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Exploring the challenges of implementing design for excellence in industrialized construction projects in China

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ABSTRACT

It is recognized that design for excellence (DfX) methods could deliver significant performance improvements in industrialized construction (IC) projects. However, DfX methods in IC projects in China have been stifled, and existing solutions have failed to deliver expected outcomes. This study investigated the significance of thirty-one challenges of implementing DfX methods in IC projects in China using a questionnaire survey of domain practitioners and academics. Statistical analysis showed that all the challenges were perceived as significant. The top five significant challenges are linked to limited systematic rules, required additional commitment, code compliance complexities, higher design costs, and requirements for continuous design performance evaluation. The study established four principal constraints: limited knowledge and organizational readiness, unsupportive entrenched industry practices, increased organizational financial burden, and deficits in bespoke technical requirements. Therefore, the study offers a fresh insight into the challenges of implementing DfX methods in IC projects in China. It provides supporting evidence for developing countermeasures to improve the wider implementation of DfX in IC projects. The investigated challenges contribute to the theoretical checklist of constraints to implementing DfX methods in IC projects and may form a useful basis for future research.

Keywords: barriers; challenges; constraints; design for excellence; industrialized construction

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Introduction

Industrialized construction (IC) is a modern construction method that re-engineers and adapts the traditional construction approach through incorporating manufacturing principles, innovative processes, and smart technologies in the design, factory production, transportation, and assembly of components and structures (Bertram et al., 2019). It includes all levels of prefabrication, modular construction, offsite manufacturing, standardization, mechanization, and automation. IC projects are often designed based on manufacturing principles, whereby value-added structural components of a building are manufactured in a controlled factory environment and then transported in sections to a site for assembly and installation (Goodier et al., 2019). Using IC in a project generate benefits such as reduced construction time, improved quality control, improved safety of workers, enhanced labour productivity, and reduced environmental impacts (Blismas, Pasquire, & Gibb, 2006; Kamali & Hewage, 2017). With a manifesto to improve construction performance, the last few decades witnessed the epic rise of IC in many countries, including China (Wuni & Shen, 2020).

Under the backdrop of the New Urbanization Policy 2014 – 2020 and China's 14th Five-Year Plan (2021-2025), the Chinese government is promoting IC in new construction projects to improve the construction industry's labour productivity and competitiveness (Jiang, Mao, Hou, Wu, & Tan, 2017). However, China's implemented IC projects have not consistently and successfully delivered their manifestos, especially the cost savings (Mao et al., 2016). Though several reasons hinder realizing the maximum benefits of IC, a consistent villain in IC projects' failure is ineffectively regulating and controlling performance at the earliest phase of the project lifecycle (Sutrisna & Goulding, 2019). It is recognized that the full benefits of IC in construction projects cannot be realized unless it is combined with integrated production design best practices (KPMG, 2016).

The IC design is a strategic phase to improve performance because it embodies the project's objectives and constitutes the earliest stage where performance requirements can be controlled in the project lifecycle (Bogue, 2012; Boothroyd, 2005). The design stage can proactively identify and resolve costly downstream delivery challenges and constraints (KPMG, 2016). Considering IC is not appropriate for every project blueprint, the design stage must explicitly consider the use of IC to realize its full benefits (Blismas, Pendlebury, Gibb, & Pasquire, 2005). Additionally, design decisions have cascading implications on the overall project performance and typically controls the total project costs (Bogue, 2012).

However, despite building information modelling, design issues persist in IC projects in China and have rendered desirable design optimization an extended reality. Hence, there remains a gap between the theory and practice of IC project design optimization. Typically, the IC design problems are wicked ones with many interdependencies, making them obscure to resolve and control. Consequently, IC industry practitioners and researchers have turned to the manufacturing industry as a point of reference and a potential source of innovation to overcome the challenges associated with IC project design optimization (Fox, Marsh, & Cockerham, 2001). A concept known as design for Excellence (DfX) has become a focal point of research as a strategic path to radically improve design optimization and IC project performances in China (Chen & Lu, 2018). As a collaborative design philosophy and methodology, DfX denotes a suite of goal-specific methods, guidelines, and standards for regulating and controlling project performance outcomes at the design phase (Becker & Wits, 2013).

DfX methods have leveraged radical product performance improvements in the manufacturing industry, with many promises for the construction industry. It has been recognized that adapting and applying DfX methods in IC projects could resolve the design optimization issues and leverage radical performance improvements (Fox et al., 2001). Despite

the long-standing recognition, implementation of DfX methods in IC projects in China has been constrained, and prevailing DfX solutions failed to deliver fully desired outcomes (Chen & Lu, 2018). Yet, there is a dearth of knowledge regarding the challenges and constraints of implementing DfX methods in IC projects. This study aims to address the gap through empirical evaluation of the challenges of implementing DfX methods in IC projects. The objectives include: (1) to identify principal challenges to implementing DfX in IC projects and (2) to propose recommendations for addressing the challenges to implementing DfX in IC projects in China.

Conceptual and theoretical background

Overview of DfX

The DfX concept originated from the manufacturing industry (Huang, 1996; Kuo, Huang, & Zhang, 2001). It emerged when Ford and Chrysler employed design for manufacture and assembly (DfMA) principles in their weapon production process during World War II (Boothroyd, 1994). DfMA is a compound design methodology comprising design for manufacture (DfM) and design for assembly (DfA). It is an integrated design process that provides a methodology to specify rules and parameters in product design to ease downstream manufacture and efficient assembly of parts (Lu et al., 2020). It provides a proactive methodology for evaluating the IC project design to ensure that production engineers can economically manufacture significant design elements in a factory environment and efficiently assemble the components onsite (Tan et al., 2020). DfMA simplifies the product, minimizes parts, determines the cost impact of materials and processes, and derives the most efficient use of the component design (Bogue, 2012).

