be overcome with the development, and we should wait for some time.
28	Cost is a crucial factor for the application of C3DP. It is essential to conduct research aiming at decreasing the cost.
29	Subsidies can be provided to C3DP manufacturers by the government to help them lower the product price.
(C4) Entrepreneurial Experimentation	
30	Materials and labour that can reduce the construction process make C3DP more attractive.
31	The government should strengthen cooperation with both big and small enterprises to popularise the application of C3DP.
32	Low-interest rate loans and risk investments can be offered to stimulate entrepreneurship and improve their financing ability.
33	The government should encourage entrepreneurship to promote breakthroughs in 3D printing technology and enrich the product types in the 3D printing construction market.
(C5) Resource Mobilisation	
34	Coordination of resources from multiple industries is significant for intensifying the feasibility and influence of the C3DP.

(*continued on next page*)

Table 5 (*continued*)

No.	Statements
35	Information sharing, including patents and code, is important to drive the development and application of C3DP.
36	The government is supposed to establish a cooperative alliance to strengthen communication and information sharing between research institutions, enterprises, and the government.
37	The cooperation between the universities and enterprises should be reinforced to cultivate more talent for C3DP.
38	Multi-channels and diverse financial mechanisms should be built to render more venture capital and equity investment inclined to the C3DP field.
(C6) Support from powerful groups/legitimation	
39	The support of the upstream industries (such as machinery, materials, etc.) will play a significant role in the development of the technology.
40	Enterprises tend to be conservative towards new technology. The attitude of the leaders plays a crucial role in the successful application of C3DP.
41	The government are encouraged to establish a C3DP development steering group for plan formulation, organisation, coordination, and management.
42	The development of C3DP requires an independent and complete supportive scheme but not only as a complementary technology for MIC (Modular Integrated Construction).
43	Government procurement can adopt C3DP to take the lead in the initial stage of C3DP development.
(C7) Influence on the direction of search	
44	The R&D direction of C3DP should avoid mismatch or duplication among universities, institutions and companies, which may lead to the homogenisation and singleness of the products.
45	The government should clearly define the development principle, stage target, technical route, key task, policy and action to make a top-level design and overall planning and coordination.
46	The China government can refer to the advanced technology programme in developed countries to build Generic technology R&D system
47	The government should build a scientifical industry landscape to promote the development of the whole industry chain for C3DP.
48	The promotion of C3DP requires integrating other advanced technologies, including BIM, to construct a new digital manufacturing system.

considered insignificant and disregarded. However, interpreting the factors extracted from PCA can be challenging when the sub-space is expressed as a dense basis with numerous non-zero weights. To address this, varimax rotation is introduced to rotate the four factors with eigenvalues >1.0 obtained in the previous step (Chang et al., 2019; Webler et al., 2009).

4. Results

4.1. Loading results and factor arrays

Table 7 presents the factor loading results and their characteristics, where the results of the loading range from 1.0 (strong association) to −1.0 (strong dissociation). The auto-flagging function in PQMethod is applied in this study using a threshold p-value of <0.05. Respondents with correlation scores above the threshold of 0.5 are auto flagged (marked with ✕).

Based on the results, the majority of participants align with factor 1, which includes one designer, two engineers, and three researchers. Factor 2 comprises two enterprise managers. Both factor 3 and factor 4 are represented by three participants. One participant (ID:11) does not show a significant correlation with any factors and is considered confounded, thus excluded from further analysis and discussion.

4.2. Perspective interpretation

Fig. 3 shows the result of the overall configuration of prototype factor arrays. These arrays reveal the different arrangements of statements for each factor, enabling the identification of distinct perspectives (Zabala, 2014). The four-factor arrays represent the aggregated viewpoints of specific stakeholder groups and have been summarised as following four perspectives 1) Conservatively Exploration; 2) Aggressive progression; 3) Intensive Investigation; 4) Tentative Stimulation. The study interpreted the four perspectives based on the collected data to gain insights into the opinions of different stakeholder groups.

Fig. 4 shows an overview of the distribution of statement ratings from the four perspective arrays. Furthermore, interview records have been quoted to support the explanation and validation of the identified

Table 6
Profile of respondents.

ID	Category of Group	Years of Experience in C3DP
1	Designer	1 year
2	Enterprise Manager	10 years
3	Designer	1 year
4	Enterprise Manager	5 years
5	Enterprise Manager	8 years
6	Researcher	1 year
7	Engineer	4 years
8	Researcher	5 years
9	Engineer	2 years
10	Engineer	11 years
11	Researcher	2 years
12	Engineer	4 years
13	Designer	7 years
14	Researcher	3 years
15	Researcher	7 years

Strongly Disagree -3	-2	-1	Neutral 0	1	2	Strongly Agree 3

Fig. 2. Quasi-normal distribution table.

Table 7
Rotated factor matrix and factor characteristic.

ID	Interviewee Group	Factor 1	Factor 2	Factor 3	Factor 4
1	Designer	0.0414	0.0049	**0.7578×**	0.0758
2	Enterprise Manager	0.1097	0.224	−0.2124	**0.7514×**
3	Designer	**0.6978×**	0.224	0.105	0.1779
4	Enterprise Manager	0.3178	**0.8114×**	−0.0936	0.1375
5	Enterprise Manager	0.0139	**0.7424×**	0.1381	0.3403
6	Researcher	−0.1287	0.0854	0.2174	**0.6570×**
7	Engineer	**0.6915×**	0.0335	0.0008	−0.0744
8	Researcher	**0.7965×**	−0.1187	0.0075	0.1763
9	Engineer	0.0945	0.2085	**0.7011×**	0.2589
10	Engineer	0.2761	−0.3961	**0.6387×**	−0.0534
11	Researcher	0.4473	0.3033	0.096	0.3619
12	Engineer	**0.6416×**	−0.4346	−0.038	0.3619
13	Researcher	0.1767	0.1209	0.2539	**0.6596×**
14	Researcher	**0.6986×**	0.2354	0.3481	−0.0633
15	Designer	**0.5726×**	0.2177	0.3432	−0.18312
Explained Variance (%)		22	13	13	14
Number of variables		6	2	3	3
Average relative coefficient		0.8	0.8	0.8	0.8
Composite reliability		0.96	0.889	0.923	0.923
Standard error of factor scores		0.2	0.333	0.277	0.277

Note: "×" indicates defining factor loading flagged for computing factor scores.

perspectives.

4.2.1. Perspective 1: conservative exploration

Perspective 1 comprises six participants, consisting of two designers, two engineers, and two researchers. It accounts for 22% of the variance in the study. Individuals holding this perspective view C3DP as a complementary technology in the construction market [Statement 3; +3], but they doubt whether the C3DP can fully replace traditional construction methods in the future [Statement 2; −3].

> *… I think it is difficult for 3D printing to completely replace the current set of industrial systems at present, so I think it is unable to eliminate the current technology, but it can only join as a complementary technology … (#15)*

With the rapid development of advanced technology, intelligent construction has emerged as a prominent trend and various innovative construction technologies have demonstrated their capabilities and are being actively implemented. While C3DP possesses unique advantages, respondents still perceive it as occupying a portion of the market rather than becoming mainstream [Statement 1; +2]. This perspective is also reflected in their disagreement that C3DP is the sole solution for achieving construction sustainability [Statement 5; −3]. Furthermore, stakeholders strongly dispute the aggressive promotion of C3DP [Statement 2; −3]. Their concerns revolve around potential negative outcomes such as an opaque industry, market disorder, the *"bad money drives out good"* phenomenon, and widespread scepticism (Statement 14; 1).

Participants in Perspective 1 believe that the immaturity of skills and products is a significant hindrance to the promotion of C3DP [Statement 9; +3]. They emphasise the importance of making progress and breakthroughs in C3DP to facilitate its widespread application. Besides, participants in this perspective prioritise the acceleration of the formulation of design, construction, and inspection standards. They believe that these regulations and standards are essential for ensuring the quality and safety of C3DP and reducing the risk of skill and product instability [Statement 21; +3]. Some participants also view this policy as a means to establish a niche market by instilling market confidence in C3DP products.

Another obstacle recognised by Perspective 1 is the cost [Statement 27; −3]. The cost of C3DP skills, materials, and equipment is high due to its early stage of development and the limited production scale of C3DP. Nevertheless, representatives of Perspective 1 strongly disagree with the idea of providing subsidies to additive manufacturing contractors to the government [Statement 29; −3]. This disagreement is particularly evident when comparing the z-score of this statement with the other perspectives (Fig. 5). They highlighted that market demand, rather than companies' capabilities, drives the motivation for mass production. Also, technology assistance, rather than financial assistance, was considered more effective in reducing manufacture costs through technological improvements. In terms of market entry, this group expressed relative support for starting with 3D printing components, as it can have a promotional and demonstrative effect [Statement 24, 1].