Although DfX is well-developed in the manufacturing industry, it constitutes an emerging design concept in the construction industry with antecedents, including DfMA, buildability, lean construction, value engineering, and lifecycle costing. Though with slightly different

objectives, these antecedents, including DfMA, focused on using the design to control and improve product performance but commonly considered production efficiency (Lu et al., 2020). However, the rapidly changing regulatory and client requirements imposed the need to consider multiple goals, including reduced life cycle environmental impact and costs through innovation in the product design (Kuo et al., 2001). These multiple design requirements hatched the concept of DfX, a more holistic design process capable of explicitly considering and incorporating wide-ranging performance issues and requirements in the optimal design solution (Huang, 1996). DfX has various definitions in the manufacturing and construction literature. It has been defined as a concurrent engineering design technique (Huang, 1996), value engineering process (Bogue, 2012), lifecycle design methodology (Becker & Wits, 2013), integrated design methodology and philosophy (Gao, Jin, & Lu, 2019), and systematic design strategy (Lu et al., 2020). The varied definitions reflect not only a lack of consensus, but an implicit indication that DfX is a higher-order design concept encompassing the five different perspectives.

This paper treats DfX as an integrated design methodology that provides a more holistic approach to IC project design that considers lifecycle performance. Specifically, DfX is a proactive purpose-driven design methodology, leveraging rules, standards, and guidelines to control and improve specific aspects of project performance requirements during the design stage. It is a cohesive goal-oriented design process that provides a standard philosophy, methods, and tools to optimize the design (Kuo et al., 2001). DfX serves as a placeholder for different design objectives and performance aspects (Becker & Wits, 2013). Strictly, the DfX concept is better understood as design for "X," where the variable X denotes several areas of design focus and interchangeable with one of many values depending on the design's objectives. The variable X may denote excellence in any aspect of the project design goal, including manufacturability (i.e., fabrication-aware design),, assemblability, productivity,

cost, sustainability, flexibility, maintainability, and circularity (Lu et al., 2020). Examples of DfX methods for IC projects include design for: technical merit, productivity, health and safety (i.e., Prevention-through-design), resilience, lean construction, circular economy, climate change, adaptability, flexibility, reconfiguration, deconstruction, procurement, and supply chain. These concepts embody specific design objectives and performance aspects of IC projects.

It shows wide-ranging goal-specific design solutions for IC projects, focusing on meeting a unique design requirement. However, the DfX methods for IC projects are not often standardized and sometimes even contradict rules, leading to an increase in organizational entropy in DfX processes (Becker & Wits, 2013). DfX constitutes a more holistic design process than DfMA, modularity, and modularization. At the very least, DfX for IC projects must incorporate DfMA to facilitate the factory production and onsite assembly of components, primarily differentiating IC projects from the site-built projects. The most widely implemented DfX methods for IC projects in China include DfMA, design for quality, design for lifecycle, and design for circular economy (Tan et al., 2020). A detailed description of the DfX methods is beyond this paper's scope and can be found elsewhere (Huang, 1996; Kuo et al., 2001).

DfX requires and enables key project partners to work together to examine, identify, and resolve downstream issues early in the design phase to control project performance (Becker & Wits, 2013). Thus, it allows a multidisciplinary team of designers, production engineers, suppliers, clients, and contractors to explicitly consider regulatory requirements, downstream constraints, and negotiate trade-offs in stakeholder expectations during the design phase. This design process and strategy allows the DfX team to control and regulate IC project lifecycle performance at the earliest stage of the delivery chain, even before the detailed design and models hit the production line (Lu et al., 2020).

Similarities and differences between DfX IC and manufacturing

Using advanced factory production methods from automotive manufacturing in IC projects demonstrates cross-industry breeding, learning, and transfer of expertise, principles, and management between IC and manufacturing (Gann, 1996). Thus, there are similarities between the two. First, both manufacturing and IC products are designed to support downstream manufacture and assembly. Consequently, they have similar supply, value, and delivery chains, especially design, manufacture, and assembly, albeit with different configurations. Typically, automotive and IC project components are manufactured in a controlled factory environment and operate based on a common principle of making a product or project development process more controllable to regulate the finished product's performance (Tan et al., 2020). Thus, both IC and manufacturing provide a streamlined approach to product development and offer tighter quality and managerial control opportunities than conventional construction. Second, leveraging repetitive design and mass production principles, an increase in the volume of units in IC and manufacturing results in economies of scale, as the production cost per unit reduces more quickly (Gann, 1996). Third, manufacturing and IC achieve a trade-off between standardization and flexibility of products using standard sub-assemblies and 'platform' design approaches along with computerized component optimization techniques (Gann, 1996).