> *… Providing subsidies to stimulate the adoption of C3DP is unable to solve the root problem, which is a technical breakthrough. Incentive policies of the government are short-term, which is just temporary relief (#12).*

Array of Factor 1

-3	-2	-1	0	1	2	3
2	8	6	10	13	1	3
5	16	17	11	14	7	4
27	20	18	19	15	12	9
29	32	26	30	23	22	21
	40	33	31	24	28	
	42	35	36	25	45	
		38	37	34		
		41	39	47		
		44	43	48		
			46			

Array of Factor 2

-3	-2	-1	0	1	2	3
2	1	3	7	10	4	14
6	5	9	8	18	11	15
25	19	12	13	23	17	37
26	20	32	16	31	34	38
	27	40	21	33	39	
	30	41	22	35	42	
		43	24	36		
		44	28	45		
		46	29	47		
			48			

Array of Factor 3

-3	-2	-1	0	1	2	3
18	2	8	1	15	3	4
20	14	10	17	21	5	7
24	23	11	26	25	6	9
44	28	12	29	27	30	13
	31	16	33	36	34	
	32	19	35	37	42	
		22	38	45		
		40	39	46		
		47	41	48		
			43			

Array of Factor 4

-3	-2	-1	0	1	2	3
8	6	2	1	5	13	3
12	11	4	7	17	15	14
26	19	9	18	27	16	22
44	20	10	25	33	21	31
	28	24	32	34	23	
	35	29	36	40	37	
		30	38	45		
		39	41	46		
		42	43	48		
			47			

Fig. 3. Four rotated factor arrays.

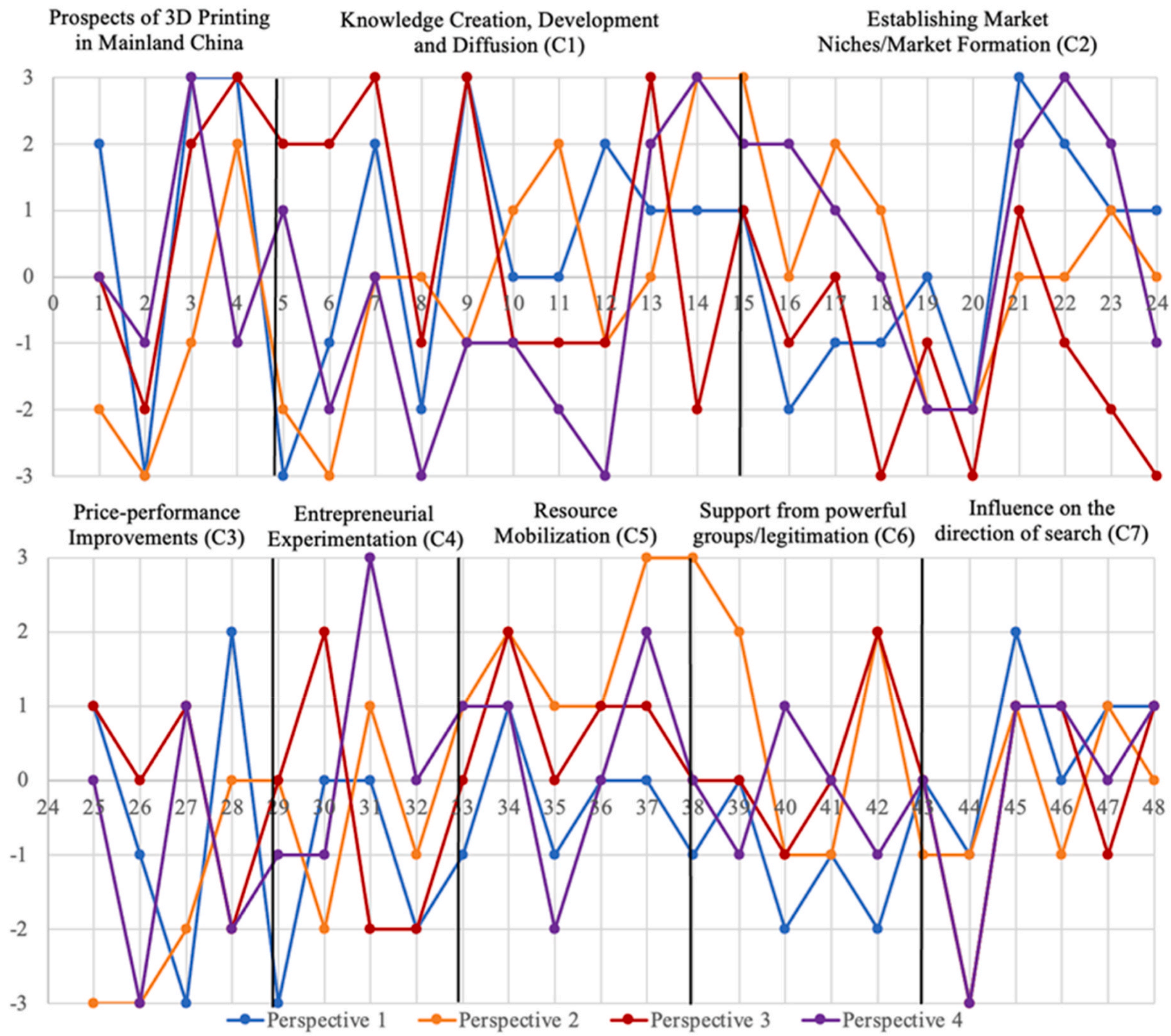

Fig. 4. Comparision of 4 perspectives' statement scores.

… it (subsidies) may breed opportunism, market chaos, and waste of funds without a detailed review mechanism and strict implementation for subsidy distribution (#14).

Overall, Perspective 1 takes a cautious and optimistic view of the future of C3DP, perceiving it as a niche option within the construction industry alongside other rapidly advancing techniques. The development strategy proposed under this perspective emphasises the accumulation of knowledge (C1) and the exploitation of niche markets (C2). The focus is on establishing a strong foundation of technical and non-technical knowledge before widespread implementation. The approach to market creation is seen as exploratory and moderate, aimed at generating interest and establishing a solid market base.

4.2.2. Perspective 2: aggressive progression

Perspective 2, represented by two enterprise managers, stands out as an intriguing contrast in this study, explaining 13% of the variance. Different from other perspectives, they believe that C3DP has the potential to become mainstream in the market [Statement 1, -2]. This viewpoint is further supported by the notable difference in the z-score compared to the other three perspectives [Statement 3, Fig. 6], where it stands at −0.39 while the other perspectives consistently lean towards positive extremes.

… Facing labour shortages, environmental challenges, and increasing customisation demand, the advantages of C3DP are becoming prominent. It is possible for C3DP to overcome its limitation in the distant future … (#5)

Perspective 2 expresses confidence in the state-of-the-art development of C3DP in Mainland China [Statement 6; −3]. Interviewees argued that China is considered one of the leading countries in C3DP, evident from the development of robotic 3D printing systems by Chinese universities and the geographical distribution of C3DP service providers, which are primarily located overseas. This comment aligns with their disagreement regarding the need to lower prices by importing materials or equipment from the global supply chain [Statement 26; −3]. Unlike the other three perspectives, they argued that local products are capable of meeting their requirements, and the price of C3DP generally aligns with their expectations based on their prior experience [Statement 25; −3].

Perspective 2 emphasises the significance of incorporating C3DP-related modules into college curricula to facilitate knowledge dissemination [Statement 14; +3]. It highlights the need for new talent to harness this emerging technology, particularly in response to concerns about the conservation of traditional labour practices and labour shortages. Furthermore, this perspective strongly acknowledges the importance of interdisciplinary coordination in advancing C3DP [Statement 15; +3].

… It (C3DP) involves many aspects, including materials, equipment, as well as the printing process etc … If these disciplines are not interlinked,

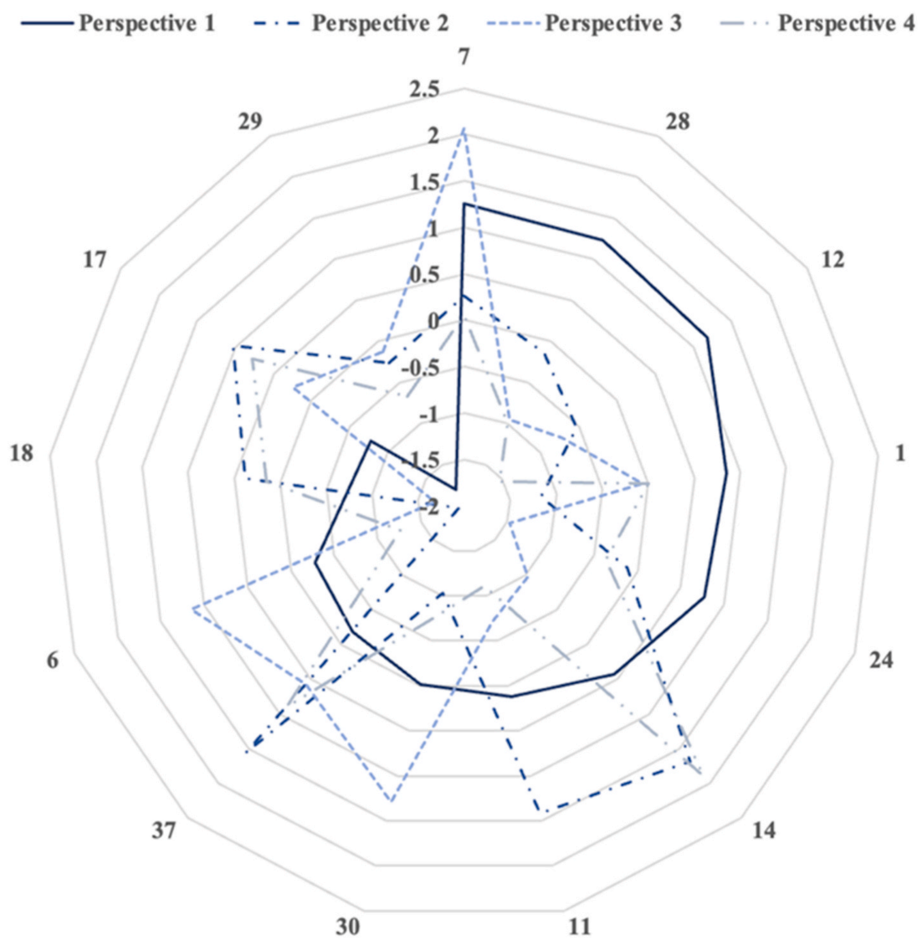

Fig. 5. Z-score for the distinguishing statements of perspective 1.

the whole research and advancement in a single field will be hindered … (# 4)

Perspective 2 stands out for its strong support of all policy functions under Resource Mobilisation (C5). This can be attributed to the immense scale of the construction industry and its corresponding resource demands. Therefore, Perspective 2 gave prominence to the cooperation between tertiary institutions and companies to exchange qualified personnel and knowledge [Statement 37; +3]. Such collaboration benefits universities by securing funding, facilitating research result transformation, and offering students practical opportunities. Similarly, enterprises can leverage this cooperation to update their technology, provide training, and bring in new talent. Perspective 2 not only emphasises the collaboration between academia and industry but also places high value on information sharing among industry stakeholders and other institutions.