Though the similarities between automotive manufacturing and IC provide an unprecedented opportunity for DfX in construction, there are considerable differences between the two's production processes and end products. As such, transplanting DfX principles from manufacturing to IC first demands understanding the distinctions between the industries. First, automotive products are wholly manufactured, assembled, and completed in assembly lines at factories, whereas IC projects are partly completed offsite and installed onsite (Gann, 1996). Significant components of IC projects can be manufactured in the factory, but a considerable portion of the assembly work must be completed onsite (Tan et al., 2020). Relative to typical

manufacturing products, IC projects are larger and usually immobile. The size and fixity of IC projects demand that they are assembled at a consumption point, unlike their counterparts in manufacturing that can be wholly transported to the market (Gann, 1996). Second, IC projects have longer production cycles than typical automotive products. The relatively longer production cycles in IC projects generate several contingencies and risks, which are more challenging to plan, control, and manage proactively (Gao, Low, & Nair, 2018). Similarly, IC projects are designed for much longer service life, durability, and delivered at a higher cost than typically manufactured goods. The durability and longer economic lifecycle of IC projects introduce greater degrees of uncertainties, problems, and challenges in testing new materials, components, and production techniques (Gann, 1996).

Third, automotive manufacturing typically constitutes a product-based activity leveraging standardized workflows. In contrast, the site-specific and project-based nature of IC projects present intractable challenges in utilizing standardized routines and workflow of other successful projects (Koskela & Ballard, 2003). With rare exceptions, IC projects involve highly localized activities under the influence of local geographic, economic, social, and climatic constraints (Tan et al., 2020). Fourth, the standardized design of automotive components facilitates mass production, whereas the site-specific, client-driven nature of the IC project imposes customized design (Tan et al., 2020). Automotive products are manufactured without a specific customer, but most IC projects are client-driven and highly individualized. Automotive manufacturing employs standardized design rules and detailed interface specifications to make products that meet the needs of many undesignated end-users, but with rare exceptions, IC projects only start after the contractor has a client in the market. Realistically, standardized functional design of IC solutions cannot satisfy the varied and highly individualized needs of construction clients. Fifth, automotive products are relatively less complex, enabling a higher degree of standardizing interchangeable parts, whereas IC

projects have a higher degree of complexity in the number and range of parts. IC projects are more complex, involving several component parts, assortment of different interconnections between components, and varying degrees of uniqueness in the final product, limiting standardization and use of mechanized production techniques (Fox et al., 2001; Gann, 1996). The enormously varied client specifications, larger construction materials, greater number of parts, and wider range of permutations in IC projects limit standardization.

Theoretical checklist of constraints to implementing DfX in IC projects

As in any evolving research area in construction management, a few studies have emerged attempting to unravel the challenges of implementing various DfX methods in IC projects in different countries, summarised in Table 1.

The most cited challenge of implementing DfX methods in IC projects is limited relevant knowledge and practical experience. An early empirical study in the UK found that limited knowledge of DfM inhibited its implementation in construction projects (Fox et al., 2001). Findings of more recent studies suggest that this challenge persists and impedes the implementation of DfX methods. For instance, Gao et al. (2018) found that limited practical knowledge inhibits the DfMA adoption in IC projects in Singapore. Similarly, the limited technical skills, capabilities, knowledge, and practical experiences of designers stifle the implementation of prevention through design (PtD) principles in IC projects in Palestine (Abueisheh, Manu, Mahamadu, & Cheung, 2020) and Malaysia (Che Ibrahim, Belayutham, Manu, & Mahamadu, 2020). Effectively, insufficient hands-on training and re-training for designers, including architects and engineers, inhibit DfX methods' application in IC projects (Lu et al., 2020).

Typically, design for maintainability (DfMt) requires designers to have a good knowledge of maintainability problems during the service life of IC projects and criteria for selecting appropriate materials (Zhu, Shan, & Hwang, 2018). Designers also require knowledge and

understanding of site conditions, construction methods, and management issues to effectively implement PtD in IC projects (Abueisheh et al., 2020). DfX methods require the design team members to share advanced technical know-how to consider heavy equipment, assembly works, and interface tolerances in the design (Peltokorpi, Olivieri, Granja, & Seppänen, 2018; Tan et al., 2020). However, veteran architects have limited capabilities to manage module configuration processes and interfaces among subsystems in DfMA (Bogue, 2012). The limited knowledge and experience of designers exposes them to technical vulnerabilities when implementing DfX methods in IC projects. Designers face difficulties in deploying appropriate DfX tools and methods in each phase to manage client expectations and specifications in the design effectively (Gosling, Pero, Schoenwitz, Towill, & Cigolini, 2016). It further triggers the inability to freeze design early to deliver the full manifestos of DfX methods in IC projects (Gao et al., 2019).

Table 1. Potential challenges and constraints of implementing DfX in IC projects

Code	Challenges	Representative Source
C1	Lack of systematic rules, codes, and standards for DfX methods	Abueisheh et al. (2020)
C2	Specialized labour requirement	Bogue (2012)
C3	Few market options available	Bogue (2012)
C4	Need to evaluate performance at every design stage	Gosling et al. (2016)
C5	Customer rejection due to poor image of IC	Gao et al. (2018)
C6	Definition of standard details and connections	Gao et al. (2018)
C7	Lack of competition among IC solutions	Bogue (2012)
C8	Lack of innovativeness as product architecture is locked	Gao et al. (2018)
C9	Management of interfaces with subsystems	Peltokorpi et al. (2018)
C10	Management of assembly works and interface tolerances	Bogue (2012)
C11	Learning diminishes performance in the first few installations	Peltokorpi et al. (2018)
C12	Requirement for early commitment and communication among diverse stakeholders	Zhu et al. (2018)
C13	Need for additional project planning and design efforts	Peltokorpi et al. (2018)
C14	Necessity of first-run prototypes	Gosling et al. (2016)
C15	Requires both trade and location-based division of procurement	Che Ibrahim et al. (2020)
C16	Management of customer expectation in design	Gosling et al. (2016)
C17	Complex code compliance and inspection process	Abueisheh et al. (2020)
C18	Increased organizational requirements and investment	Abueisheh et al. (2020)
C19	Higher design costs than the traditional engineering design	Lu et al. (2020)
C20	Conflicting cultures between project deliveries and the engineering design of IC solutions	Peltokorpi et al. (2018)
C21	Difficulty in identifying appropriate tools and methods in each phase of the DfX process	Bogue (2012)
C22	Lack of coordination between phases and contractors	Peltokorpi et al. (2018)
C23	Lack of capabilities to manage the module configuration process	Bogue (2012)