… The university has some testing equipment or methods of building materials and structures while we have printing equipment. Students can come to our laboratory to print some products. Our products can be tested by the university, and these data can be shared …

… When we tried to print residential buildings, we also sought professional engineers and qualified construction units for cooperation. The combination of the two parties can ensure security and pass the qualification review while realizing the C3DP application … (#4)

Furthermore, Perspective 2 places a high value on financial resources, distinguishing itself from other viewpoints [Statement 39; +2]. This emphasis can be attributed to the capital-intensive nature of the construction sector. The role of the 2 participants (Enterprise Manager) also reflects the demand for expanding operations in a company.

In conclusion, Perspective 2 can be characterised as aggressive and ambitious, with an optimistic outlook on the present situation and future prospects of C3DP. The two enterprise managers in this perspective hold a long-term view and have a strong belief in the growth potential of the technology. They emphasise the importance of Knowledge Diffusion (C1) and Resource Mobilisation (C5) policy functions for industry growth and expanding the influence of C3DP.

4.2.3. Perspective 3: intensive investigation

One designer and two engineers belong to Perspective 3, accounting for 13% of the explained variance. Perspective 3 holds a nuanced view of the future of C3DP. While they agree that C3DP is a complementary technology [Statement 3; +2], they are uncertain about its potential to completely replace traditional methods [Statement 2; −2] or become mainstream. They share a common opinion on adopting a gradual development path [Statement 4]. Notably, Perspective 3 recognises the importance of C3DP for the sustainability mission in China [Statement 5; +2].

… C3DP is environmentally friendly. It saves construction materials, reduces construction waste, as well as generates little dust during construction (#10).

… C3DP has the potential to replace human beings working in harsh environments and even achieve unmanned construction, which improves safety and achieves sustainability … (#1)

Perspective 3 acknowledges the need for further research and improvement in the development of C3DP [Statement 9; +3], recognises the developmental gap between C3DP in China and more developed

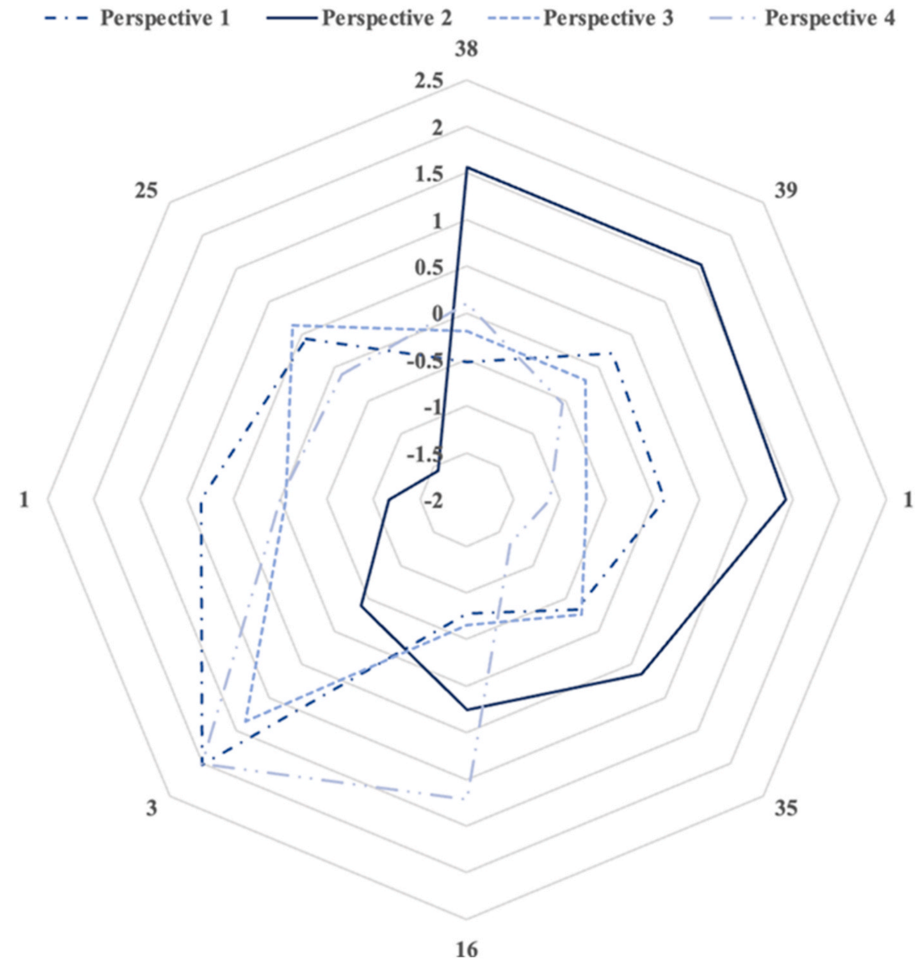

Fig. 6. Z-score for the distinguishing statements of perspective 2.

countries [Statement 6; +2], and emphasises the importance of fostering communication and collaboration among academics, enterprises, and institutions [Statement 13; +3]. However, they disagree with the importance of design flexibility and market demand for customisation in C3DP development in China. Perspective 3 emphasises the need for systematic quantification of C3DP in China and highlights that quantification will enable a better understanding of C3DP's advantages for both society and the industry [Statement 7; +3].

... Systematically quantifying the benefits of C3DP can refine the advantages of C3DP ... so as to analyse the future development direction and market position of 3D printing architecture .... (#10)

... Specific and clear quantitative results and data can eliminate the misunderstanding ... the more prominent its advantages are, and the more people will be willing to participate in the research and application ... (#1)

Perspective 3 expresses a largely unfavourable view towards the policy suggestions under Establishing Market Niche/Market Formation (C2), disagreeing with the idea of demonstrating C3DP through 3D printing building components [Statement 24; −3] and exhibiting reservations about utilising C3DP in landmark or major projects [Statement 23; −2]. They concerned about potential marketing gimmicks and excessive market expectations associated with too many demonstration programs.

... Their surface quality is poor ... Therefore, they considered it might fail to provide customers with intuitive feelings ... over-marketing by social media led to marketing gimmicks and high market expectations ... The market has gradually lost confidence in C3DP ... (#9)

Fig. 7 shows that Perspective 3 is more aligned with the belief that the current cost of C3DP is expensive and presents a barrier [Statement 30] than the other perspectives. They discourage the suggestion of providing additional scores for C3DP projects in green building evaluation standards to enhance its appeal [Statement 18; −3]. Instead of blindly stimulating the market, Perspective 3 emphasises the utmost importance of understanding C3DP's market potential and positioning in China, advocating for thorough investigation and research before implementing incentives to avoid the wastage of resources. They also highlight the necessity of a conducive and comprehensive R&D environment for C3DP's development, promoting technology complementarity and collaboration among different research entities [Statement 44; −3].

Overall, Perspective 3 acknowledges the potential of C3DP for sustainability but emphasises the need for clarity regarding its market potential and positioning in China. Rather than rushing into the market (C2) and implementing incentives, they advocate prioritising research and development (C1) to quantify the advantages of C3DP and evaluate its market potential.