C24	Inability to exercise early design freeze	Gao et al. (2019)
C25	Lack of awareness of DfX benefits among owners/developers	Fox et al. (2001)
C26	Limited DfX knowledge and experiences	Fox et al. (2001)
C27	High criticality of the know-how that must be shared with other stakeholders	Tan et al. (2020)
C28	Lack of trust and collaboration between buyers and their suppliers	Tan et al. (2020)
C29	Lack of coordination and collaboration between stakeholders	Gosling et al. (2016)
C30	High frequency of radical innovation	Tan et al. (2020)
C31	Scarce availability of resources for component development	Tan et al. (2020)

The second most cited challenge is the poor collaboration culture in the construction industry (Che Ibrahim et al., 2020; Gao et al., 2019; Zhu et al., 2018). DfX methods require early involvement of relevant players, collaborative working, and information sharing. These render integrated procurement methods appropriate for their application in IC projects. However, fewer procurement systems and project delivery methods provide the needed collaborative working environment. Based on several case studies, Gosling, Pero, Schoenwitz, Towill, & Cigolini (2016) found that poor collaboration between stakeholders significantly inhibited design innovation for IC projects. A review reinforced the fact that limited collaboration between designers and maintenance teams during design inhibits the application of DfMt (Zhu et al., 2018). Non-involvement of facility managers during the design stage in design-bid-build projects was found to inhibit effective application of DfMt (Zhu et al., 2018). The non-involvement of manufacturers early enough in design also inhibits effective DfMA in IC projects (Lu et al., 2020). The unsupportive procurement systems and project delivery methods effectively generate fragmentation of design responsibilities (Zhu et al., 2018).

Another highly cited challenge is the lack of a suitable ecosystem of codes, standards, guidelines, and technologies for DfX methods. For example, limited industry codes and guidelines inhibit the application of design for safety (DfS) principles in IC projects in Palestine (Abueisheh et al., 2020). Similarly, insufficient codes, regulations, tools, and guidelines are constraints to implementing PtD principles in IC projects in Malaysia (Che Ibrahim et al., 2020). Likewise, Lu et al. (2020) also discussed inadequate standards, guidelines, and

affordable technologies as constraints to the wider adoption of DfMA in IC projects. In addition, the general lack of legislative frameworks of bespoke codes and standards (Abueisheh et al., 2020) invoke poverty of systematic definition of design details and metrics (Gao et al., 2018), inhibiting the development of DfX best practices (Abueisheh et al., 2020; Zhu et al., 2018). Collectively, these constraints lead to a lack of shared understanding of relevant DfX principles among relevant project participants (Fox et al., 2001).

Some studies also cited higher design costs as a constraint to implementing DfX methods in IC projects (Abueisheh et al., 2020; Peltokorpi et al., 2018). Relative to traditional design practices, DfX methods require additional organizational investment and commitment due to the need for specialized labour and technical skills (Bogue, 2012; Lu et al., 2020). In addition, applying DfX methods in IC projects demand performance evaluation at every stage of the design and first-run prototypes (Gosling et al., 2016). DfX methods are also associated with complex code compliance (Abueisheh et al., 2020). The attendant higher initial capital costs and increased design effort constitute disincentives to implementing DfX methods in IC projects (Lu et al., 2020). Closely associated with the cost challenge relates to the undeveloped market for DfX methods. Studies suggest few market options available and limited competition among DfX solutions for IC projects (Bogue, 2012; Peltokorpi et al., 2018). A more recent study in Singapore established that DfX methods are unattractive to clients due to the entrenched poor image of IC inherited from the hastily implemented post-war prefabricated buildings (Gao et al., 2018).

The preceding review suggests that previous studies have recognized and implicitly documented some constraints to implementing DfX methods in IC projects, evident in older and more recent studies, suggesting that several challenges persist. However, none of these studies empirically evaluated the relative significance of the constraints in a specific context. Additionally, the constraints are scattered across the literature, depriving relevant stakeholders

of a holistic perspective of the challenges. This study has organized the constraints into a holistic framework through this review, providing a basis for empirically evaluating and ranking their relative significance in a specific context such as China.

Research methods

Data collection and presentation

Following the literature review, a questionnaire was designed to evaluate the relative significance of the challenges in the context of China. The content and structure of the questionnaire were modified following both expert review and pilot study with three industry experts in China with relevant knowledge and experiences. The final questionnaire was sent by email to 300 IC practitioners and academics (excluding students) in China with relevant knowledge and experiences. The respondents were recruited using the purposive and snowballing sampling techniques. Respondents were invited to complete the survey at their earliest convenience and forward it to other suitable respondents interested in contributing to the research. The questionnaire collected the background information of the respondents and their assessment of the challenges using a five-point rating scale comprising 1 (very insignificant) and 5 (very significant). Following weekly email reminders to respondents, 229 valid responses were received.