4.2.4. Perspective 4: tentative stimulation

Two researchers and one enterprise manager were primarily associated with Perspective 4, explaining 14% of the research variance. Compared to the other three perspectives, Perspective 4 is uncertain about the growth potential and prospects of C3DP, firmly believing that it cannot fully replace the traditional construction methods [Statement

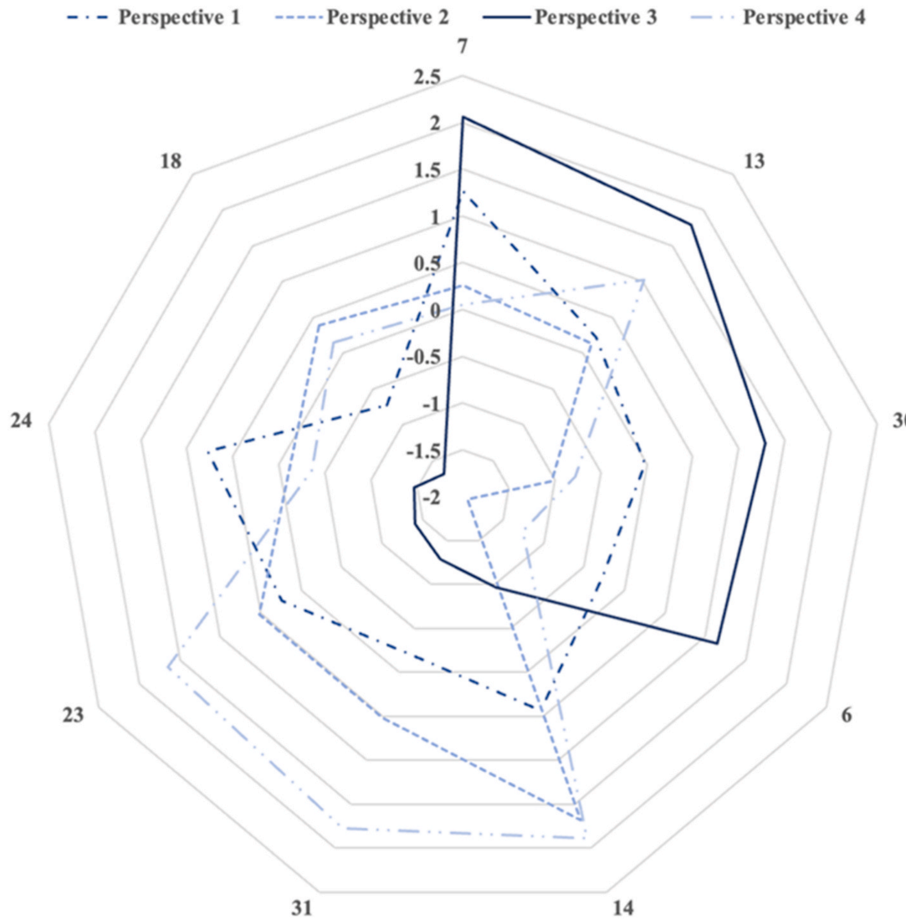

Fig. 7. Z-score for the distinguishing statements of perspective 3.

3; +3]. this perspective slightly agrees that the promotion of C3DP is insufficient due to the limited number of individuals involved in this field in China (Fig. 8).

Hence, Perspective 4 supports various incentives to stimulate the market. While differing on the hindrances of high R&D costs [Statement 8; −3] and insufficient non-technical research [Statement 12; −3], Perspective 4 recognises the importance of knowledge diffusion policies [Statement 13; Statement 14; Statement 15].

> *… if this industry wants to move forward, new blood is necessary to promote it … (#6)*

> *A diffusion of knowledge of C3DP is necessary. The resistance in the process of application will be reduced when people have a certain understanding of it … it is very helpful for the development of this technology … (#2)*

Promoting market initiatives (C2) and fostering entrepreneurship (C4) are deemed crucial. Perspective 4 suggests that C3DP can explore niche markets [Statement 22; +3], such as villas, public lavatories, and featured landscapes, as a starting point for creating its market.

> *… These small-scale projects with less strength and size requirements fit with the current technology level of C3DP, enabling C3DP to try to open its market … (#2)*

Although uncertain about the development trend of C3DP, Perspective 4 recognises its advantages and market potentials, such as cost savings in material and labour [Statement 17; +1]. They also recognise the design flexibility of C3DP and believe it will be a strong attraction for customisation [Statement 16; +2], suggesting undertaking projects with complex design work. However, Perspective 4 raises concerns about the potential impact on existing enterprises [Statement 40] and supports collaboration between C3DP start-ups and leading contractors [Statement 31; +3] to facilitate the integration of C3DP into the market and promote the development of emerging enterprises. In terms of future research direction (C7), Perspective 4 advocates for non-intervention, allowing free products to lead to a flourishing future [Statement 44; −3].

In summary, Perspective 4 acknowledges the uncertain development trend and the prospect of C3DP but recognises its promising advantages. Therefore, it suggests exploring the potential of C3DP through knowledge diffusion (C1), market creation (C2), and entrepreneurship (C4) to stimulate its growth.

4.3. Consensus among perspectives

As demonstrated in Table 8, despite the presence of differences, several common views are shared among the four perspectives. The consensus policies emphasise resource mobilisation and the influence of research direction. These policies encompass the definition of clear development principles and plans, the fostering of interdisciplinary research, the coordination of resources, the integration of C3DP with other advanced technologies, and the establishment of a collaborative C3DP alliance. There is unanimous disagreement regarding the replacement of traditional construction methods by C3DP shortly and an emphasis on the importance of customisation for its development. Additionally, there is slight opposition to the government's establishment of a C3DP development steering group. All stakeholders confirm the crucial role of policy in driving innovative technology development. By leveraging its influence and establishing collaboration platforms, the government can enhance efficiency.

The stakeholders of the four Perspectives all believe that the

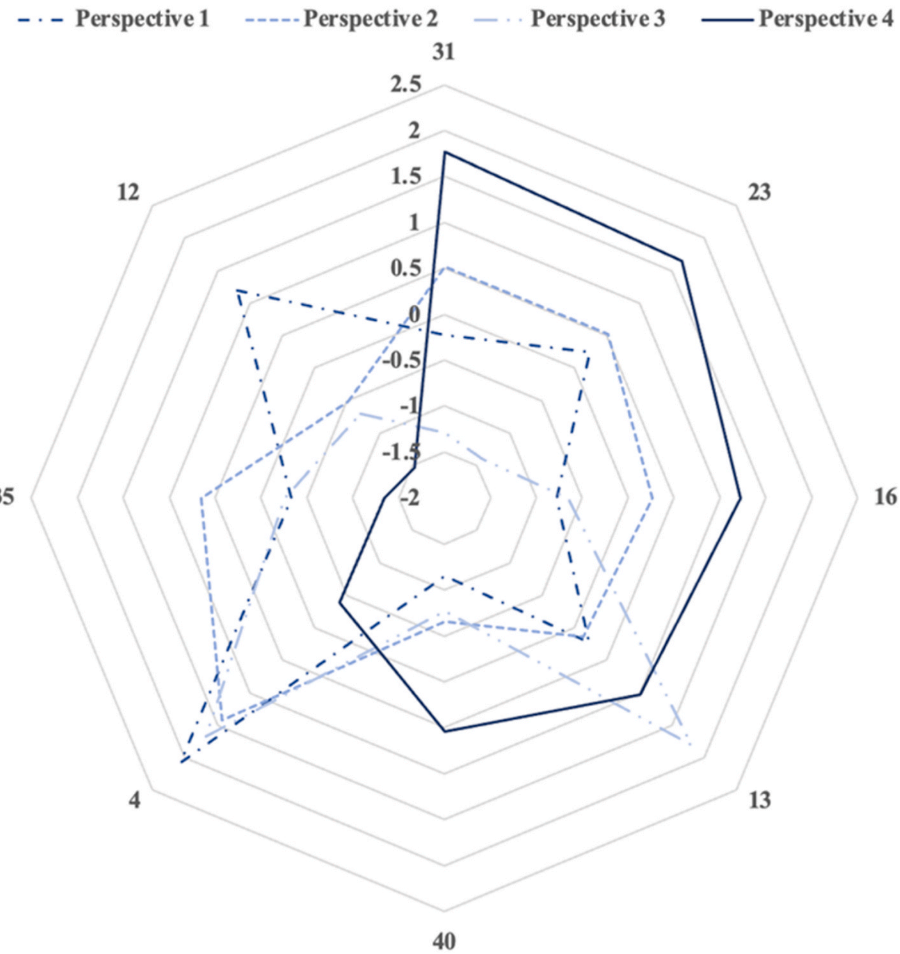

Fig. 8. Z-score for the distinguishing statements of perspective 4.

government should formulate clear development principles and plans to provide clear guidelines for the future of the industry. The plans and roadmaps can help all parties in the industry to better understand the direction and goals of the industry and provide guidance for their decisions and practices. The guiding role of the government can promote the rational allocation of resources, help the industry standardise its development, and improve the competitiveness and influence of the C3DP (Statement 45).

In the development of the C3DP industry, cooperation between all parties is crucial. Stakeholders believe that the government can establish an open platform to help coordinate the communication and cooperation among academics, enterprises and the government, so that various stakeholders can share information, for example, to promote the feasibility of C3DP becoming a widely used practice in the construction industry, the costs and benefits of C3DP, China's R&D capabilities and market demand, in order to provide advice on the development of C3DP and formulate a blueprint for the development of C3DP in China (Statement 36). The government can exert its influence to promote cooperation among different stakeholders and improve cooperation efficiency.

However, the stakeholders object to the government's excessive interference in the development of the C3DP industry. They believe that the government should provide support and coordination for cooperation among all parties, rather than too much interference in cooperation methods and arrangements. They emphasised that the role of the government should be to promote a virtuous circle of industry development and help resolve obstacles that may be encountered in cooperation, so as to promote the prosperity and development of the industry (Statement 41).

In addition, the stakeholders oppose the view that C3DP technology will replace traditional construction technology within 10–20 years (Statement 2). This implies that none of the stakeholders sees the development of C3DP as contradictory to traditional construction techniques. On the contrary, C3DP can serve as a supplement to traditional construction technology and promote the transformation of the construction industry. Therefore, the government provides corresponding policies to promote the integration of the traditional construction industry and C3DP enterprises. On the one hand, the government can encourage traditional contractors to actively embrace C3DP technology. For example, let registered engineers understand the advantages and operating procedures of the technology through industry training and publicity. On the other hand, the government can also help C3DP enterprise Datong and the barriers between traditional contractors. For example, the government can promote supply chain integration and professional exchanges among these enterprises, assist them to complement each other and promote cooperation among them. These policies can integrate existing C3DP companies that are outside the industrial chain of the construction industry into practical scenarios.