The demographic breakdown of the respondents was as follows. Regarding sector of work, 104 (45.41%) worked in academia, and 125 (54.59%) were industry practitioners. Two-hundred and fifteen had less than 5 years, ten had 6 – 10 years, and four had 11 – 15 years of relevant experience in IC projects that implemented DfX solutions. Most of the respondents had limited years of experience in IC projects that incorporated DfX methods, which could be because both DfX and IC were not formally promoted until their incorporation in China's 2014-2020 New Urbanization Policy. Nevertheless, they had significant construction industry experience. The respondents had been involved in several IC project types that implemented

DfX methods. These projects included house/real estate (58.08%), schools/education (34.50%), transportation (17.03%), commercial/office (13.97%), health/hospital (10.92%), industrial (6.99%), energy/power (5.68%), prisons/defence (3.49%), and water/wastewater treatment systems (3.06%). Hence, diverse views from varied IC project types were captured in the assessment of the challenges.

Statistical data analyses

The collected data was coded, managed, and analysed using the Statistical Package for the Social Sciences (IBM SPSS v.25). All statistical tests were conducted at a 95% confidence interval (i.e., $\alpha = 0.05$). The study conducted the Shapiro-Wilk test to check the normality of the data (Chou, Polansky, & Mason, 1998). The results showed that the data was non-normally distributed, imposing the use of non-parametric statistical tests. Consequently, the Mann-Whitney U test was conducted to ascertain whether there were significant differences in the opinions of the two groups (i.e., academics & practitioners) based on their professional backgrounds. Mean scoring and factor analysis were used to analyse the data. The study investigated the suitability of the data for exploratory factor analysis (EFA) using several indicators. Table 2 summarizes the results of these statistical indicators, including the minimum acceptable threshold for each.

Table 2. Test statistics for verifying the suitability of the dataset for exploratory factor analysis

Test statistic		Data results	Acceptable range
Factor to sample size ratio		1:7	≥ 1: 5
Cronbach's Alpha		0.973	0.70 – 1.0
Anti-image correlation (coefficient) matrix		> 0.50	> 0.5
Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.962	0.8 – 1.0
Bartlett's Test of Sphericity	Approx. Chi-Square	5528	N/A
	df	465	N/A
	Sig.	0.000	< 0.05

The factor (challenge) to sample size ratio of 1:7 (31/229) exceeded the minimum acceptable ratio of 1: 5 (Lingard & Rowlinson, 2006). The Cronbach's Alpha value of 0.973 surpassed the

minimum acceptable value of 0.7 (Tavakol & Dennick, 2011). The Kaiser-Meyer-Olkin test statistic of 0.962 exceeded the minimum value of 0.8 (Pett, Lackey, & Sullivan, 2003), corroborating the adequacy of the sample size for EFA. Bartlett's Test of Sphericity, with a Pearson Chi-Square, $\chi^2 = 3590.1$, and $p < 0.000$ showed that the correlation matrix of the challenges was significantly different from an identity matrix. The anti-image correlation coefficients between the challenges exceeded the 0.5 minimum threshold. The pre-testing outcomes demonstrated that the data was suitable for EFA. The EFA employed principal component analysis as the extraction method and varimax with Kaiser Normalization as the rotation method. The rotation converged in 8 iterations and generated a 4-factor solution with eigenvalues greater than 1.0 and explaining about 62.87% of the challenges' variance.

Results

Significant challenges of implementing DfX in IC projects

Table 3 presents the outcomes of the test of distribution and agreement among the responses. The p-values of the Shapiro-Wilk test are less than 0.05 for the investigated challenges, indicating that the ratings of the significance levels of the 31 challenges are non-normally distributed. The p-values of the Mann-Whitney U test are all higher than 0.05, indicating no statistically significant differences were perceived by the respondents based on their professional backgrounds. The outcome provided statistical legitimacy to treat the data holistically for further analysis. Table 3 also summarizes the mean scores and rankings of the 31 challenges of implementing DfX methods in IC projects in China. Each challenge obtained a mean score higher than 3.6 on the 5-point rating scale, indicating that the respondents assessed all challenges as significant. When two challenges scored the same mean significance index, the one with the lowest standard deviation is ordered higher. Table 3 indicates that C1, C13, C17, C19, C4, and C25 constitute the six most significant challenges to implementing

DfX methods in IC projects in China. Due to space restrictions, only these top six challenges are described.

Table 3. Mean significance indices of the challenges to implementing DfX in IC projects

Code	Challenge	S-W test	M-W test	Mean (μ)	SD	Rank
C1	Lack of systematic rules, codes, and standards for DfX methods	0.000**	0.977	4.10	0.87	1
C13	Need for additional project planning and design efforts	0.000**	0.897	4.09	0.91	2
C17	Complex code compliance and inspection process	0.000**	0.545	4.02	0.82	3
C19	Higher design costs than the traditional engineering design	0.000**	0.171	4.00	0.85	4
C4	Need to evaluate performance at every design stage	0.000**	0.335	4.00	0.90	4
C25	Lack of awareness of DfX benefits among owners/developers	0.000**	0.544	3.97	0.90	6
C14	Necessity of first-run prototypes	0.000**	0.912	3.95	0.87	7
C18	Increased organizational requirements and investment	0.000**	0.503	3.94	0.82	8
C2	Specialized labour requirement	0.000**	0.631	3.94	0.90	8
C22	Lack of coordination between phases and/or contractors	0.000**	0.961	3.94	0.90	8
C9	Management of interfaces with subsystems	0.000**	0.247	3.94	0.93	8
C16	Management of customer expectation in design	0.000**	0.274	3.93	0.85	12
C29	Lack of coordination and collaboration between stakeholders	0.000**	0.551	3.92	0.86	13
C10	Management of assembly works and interface tolerances	0.000**	0.17	3.90	0.87	14
C12	Requirement for early commitment and communication among diverse stakeholders	0.000**	0.388	3.87	0.92	15
C15	Requires both trade and location-based division of procurement	0.000**	0.364	3.87	0.91	15
C23	Lack of capabilities to manage the module configuration process	0.000**	0.553	3.86	0.86	17
C26	Limited DfX knowledge and experiences	0.000**	0.306	3.86	0.89	17
C3	Few market options available	0.000**	0.743	3.86	0.86	17
C5	Customer rejection due to poor image of IC	0.000**	0.071	3.86	0.87	17
C21	Difficulty in identifying appropriate tools and methods in each phase of the DfX process	0.000**	0.128	3.85	0.81	21
C28	Lack of trust and collaboration between buyers and their suppliers	0.000**	0.444	3.85	0.85	21
C30	High frequency of radical innovation	0.000**	0.965	3.85	0.87	21
C31	Scarce availability of resources for component development	0.000**	0.877	3.85	0.86	21
C27	High criticality of the know-how that must be shared with other stakeholders	0.000**	0.237	3.83	0.94	25
C24	Inability to exercise early design freeze	0.000**	0.725	3.82	0.90	26
C6	Definition of standard details and connections	0.000**	0.24	3.79	0.92	27

C20	Conflicting cultures between project deliveries and the engineering design of IC solutions	0.000**	0.835	3.78	0.92	28
C8	Lack of innovativeness as product architecture is locked	0.000**	0.086	3.78	0.97	28
C7	Lack of competition among IC solutions	0.000**	0.366	3.76	0.92	30
C11	Learning diminishes performance in the first few installations	0.000**	0.221	3.66	1.01	31

Legend: S-W t = Shapiro-Wilk test, M-W t = Mann-Whitney test, ** The Shapiro-Wilk test was significant at a 0.05 significance level.

With the highest assessment of 4.10, C1 "lack of systematic rules, codes, and standards for DfX methods" was rated the most significant challenge of implementing DfX methods in IC projects in China. Systematic design rules and protocols rather than generic guidelines formed the basis on which DfX methods leveraged radical performance improvements in the manufacturing industry. Though generic design guidelines or qualitative procedures can simplify the individual parts, they result in product complexity, low product quality, and expensive design arising from extensive overhead due to large inventory, increased suppliers, and greater record-keeping requirements (Boothroyd, 1994). Currently, the Chinese IC industry continue to rely on generic guidelines from manufacturing, resulting in lack a suitable bespoke ecosystem of systematic design improvement rules, metrics, and technologies governing the application of DfX methods in IC projects (Lu et al., 2020).

C13 "need for additional project planning and design efforts", with a mean index of 4.09 was rated as the second major constraint to implementing DfX methods in IC projects. The reactive nature of traditional construction design practices encourages downstream resolution of design errors , but DfX proactively seeks to address downstream issues, risks, requirements, and challenges early upfront at the design stage (Becker & Wits, 2013). Hence, it requires collaborative front-end planning and design, translating into significant additional effort. The extra effort translates into additional design costs, but the cost of more comprehensive design efforts can be compensated by reduced downstream costs (Wübbenhorst, 1986).

C17 "complex code compliance and inspection process", with a mean significance index of 4.02, was assessed as the third most significant challenge to implementing DfX methods in IC projects in China. Codes, standards, metrics, and parameters for DfX methods are relatively systemic because they embody a lifecycle design thinking philosophy (Kuo et al., 2001). At the learning curve's current stage, IC industry practitioners in China find compliance and adherence to these guidelines complicated. However, future systematic DfX rules could minimize this constraint due to the increasing simplification and standardization of IC project design improvement rules and evaluation metrics (Gbadamosi et al., 2019).

C19 "higher design costs than the traditional engineering design", with a mean significance index of 4.0 and standard deviation of 0.848, was assessed as the fourth most significant challenge. Relative to traditional construction design practice, the higher initial capital cost of deploying DfX methods makes them less competitive. Currently, implementing DfX methods in IC projects requires bespoke organizational investment in specialist design teams, capabilities improvement, additional planning, and design information generation (Bogue, 2012; Fox et al., 2001). These requirements increase design costs in DfX methods. Yet, investment in innovative and disruptive technologies by construction companies in China is still largely profit-driven (Luo, Mao, Shen, & Li, 2015). Hence, the additional cost of implementing DfX methods serves as a significant disincentive to its wider application. The perceived higher design costs of DfX methods reflect the limited application of lifecycle costing (LCC) that trades the cost of more comprehensive design efforts for significant reduction in downstream costs (Wübbenhorst, 1986).