Stakeholders agree that multi-industry resource collaboration is of great significance in enhancing the feasibility and influence of C3DP (Statement 34). They realised that the development of C3DP requires the integration and sharing of resources and expertise from different industries. The status quo of China's CD3P industry is usually that various institutions invest in all aspects of C3DP such as materials, equipment and technology, which leads to waste of resources and low efficiency of development. They believe that through the collaboration of multi-industry resources, professionals and enterprises in different fields can participate in the R&D, design and implementation process of C3DP, and

Table 8
Consensus statements among all perspectives.

No.	Statement	Z-Score of Each Perspective			
		P1	P2	P3	P4
45	The government should clearly define the development principle, stage target, technical route, key task, policy, and action to make a top-level design and overall planning and coordination	0.77	0.38	0.48	0.22
15	Cross-disciplines research should be encouraged in the R&D of C3DP	0.75	1.67	0.83	1.10
34	Coordination of resources from multiple industries is significant for intensifying the feasibility and influence of the C3DP	0.41	1.03	0.97	0.55
48	The promotion of C3DP requires integrating other advanced technologies, including BIM, to construct a new digital manufacturing system.	0.35	0.27	0.77	0.33
36	The government is supposed to establish a cooperative alliance to strengthen the communication and information sharing between research institutions, enterprises and the government.	0.19	0.91	0.95	0.22
2	C3DP (Additive Manufacturing in Construction) will gradually supersede the conventional construction method in China in the next 10–20 years.	−1.86	−1.94	−1.08	−0.99
20	The development of C3DP largely depends on the degree of customisation requirements in the construction industry	−0.99	−1.29	−1.54	−0.99
41	The government are encouraged to establish a C3DP development steering group for plan formulation, organisation, coordination, and management	−0.68	−0.38	−0.05	−0.22

share their experience and technology, thereby enhancing the feasibility of C3DP. Multi-industry resource collaboration can promote knowledge exchange and integration, stimulate innovative thinking, and improve the technical level and research and development capabilities.

Also, stakeholders believe that the R&D of C3DP should encourage interdisciplinary research (Statement 15). They recognise that the development of C3DP involves multiple disciplines, including engineering management, material science, architectural design, and project management. Interdisciplinary research can promote knowledge exchange and integration in different disciplines, stimulate innovative thinking, and provide more comprehensive and comprehensive solutions for the research and development of C3DP. Through interdisciplinary cooperation, researchers from different disciplines can participate in the R&D process of C3DP and share their respective professional knowledge and technologies, thereby promoting the innovation and progress of C3DP technology.

Stakeholders agree that the promotion of C3DP needs to be integrated with other advanced technologies, especially with technologies such as building information modelling (BIM) (Statement 48). Combining C3DP with advanced technology can realise the digital process from design to manufacturing, promote information sharing and collaboration, improve project visualisation and simulation capabilities, and reduce errors and costs. They called on all parties to strengthen cooperation and innovation, promote the application and development of advanced technologies, and jointly promote the extensive application and promotion of C3DP technology.

5. Discussion

C3DP is a novel and promising strategy for the sustainable development of the construction sector. A policy mix can play an important role in accelerating its development and adoption. This study employs the Creative Destruction framework for policy mix to identify policy suggestions through a comprehensive literature review and employs the Q methodology to examine various stakeholder perspectives on the prospect and direction of C3DP policy suggestions. The findings revealed four distinct perspectives: (1) Conservative Exploration, (2) Aggressive Progression, (3) Intensive Investigation, and (4) Tentative Stimulation.

The second perspective, termed Aggressive Progression, anticipates a larger market for C3DP and emphasises the necessity for knowledge diffusion and cross-industry support to broaden its influence. This group primarily consists of practitioners in innovative industries who are generally optimistic about the development of C3DP in the construction industry. Their primary policy support needs include (1) knowledge creation and development, and (2) resource mobilisation. The first policy demand involves nurturing more professional practitioners who are well-versed in C3DP technology. Currently, a limited number of universities offer courses on C3DP and its applications in civil engineering, engineering management, or mechanical engineering. However, the technical research and development of C3DP necessitate a significant number of professionals in the fields of materials, machinery, computers, and civil engineering. The scarcity of such talent has become a significant constraint on the development of C3DP enterprises. This policy demand also encompasses the rapid promotion of C3DP R&D, including patent rights protection, support for professional talents, etc. The second demand necessitates innovation in the existing industry structure and the promotion of the C3DP market through monetary incentive policies such as government orders and tax exemptions.

On the other hand, practitioners in traditional industries, such as architectural designers and engineers from traditional contractors and developers, prioritise maintaining the stable development of the industry. These stakeholders are primarily distributed in the first and third perspectives. The 'Conservative Exploration' perspective views C3DP as a supplement to mainstream construction techniques and underscores the importance of policies for knowledge and market development. The 'Intensive Investigation' perspective recognises the sustainability potential of C3DP and underscores the need for an in-depth investigation and development of knowledge. These stakeholders tend to gradually promote the application of C3DP technology under the existing industry structure. Also, they focus more on improving the price competitiveness of C3DP. The first perspective opposes strong interventions in technology promotion by powerful groups, such as mandatory technology application requirements. There were many stakeholders who expressed concerns that these policy-driven technology applications would impact their product or design performance. The third perspective values C3DP's excellence in sustainability, while they believe that more research, transparent data, and actual cases are needed to assist their decision-making.

The 'Tentative Stimulation' perspective advocates for attempts and experimentation in the market to further explore the technical potential of C3DP. This group comprises some C3DP business practitioners and academics. They are not in favour of rapid technological development under financial incentives, as this may lead to the formalisation of some technological research and development processes. These stakeholders advocate for providing more application scenarios for the development of C3DP. Stakeholders who hold such a perspective believe that it is challenging for early technology applications to achieve universal applicability. Although they present less support for forcing companies in the existing construction industry chain to actively apply emerging technologies like C3DP, they advocate providing practical cases and data collection opportunities for the application of C3DP technology through subsidies or government-led pilot projects. Through application in small-scale government-led cases, researchers and C3DP companies can further understand industry needs and technical deficiencies, thereby promoting technological progress.

Despite the differences among stakeholders, there is a consensus on certain issues. By studying this consensus, decision-makers can understand the most crucial policy needs and decision-making directions in promoting C3DP technology. Firstly, the stakeholders in the study unanimously agreed on the importance of knowledge creation, development, dissemination, and resource mobilisation. It was found that all stakeholders desire a clear and transparent understanding of the industry situation, which includes (1) clear views and plans on the technology of decision-makers, (2) effective industry needs and technology development, and (3) product standards and requirements. Secondly, they emphasised the significant role of interdisciplinary technology collision and research and development in the development and application of C3DP. Many stakeholders encourage the establishment of relevant disciplines and courses to directionally cultivate interdisciplinary talents who are familiar with C3DP technology. Thirdly, they expressed expectations for cooperation among companies in the industry. Currently, most C3DP companies are independently developing printing equipment, printing materials, and software. Many stakeholders suggest that companies can focus R&D funds and talents on a specific part and reduce resource waste through extensive upstream and downstream industry collaboration and cooperation networks.

In practical terms, these suggestions can chart the course for the future development of the C3DP industry. Firstly, policymakers should prioritise the exchange, dissemination, and promotion of knowledge. Through the establishment of information-sharing platforms and support for research and development projects, governments can facilitate the transfer of knowledge within industries, thereby expediting innovation and progress. Furthermore, policies should place an emphasis on training programs to ensure that the next generations of workers acquire the requisite skills and knowledge. Secondly, the efficient usage of resources lies at the heart of sustainable development. The C3DP industry must commit to reducing resource wastage, and policymakers can encourage enhancements in resource efficiency by incentivising sustainable practices and technological innovation, and by fostering collaboration and resource-sharing among enterprises. In addition, collaboration between upstream and downstream industries is of paramount importance. All segments of the C3DP industry must cooperate closely to ensure the seamless functioning of the entire value chain. Governments can promote this cooperation both within and across industries by offering support and incentives to all parties involved. In summary, the findings of this study offer valuable guidance for the C3DP industry, with talent development, resource utilization, collaboration, and policy formulation being pivotal elements for the industry's ongoing success and sustainable growth. This will contribute to propelling the C3DP industry towards greater accomplishments in the future, yielding positive impacts on both society and the environment.

Taking the Chinese construction industry as an exemplar, this study uncovers the diverse opinions and consensus among stakeholders on the promotion and development of C3DP in fast-developing countries. By employing Q methodology, this study integrates quantitative and qualitative analysis methods to examine the policy needs and perspectives of various stakeholders. The discussion in this article reveals heterogeneity in the policy needs of stakeholders with different roles. Simultaneously, by summarising the consensus among different stakeholders on policy needs, policymakers can identify the most urgent and necessary policy directions. The research findings of this research will assist policymakers in revising or updating the policy mix of C3DP more effectively, thereby promoting emerging construction technologies and facilitating the green transformation of the construction industry in rapidly growing regions and countries. This research constructs a novel roadmap for C3DP policy promotion. In addition, this article can also provide a policy reference for rapidly developing regions and countries with a high demand for construction.