C4 "need to evaluate performance at every design stage", with a mean significance index of 4.0 and standard deviation of 0.896, was rated as the fifth most significant constraint to implementing DfX methods in IC projects in China. Every stage of the design in the DfX methods is evaluated based on predefined criteria and metrics to incorporate the right dose of

each design rule and parameter (Becker & Wits, 2013). However, the performance evaluation at every stage requires bespoke expertise and additional time to execute, translating into marginal IC project design tasks, costs, and times.

C25 "lack of awareness of DfX benefits among owners/developers" with a mean significance index of 3.97, was rated as the sixth most significant challenge to implementing DfX methods in IC projects in China. Implementing DfX methods in IC projects is a quintessential example of innovation diffusion. Hence, widespread recognition and implementation would be influenced by the perception of whether the DfX methods offer improved performance improvements, utility, and profit over the traditional design practices (Wuni & Shen, 2020). Currently, DfX methods are considered relatively expensive to implement, hinting a limited understanding of its lifecycle benefits since optimal DfX solution can control and reduce overall development costs of construction (Gao et al., 2018). The limited awareness of DfX business value among IC project stakeholders renders conventional design practices relatively more attractive under a profitability lens. It appears that the IC industry's dilemma over the worth, or otherwise, of DfX and accompanying demands such as standardization and customization is creating a smoke screen that makes accurate evaluation of business benefits difficult to achieve (Gibb, 2001). Thus, domain researchers must credibly demonstrate the competitive business benefits of DfX to encourage widespread adoption in IC projects (Blismas et al., 2006).

Principal challenges of implementing DfX in IC projects

Table 4 summarizes the factor loadings, eigenvalues, and explained variances of the challenges and four principal challenges (PC) of implementing DfX methods in IC projects in China. These PCs include PC1 "limited knowledge and organizational readiness", PC2 "unsupportive entrenched industry practices", PC3 "increased organizational financial burden", and PC4

"deficits in bespoke technical requirements". These labels were considered the best descriptors of the different challenges within each factor grouping. The PCs are described next.

Table 4. Factor loadings and Eigenvalues of the principal benefits of DFX in IC projects

Code	Challenge(C)/ PC	Factor Loading	Eigen value	% of variance explained	Cumulative % of variance explained
PC1	**Limited knowledge and organizational readiness**		**7.259**	**23.42**	**23.42**
C11	Learning diminishes performance in the first few installations	0.772			
C23	Lack of capabilities to manage the module configuration process	0.771			
C26	Limited DfX knowledge and experiences	0.719			
C25	Lack of awareness of DfX benefits among owners/developers	0.707			
C1	Lack of systematic rules, codes, and standards for DfX methods	0.690			
C24	Inability to exercise early design freeze	0.668			
C8	Lack of innovativeness as product architecture is locked	0.635			
C21	Difficulty in identifying appropriate tools and methods in each phase of the DfX process	0.505			
PC2	**Unsupportive entrenched industry practices**		**6.615**	**21.34**	**44.76**
C5	Lack of competition among IC solutions	0.685			
C5	Customer rejection due to poor image of modular solutions	0.665			
C28	Lack of trust and collaboration between buyers and their suppliers	0.651			
C22	Lack of coordination between phases and/or contractors	0.623			
C29	Lack of coordination and collaboration between stakeholders	0.606			
C3	Few market options available	0.586			
C20	Conflicting cultures between project deliveries and the engineering design of IC solutions	0.564			
C16	Management of customer expectation in design	0.548			
C12	Requirement for early commitment and communication among diverse stakeholders	0.485			
C30	High frequency of radical innovation	0.467			
PC3	**Increased organizational financial burden**		**3.828**	**12.35**	**57.11**
C4	Need to evaluate performance at every design stage	0.796			
C14	Necessity of first-run prototypes	0.628			
C13	Need for additional project planning and design efforts	0.628			
C17	Complex code compliance and inspection process	0.610			
C18	Increased organizational requirements and investment	0.604			
C15	Requires both trade and location-based division of procurement	0.587			
C19	Higher design costs than the traditional engineering design	0.550			

C31	Scarce availability of resources for component development	0.490			
PC4	**Deficits in bespoke technical requirements**		**1.787**	**5.76**	**62.87**
C27	High criticality of the know-how that must be shared with other stakeholders	0.695			
C10	Management of assembly works and interface tolerances	0.681			
C9	Management of interfaces with subsystems	0.637			
C2	Specialized labour requirement	0.517			
C6	Definition of standard details and connection	0.497			

PC1 "limited knowledge and organizational readiness" obtained the highest eigenvalue of 7.259, explaining about 23.42% of the total variance in the EFA. PC1 contains eight challenges associated with poor understanding of DfX, skills gap, and uninformed perceptions about the DfX methods. Effectively applying DfX methods require a good technical knowledge of computational and optimization techniques (Boothroyd, 1994). For instance, to implement DfA, it is essential for the designers to be equipped with the technical knowledge of how to simplify the project structure, reduce the number of parts without compromising quality and functionality, and computational techniques to estimate the cost of the elements at the early design phase (Boothroyd, 1994). But, such detailed technical knowledge in the Chinese IC industry is not well-developed, with few engineers having a detailed knowledge of all the different DfX processes, materials, and technologies. These few knowledgeable designers usually develop rarely optimized solutions based on typical design protocols, and problems frequently arise when iterations are made to the fabrication process, the assembly method, or altered materials (Bogue, 2012).