6. Conclusion

As a significant pillar of urban development, the construction industry exerts an influence on energy consumption, carbon emissions, and climate change. This has spurred the emergence of C3DP to address the environmental and labour challenges facing the construction sector. C3DP holds the potential to reduce construction waste and energy consumption, lower construction risks and costs, and facilitate the adoption of digital construction techniques. Nevertheless, the progression of the C3DP industry has been sluggish, with one of the primary reasons being the uncertain policy requirements concerning stakeholder support and collaboration.

To tackle this issue, the objective of this study is to examine the policy requirements of various stakeholders regarding the prospects of C3DP promotion and its associated policy functions, in order to determine their theoretical and practical significance for policy formulation. Firstly, this study reviews the current status of C3DP development, application, and policies. Subsequently, the research uses the Q methodology, which combines qualitative and quantitative elements to develop a Q set to gather the opinions of typical stakeholders of C3DP promotion policies and in-depth interviews were conducted to gain insights into the perspectives regarding policy expectations. The research findings reveal that stakeholder viewpoints can be categorised into four distinct perspectives: Conservative Exploration, Aggressive Progression, Intensive Investigation, Tentative Stimulation. Although stakeholders with different perspectives may disagree on certain aspects, they still find common ground on numerous fronts. They agree that knowledge creation, development, dissemination, and resource usage, as well as active collaboration within the industry and cross-industry technical cooperation, will positively impact the development of C3DP.

The findings of this study can offer valuable insights into the C3DP industry's development. The advancement of C3DP should place emphasis on nurturing talent, efficient resource usage, and facilitating collaboration between upstream and downstream sectors. Besides, this research makes a significant contribution to policy formulation. Through the outcomes, policymakers can delve into the policy requirements of the C3DP industry. Policy composition and design should give priority to the exchange, propagation, and dissemination of knowledge, facilitating collaboration within the industry and establishing partnerships between the construction sector and other external industries.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Appendix 1. 3D Printing Construction Projects in Mainland

Year	Location	Project Name	Printing Product	Project Team	Size	Type & Equipment	Material
2014	Shanghai	Ten single-storey houses	Whole building	WinSun (China)	200m^2 each	Contour Crafting; Gigantic 3D printer of size 150 m × 10 m × 6 m;	High-grade quick dry cement and glass fibre
2015	Suzhou	Apartment	Whole building	WinSun (China)	/	Concrete Printing; Gantry system	Concrete
2015	Beijing	The VULCAN pavilion	Structure	Laboratory for Creative Design (China)	24m^2; 3 m in height	/; Gantry system	/
2015	Urumqi	"Dragon eye" in the railway station	Roof Component	Urumqi High-speed Railway Hub Comprehensive Development and Construction Investment Co. LTD	/	/	Steel reinforced concrete
2015	Shanghai	Villa	Separated Component	WinSun (China)	1100m^2	Extrusion type; Gantry system	/
2015	Suzhou	A five-storey apartment	Separated components	WinSun (China)	1000m^2	Contour Crafting; 3D printer	a mixture of recycled construction waste, glass fibre, steel, cement, and special additives.
2016	Suzhou	Public bathrooms	Separated components	WinSun (China)	/	/	Construction waste and mine tailings
2016	Suzhou	Chinese Courtyard	Whole building	WinSun (China)	130m^2 and 80m^2	Concrete Printing; Gantry system	Concrete
2016	/	3D Printed Two-Story villa	Whole building	HuaShang Tengda (China)	400m^2	Contour Crafting; Tower Crane Printing system	Concrete
2017	Shanghai	Cloud Pavilion	Whole building	Tongji University, Fab-Union & Archi-Union	121m^2; 6 m in height	Extrusion type; KUKA robotic arm	Plastic
2018	Hebei	Windsor Castle	Whole building	HuaShang LuHai	600m^2	/; Gantry system	Reinforced concrete
2018	Guangdong	Power distribution room	Whole Structure	China Southern Power Grid	/	/	Concrete
2018	Guizhou	Villa	Light steel keel structure	Guizhou Xinli Technology Co., Ltd	150m^2	/	Steel
2018	Hangzhou	Pavilion	Separated components	AZL Architects	/	/	Plastic
2018	Shanghai	Bridge	Whole Building	Shanghai Construction Group (SCG)	15.25 in length; 3.8 in width; 1.2 m in height	Extrusion type; Gantry system	Resin and fiberglass
2018	Sichuan	"Yaomingge" house	Separated components	The Hong Kong Polytechnic University, Winsun & Ya'an Polytechnic College	10m2	/	Steel bar, cement, bamboo fibre, steel slag
2019	Guangdong	2 storey office	Whole building	China State Construction Engineering Corporation & China Construction Second Engineering Bureau LTD	230m2; 7.2 m in height	Contour Crafting	Concrete
2019	Shanghai	Concrete bridge	Whole Building	Tsinghua University	26.3 in length; 3.6 in width	Extrusion type; Robotic arm	Concrete
2018	Hangzhou	Pavilion	Separated components	AZL Architects	/	/	Plastic
2018	Shanghai	Bridge	Whole Building	Shanghai Construction Group (SCG)	15.25 in length; 3.8 in width; 1.2 m in height	Extrusion type; Gantry system	Resin and fiberglass
2018	Hangzhou	Pavilion	Separated components	AZL Architects	/	/	Plastic
2018	Shanghai	Bridge	Whole Building	Shanghai Construction Group (SCG)	15.25 in length; 3.8 in width; 1.2 m in height	Extrusion type; Gantry system	Resin and fiberglass
2018	Sichuan	"Yaomingge" house	Separated components	The Hong Kong Polytechnic University, Winsun & Ya'an Polytechnic College	10m^2	/	Steel bar, cement, bamboo fibre, steel slag
2019	Guangdong	2 storey office	Whole building	China State Construction Engineering Corporation & China Construction Second Engineering Bureau LTD	230m^2; 7.2 m in height	Contour Crafting	Concrete
2019	Shanghai	Concrete bridge	Whole Building	Tsinghua University	26.3 in length; 3.6 in width	Extrusion type; Robotic arm	Concrete

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Year	Location	Project Name	Printing Product	Project Team	Size	Type & Equipment	Material
2019	Suzhou	River revetment wall	Whole Building	WinSun company	432 in length; 1.5 m in height	/	Concrete
2019	Quanzhou	Bridge	Whole Building	Shanghai Construction Group (SCG)	17.5 in length; 3.2 in width; 3.2 m in height	Extrusion type; Gantry system	Acrylonitrile Styrene Acrylate (ASA) and fibreglass
2019	Tianjin	Zhaozhou Bridge	Separated components	Hebei University of Technology	28.10 in length; 4.20 in width	/	Concrete
2020	Henan	Bridge	Separated components	Xingtai Road and Bridge Construction Group Co., Ltd	19.5 in length	/	Concrete, glass fibre
2020	Nanjing	Pavilion	Façade	Archi-Union Architects & Fab Union	1352m^2; 30 m in height	/	Plastic
2021	Shanghai	Book Cabin	Whole Building	Tsinghua University	30m^2	Extrusion type; Robotic arm	Concrete
2021	Shanghai	Retractable Bridge	Panel	BLUE Architects	9.34 m in length; 1.5 m in width; 1.1 m in height	Fused deposition modelling (FDM); Gantry system	Polyester Carbonate
2021	Shenzhen	Park	Landscape element	Tsinghua University & AICT	/	Extrusion type; Six-axis robotic arm-based system	Concrete
2021	Hebei	Residential House	Separated components	Tsinghua University	106m^2	Extrusion type; Robotic arm	Concrete
2021	Chengdu	Bridge	Whole Building	Shanghai Construction Group (SCG)	21.6 in length; 8 in width; 2.7 m in height	Extrusion type; Gantry system	Acrylonitrile Styrene Acrylate (ASA) and fibreglass
2021	Shanghai	Memorial Object (landscape element)	Separated components	Wutopia Lab & Roboticplus.ai	9m^2; 7 m in height	/; Robotic arm	Acrylonitrile butadiene styrene
2021	Shanghai	Retractable Bridge	Panel	BLUE Architects	9.34 m in length; 1.5 m in width; 1.1 m in height	Fused deposition modelling (FDM); Gantry system	Polyester Carbonate
2021	Shenzhen	Park	Landscape element	Tsinghua University & AICT	/	Extrusion type; Six-axis robotic arm-based system	Concrete
2021	Hebei	Residential House	Separated components	Tsinghua University	106m2	Extrusion type; Robotic arm	Concrete
2021	Chengdu	Bridge	Whole Building	Shanghai Construction Group (SCG)	21.6 in length; 8 in width; 2.7 m in height	Extrusion type; Gantry system	Acrylonitrile Styrene Acrylate (ASA) and fibreglass
2021	Shanghai	Memorial Object (landscape element)	Separated components	Wutopia Lab & Roboticplus.ai	9m2; 7 m in height	/; Robotic arm	Acrylonitrile butadiene styrene
2022	Shanghai	Two storey building	Whole building	Shanghai Construction Group (SCG)	52.8m2; 6 m in height	/	Concrete, Solid waste materials

References

Alghamdi, S.S., John, S., Choudhury, N.R., Dutta, N.K., 2021. Additive manufacturing of polymer materials: progress, promise and challenges. Polymers 13 (5), 753. https://doi.org/10.3390/POLYM13050753, 2021, Vol. 13, Page 753.

Alhumayani, H., Gomaa, M., Soebarto, V., Jabi, W., 2020. Environmental assessment of large-scale 3D printing in construction: a comparative study between cob and concrete. J. Clean. Prod. 270, 122463 https://doi.org/10.1016/J.JCLEPRO.2020.122463.

Ali, M.H., Issayev, G., Shehab, E., Sarfraz, S., 2022. A critical review of 3D printing and digital manufacturing in construction engineering. Rapid Prototyp. J. 28 (7), 1312–1324. https://doi.org/10.1108/RPJ-07-2021-0160/FULL/XML.

Anjum, T., Dongre, P., Misbah, F., Nanyam, V.P.S.N., 2017. Purview of 3DP in the Indian built environment sector. Procedia Eng. 196, 228–235. https://doi.org/10.1016/J.PROENG.2017.07.194.

Aslam, M.S., Huang, B., Cui, L., 2020. Review of construction and demolition waste management in China and USA. J. Environ. Manag. 264, 110445 https://doi.org/10.1016/J.JENVMAN.2020.110445.

Besklubova, S., Miroslaw, Skibniewski, J., Asce, M., Zhang, X., 2021. Factors affecting 3D printing technology adaptation in construction. J. Construct. Eng. Manag. 147 (5), 04021026 https://doi.org/10.1061/(ASCE)CO.1943-7862.0002034.

Boom, S., Weijschede, J., Melissen, F., Koens, K., Mayer, I., 2020. Identifying stakeholder perspectives and worldviews on sustainable urban tourism development using a Q-sort methodology 24 (4), 520–535. https://doi.org/10.1080/13683500.2020.1722076. *Https://Doi.Org/10.1080/13683500.2020.1722076*.

Buchanan, C., Gardner, L., 2019. Metal 3D printing in construction: a review of methods, research, applications, opportunities and challenges. Eng. Struct. 180, 332–348. https://doi.org/10.1016/J.ENGSTRUCT.2018.11.045.

Chan, S.S.L., Pennings, R.M., Edwards, L., Franks, G.V., 2020. 3D printing of clay for decorative architectural applications: effect of solids volume fraction on rheology and printability. Addit. Manuf. 35, 101335 https://doi.org/10.1016/J.ADDMA.2020.101335.

Chang, R., Antwi-Afari, M.F., 2023. Critical success factors for implementing 3D printing technology in construction projects: academics and construction practitioners' perspectives. Construct. Innovat. https://doi.org/10.1108/CI-04-2023-0060/FULL/XML. *ahead-of-print*(ahead-of-print).

Chang, R., Cao, Y., Lu, Y., Shabunko, V., 2019. Should BIPV technologies be empowered by innovation policy mix to facilitate energy transitions? - revealing stakeholders' different perspectives using Q methodology. Energy Pol. 129, 307–318. https://doi.org/10.1016/J.ENPOL.2019.02.047.

China Construction Technology Centre, 2017. *3D Printing System Introduction*. China Construction Co., Ltd. https://www.cic.hk/cic_data/files/CITAC/Exhibit/Stage%201/2D%20Printed%20Wall/3D%20printing%20information.pdf

Craveiro, F., Duarte, J.P., Bartolo, H., Bartolo, P.J., 2019. Additive manufacturing as an enabling technology for digital construction: A perspective on Construction 4 (0). https://doi.org/10.1016/j.autcon.2019.03.011.

Duncan Millar, J., Mason, H., Kidd, L., 2022. What is Q methodology? Evid. Base Nurs. 25 (3), 77–78. https://doi.org/10.1136/EBNURS-2022-103568.

El-Sayegh, S., Romdhane, L., Manjikian, S., 2020. A critical review of 3D printing in construction: benefits, challenges, and risks. Arch. Civ. Mech. Eng. 20 (2), 1–25. https://doi.org/10.1007/S43452-020-00038-W, 2020 20:2.

Feng, P., Meng, X., Zhang, H., 2015. Mechanical behavior of FRP sheets reinforced 3D elements printed with cementitious materials. Compos. Struct. 134, 331–342. https://doi.org/10.1016/J.COMPSTRUCT.2015.08.079.

Flanagan, K., Uyarra, E., Laranja, M., 2011. Reconceptualising the 'policy mix' for innovation. Res. Pol. 40 (5), 702–713. https://doi.org/10.1016/J.RESPOL.2011.02.005.

Forcael, E., Ferrari, I., Opazo-Vega, A., Pulido-Arcas, J.A., 2020. Construction 4.0: a literature review. Sustainability 12 (22), 9755. https://doi.org/10.3390/SU12229755, 2020, Vol. 12, *Page 9755*.

Furet, B., Poullain, P., Garnier, S., 2019. 3D printing for construction based on a complex wall of polymer-foam and concrete. Addit. Manuf. 28, 58–64. https://doi.org/10.1016/J.ADDMA.2019.04.002.

Gan, X., Zuo, J., Ye, K., Skitmore, M., Xiong, B., 2015. Why sustainable construction? Why not? An owner's perspective. Habitat Int. 47, 61–68. https://doi.org/10.1016/J.HABITATINT.2015.01.005.

Gardiner, J.B., Janssen, S.R., 2014. FreeFab. *Robotic Fabrication In Architecture*, Art and Design, pp. 131–146. https://doi.org/10.1007/978-3-319-04663-1_9, 2014.

Guerra, B.C., Bakchan, A., Leite, F., Faust, K.M., 2019. BIM-based automated construction waste estimation algorithms: the case of concrete and drywall waste streams. Waste Manag. 87, 825–832. https://doi.org/10.1016/J.WASMAN.2019.03.010.

Hao, P., Guo, J.P., Chen, Y., Xie, B.C., 2020. Does a combined strategy outperform independent policies? Impact of incentive policies on renewable power generation. Omega 97, 102100. https://doi.org/10.1016/J.OMEGA.2019.08.007.

He, Y., Zhang, Y., Zhang, C., Zhou, H., 2020. Energy-saving potential of 3D printed concrete building with integrated living wall. Energy Build. 222, 110110 https://doi.org/10.1016/J.ENBUILD.2020.110110.

Holt, C., Edwards, L., Keyte, L., Moghaddam, F., Townsend, B., 2019. Construction 3D printing. 3D Concrete Printing Technology 349–370. https://doi.org/10.1016/B978-0-12-815481-6.00017-8.

HSLH (Beijing HuaShang LuHai Technology Co., Ltd), 2014. Construction 3D Printing Equipment. http://en.bj-hslh.com/intro/2.html.

Kanyilmaz, A., Demir, A.G., Chierici, M., Berto, F., Gardner, L., Kandukuri, S.Y., Razavi, N., 2022. Role of metal 3D printing to increase quality and resource-efficiency in the construction sector. Addit. Manuf. 50, 102541.

Kern, F., Rogge, K.S., Howlett, M., 2019. Policy mixes for sustainability transitions: New approaches and insights through bridging innovation and policy studies. Res. Pol. 48 (10), 103832.

Kivimaa, P., Kern, F., 2016. Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions. Res. Pol. 45 (1), 205–217. https://doi.org/10.1016/J.RESPOL.2015.09.008.

Kothman, I., Faber, N., 2016. How 3D printing technology changes the rules of the game Insights from the construction sector. J. Manuf. Technol. Manag. 27 (7), 932–943. https://doi.org/10.1108/JMTM-01-2016-0010/FULL/XML.

Kwan, F., Wong, W., Chiang, Y.-H., Funmilayo, Abidoye, A., Liang, S., 2019. Interrelation between human factor–related accidents and work patterns in construction industry. J. Construct. Eng. Manag. 145 (5), 04019021 https://doi.org/10.1061/(ASCE)CO.1943-7862.0001642.

Labonnote, N., Rønnquist, A., Manum, B., Rüther, P., 2016. Additive construction: state-of-the-art, challenges and opportunities. Autom. ConStruct. 72, 347–366. https://doi.org/10.1016/J.AUTCON.2016.08.026.

Li, X., Yang, D., Yuan, J., Donkers, A., Liu, X., 2022. BIM-enabled semantic web for automated safety checks in subway construction. Autom. ConStruct. 141, 104454 https://doi.org/10.1016/J.AUTCON.2022.104454.

Li, X., Yuan, J., Liu, X., Wang, G., Wang, Q.C., 2023. The effects of joint-contract functions on PPP project value creation: a mediation model. Eng. Construct. Architect. Manag. https://doi.org/10.1108/ECAM-10-2022-0949/FULL/XML. *ahead-of-print*(ahead-of-print).

Lowke, D., Dini, E., Perrot, A., Weger, D., Gehlen, C., Dillenburger, B., 2018. Particle-bed 3D printing in concrete construction – possibilities and challenges. Cement Concr. Res. 112, 50–65. https://doi.org/10.1016/J.CEMCONRES.2018.05.018.

Ministry of Industry and Information Technology, 2013. The Special Action Plan for Deep Integration Between Information Technology and Industrialization (2013-2018) (in Chinese). http://www.gov.cn/zwgk/2013-09/05/content_2481860.htm.

Ministry of Industry and Information Technology, 2015. National Development and Reform Commission & Ministry Of Finance *The Plan for the Development and Promotion of the National Additive Manufacturing Industry (2015-2016) (in Chinese)*. http://www.bpea.net.cn/filespath/1425347164.pdf.

Ministry of Education, Ministry of Industry and Information Technology & National Development and Reform Commission, 2017. The Plan of Action for Accelerating and Promoting Industry Development of Additive Manufacture (2017-2020) (in Chinese). http://new.tzxm.gov.cn/zckd/fgzh/201901/t20190117_1261898.shtml.

Ministry of Industry and Information Technology, 2017. *The Action Plan for Remanufacturing of High-end Intelligent (2018-2019) (in Chinese)*. https://rd.nimte.ac.cn/uploadfiles/site4/202001/20200109144058-3226573394.pdf.

Ministry of Finance, Ministry of Industry and Information Technology & National Development and Reform Commission, 2018. Adjusting the Relevant Catalogues of the Import Tax Policies for Crucial High-Tech Equipment, as Amended 2018 (in Chinese). http://www.chinatax.gov.cn/chinatax/n810341/n810765/n3359382/201811/c4065246/content.html.

Ministry of Housing and Urban-Rural Development, 2016. The Outline for development of Informationizion in Construction Industry (2016-2020) (in Chinese). http://www.scio.gov.cn/32344/32345/33969/35217/xgzc35223/Document/1492868/1492868.htm.

Ministry of Industry and Information Technology & Standardization Administration, 2021. The guidance of Building the Standard System of national Smart manufacturing (in Chinese). http://www.gov.cn/zhengce/zhengceku/2021-12/09/5659548/files/e0a926f4bc584e1d801f1f24ea0d624e.pdf.

Ministry of Science and Technology, 2022. National Key R&D Program application guidelines for Advanced Structures and Composites (in Chinese). https://service.most.gov.cn/kjjh_tztg_all/20220427/4894.html.

Ministry of Finance & Ministry of Industry and Information Technology, 2016. The Smart Manufacturing Development Plan (2016-2020) (in Chinese). http://www.gov.cn/xinwen/2016-12/08/content_5145162.htm.

Ministry of Industry and Information Technology & Standardization Administration, 2018. The guidance of Building the Standard System of national Smart manufacturing (2018) (in Chinese). https://wap.miit.gov.cn/cms_files/filemanager/oldfile/miit/n973401/n4965332/n5136200/c6437915/part/6489131.pdf.

National Intellectual Property Administration, 2018. The Catalogue of Industries under Key Support of Intellectual Property Rights (in Chinese). http://www.gov.cn/xinwen/2017-11/11/content_5238913.htm.

Pan, Y., Zhang, Y., Zhang, D., Song, Y., 2021. 3D printing in construction: state of the art and applications. Int. J. Adv. Manuf. Technol. 115 (5–6), 1329–1348. https://doi.org/10.1007/S00170-021-07213-0/FIGURES/10.

Pons-Valladares, O., Casanovas-Rubio, M. del M., Armengou, J., de la Fuente, A., 2023. Approach for sustainability assessment for footbridge construction technologies: application to the first world D-shape 3D-Printed fiber-reinforced mortar footbridge in Madrid. J. Clean. Prod. 394, 136369 https://doi.org/10.1016/J.JCLEPRO.2023.136369.

Rogge, K.S., Reichardt, K., 2016. Policy mixes for sustainability transitions: an extended concept and framework for analysis. Res. Pol. 45 (8), 1620–1635. https://doi.org/10.1016/J.RESPOL.2016.04.004.

Sandanayake, M., Luo, W., Zhang, G., 2019. Direct and indirect impact assessment in off-site construction—a case study in China. Sustain. Cities Soc. 48, 101520 https://doi.org/10.1016/J.SCS.2019.101520.

Sepasgozar, S.M.E., Shi, A., Yang, L., Shirowzhan, S., Edwards, D.J., 2020. Additive manufacturing applications for industry 4.0: a systematic critical review. Buildings 10 (12), 231. https://doi.org/10.3390/BUILDINGS10120231, 2020, Vol. 10, *Page 231*.

Siddika, A., Mamun, M. A. Al, Ferdous, W., Saha, A.K., Alyousef, R., 2019. 3D-printed concrete: applications, performance, and challenges 9 (3), 127–164. https://doi.org/10.1080/21650373.2019.1705199. *Https://Doi.Org/10.1080/21650373*.2019.1705199.

Sneegas, G., Beckner, S., Brannstrom, C., Jepson, W., Lee, K., Seghezzo, L., 2021. Using Q-methodology in environmental sustainability research: a bibliometric analysis and systematic review. Ecol. Econ. 180, 106864 https://doi.org/10.1016/J.ECOLECON.2020.106864.

State Council of China, 2015a. Made in China (2025) (in Chinese). http://www.gov.cn/zhengce/content/2015-05/19/content_9784.htm.

State Council of China, 2015b. Opinions of the State Council on Several Policies and Measures for Vigorously Advancing the Popular Entrepreneurship and Innovation (in Chinese). https://www.lawinfochina.com/display.aspx?id=19250&lib=law&SearchKeyword=&SearchCKeyword=%b4%f3%c1%a6%cd%c6%bd%f8%b4%f3%d6%da%b4%b4%d2%b5.

State Council of China, 2016. The Development Plan of National Strategic Emerging Industries (2016-2020) (in Chinese). http://www.gov.cn/zhengce/content/2016-12/19/content_5150090.htm.

Standardisation Administration, Ministry of Industry and Information Technology, Ministry of Science and Technology, Ministry of Education, National Medical Product Administration & Academy of Engineering, 2020. The Action Plan for Piloting Standard of Additive Manufacture (in Chinese). http://www.sac.gov.cn/sxxgk/zcwj/202101/P020210122408566474790.pdf.

State Administration for Market Regulation, National Development and Reform Commission, Ministry of Finance, Ministry of Industry and Information Technology, Ministry of Finance, Ministry pf Ecology and Environment … Ministry of Science and Techonology, 2018. Opinions of Eight Departments Including the State Administration for Market Regulation on Implementing the Enterprise Standards 'Front-Runner' System (in Chinese). https://cms.qybzlp.com/u/cms/www/202007/14102601yez0.pdf.

State Administration of Market Regulation, 2022. Implementation of Enterprise Standards 'Leader' in Key Areas (in Chinese). http://amr.sz.gov.cn/xxgk/qt/ztlm/dzszbz/bzzx/content/post_9865326.html.

Tiryaki, M.E., Zhang, X., Pham, Q.C., 2019. Printing-while-moving: a new paradigm for large-scale robotic 3D Printing. IEEE International Conference on Intelligent Robots and Systems 2286–2291. https://doi.org/10.1109/IROS40897.2019.8967524.

Tuvayanond, W., Prasittisopin, L., 2023. Design for manufacture and assembly of digital fabrication and additive manufacturing in construction: a review. Buildings 13 (2), 429. https://doi.org/10.3390/BUILDINGS13020429, 2023, Vol. 13, *Page 429*.

Wang, Q., Zhang, S., Wei, D., Ding, Z., 2018. Additive manufacturing: a revolutionized power for construction industrialization. ICCREM 2018: Innovative Technology and Intelligent Construction - Proceedings of the International Conference on Construction and Real Estate Management 2018, 85–94. https://doi.org/10.1061/9780784481721.010.

Webler, T., Danielson, S., Tuler, S., Stern, P.C., Dietz, T., Fischbach, S., Kalof, L., Shockey, I., 2009. Using Q Method to Reveal Social Perspectives in Environmental Research Board of Directors. http://www.seri-us.org/sites/default/files/Qprimer.pdfwww.seri-us.org.

Wu, P., Zhao, X., Baller, J.H., Wang, X., 2018. Developing a conceptual framework to improve the implementation of 3D printing technology in the construction industry 61 (3), 133–142. https://doi.org/10.1080/00038628.2018.1450727. Https://Doi.Org/10.1080/00038628.2018.1450727.

Wu, X., Forbes, K., 2022. Multilingual identity in schools: a Q methodological study with Chinese LOTE-as-L3 learners in international and public high school contexts. J. Lang. Ident. Educ. https://doi.org/10.1080/15348458.2022.2134138/SUPPL_FILE/HLIE_A_2134138_SM4860.DOCX.

Xu, Q., Hwang, B.G., Choo, R.Q., Zheng, X., Kong, L., Wang, Q.C., Liu, X., 2023. Comparison of construction project risks before and during COVID-19 in Singapore: criticality and management strategies. Construct. Manag. Econ. 41 (10), 875–891. https://doi.org/10.1080/01446193.2023.2211179.

Zhang, M., Liu, X., Ding, Y., 2021. Assessing the influence of urban transportation infrastructure construction on haze pollution in China: a case study of Beijing-Tianjin-Hebei region. Environ. Impact Assess. Rev. 87, 106547 https://doi.org/10.1016/J.EIAR.2020.106547.

Zhang, J., Wang, J., Dong, S., Yu, X., Han, B., 2019. A review of the current progress and application of 3D printed concrete. Compos. Appl. Sci. Manuf. 125, 105533 https://doi.org/10.1016/J.COMPOSITESA.2019.105533.

Zabala, A., 2014. qmethod: A package to explore human perspectives using Q methodology. The R Journal 6 (2), 163–173.

Zhang, X., Li, M., Lim, J.H., Weng, Y., Tay, Y.W.D., Pham, H., Pham, Q.C., 2018. Large-scale 3D printing by a team of mobile robots. Autom. ConStruct. 95, 98–106. https://doi.org/10.1016/J.AUTCON.2018.08.004.