Additionally, designers in the manufacturing industry have been able to integrate production best practices into their designs because production experts have developed bespoke proprietary DfX methods and made them available to design engineers (Fox et al., 2001). These methodologies consist of systematic standard design improvement rules and evaluation metrics (ibid). However, their counterparts in the Chinese IC industry have not been provided with equivalent systematic methodologies. Hence, the integration of production best practices into

IC project designs often hinges on designers' varying experiences of traditional design practices. Consequently, the limitations and lapses of architects in traditional design practices, such as specifying inappropriate materials and limited knowledge of buildability issues (Fox et al., 2001) stifle the effective DfX implementation in IC projects in China. Similarly, some Chinese IC designers have limited knowledge of the DfX evaluation process because most architects and engineers lack knowledge of the exact number of optimum parts, assembly order, how components are supposed to be assembled, and how long an onsite operation takes. Collectively, these limited capabilities of veteran designers inhibit realization of the full benefits of DfX methods in IC projects in China (Chen & Lu, 2018).

Also, the inability to freeze design early limits the full benefits of DfX methods in IC projects because the design decisions have cascading implications on the procurement system, offsite fabrication, and details of IC (Blismas et al., 2005). Design freeze enables the design team to complete the IC project specifications and restricts design variations to commence factory production of modules. However, this is usually difficult to achieve because it requires a detailed understanding of the client's specifications and communication of such modalities to all relevant project partners to ensure design compliance. Yet, designers must get the design right early on to minimize the risk of design change orders because flexibility quickly diminishes as the IC project design progresses and the opportunity for design changes are usually limited because such alterations become economically prohibitive.

PC2 "unsupportive entrenched industry practices", with an eigenvalue of 6.615, explains about 21.34% of the total variance in the EFA. PC2 describes ten challenges related to entrenched unfavourable cultures, conditions, practices, and attitudes in the construction industry stifling DfX diffusion in China. DfX methods require collaboration and information sharing between designers, manufacturers, contractors, owners, and external stakeholders to coordinate and optimize design early (Gao et al., 2019). Usually, design consultants, suppliers,

and subcontractors need to collaborate at the conceptual design stage to leverage standard workshop guidelines to optimize and integrate the cost and performance of appropriate materials, products, and services to maximize clients' benefits (Fox et al., 2001). DfX also requires collaborative effort to review the product design and leverage feedback for improved design optimization. However, only few IC procurement modes permit these project participants to meet during the early stages of the design process (Fox et al., 2001). It is obscure to achieve full collaboration between some relevant project partners because of the potential 'turf war' between manufacturers, designers, and defence contractors who may not constitute a design-build team. Usually, the designers have no full knowledge of the manufacturers to produce the IC components from their detailed design. Similarly, defence contractors do not have the typical incentives to minimize the final project cost through optimized lifecycle design (Wübbenhorst, 1986). These varied value systems, motives, and goals discourages early commitment and collaboration among project partners. However, innovations such as integrated digital delivery offers digital collaborative platforms to integrate these stakeholders during project design.

Moreover, due to limited knowledge and understanding, some Chinese industry practitioners argue that DfX leads to projects that are more difficult to service (Chen & Lu, 2018). This assertion may reflects a misunderstanding of some underlying principles because it has been demonstrated that projects designed based on DfX methods (e.g., DfMA) are usually easier to deconstruct and reconfigure (Boothroyd, 1994). Hence, it is imperative to consider DfMA carefully and rigorously during the design stage of projects that may require continual service involving the removal of inspection covers and the replacement of various components. Additionally, there is still an on-going concern that both DfX methods and IC limit designers' flexibility and creativity, which is further corroborated by the limited portfolio of standardized design options available in the market (Wuni & Shen, 2020). The prevailing unresolved conflict

between IC design standardization and flexibility frequently result in design impotence (Gibb, 2001). Another unsupportive industry practice is the 'wait and see' attitude of some Chinese practitioners. Risk-averse IC organizations often choose to wait and see whether the giant competitors implementing DfX methods can deliver actual benefits before investing. Even though some large IC companies have already commenced DfX implementation in existing IC projects in China (Chen & Lu, 2018), others will wait until the technology matures before they invest. This attitude of organization inhibits the wider application of DfX methods in IC projects in China.

PC3 "increased organizational financial burden", with an eigenvalue of 3.828, explains about 12.35% of the total variance of the EFA. PC3 describes a host of challenges related to concerns and realities that implementing DfX methods in IC projects comes at additional effort, commitment, resources, and costs compared with traditional design practices. Historically, cost intensity is reported as one of the greatest disincentives that stifle the widespread adoption of DfX methods in construction (Gao et al., 2019). Though DfX methods provide opportunities to deliver lifecycle cost savings in IC projects, they engender higher initial design costs because of the extra upfront planning, commitment, and investment required to identify opportunities to optimize the design stage (Bogue, 2012).

PC4 "deficits in bespoke technical requirements", with an eigenvalue of 1.787, explains about 5.76% of the total variance in the EFA. PC4 contains challenges associated with the bespoke technical expertise and requirements of DfX method in IC projects. DfX methods contest the traditional project design hierarchy and reorder the implementation sequence of other valuable manufacturing tools. Hence, there is a need for specialist designers who are technically knowledgeable in DfX solutions, design improvement rules, evaluation metrics, and optimization tools to deliver maximum value-for-money (Lu et al., 2020). Typically, there is a requirement for the early use of manufacturing analysis, LCC, and application of

computational tools to quantify costs at the early stages of the IC project design (Bogue, 2012). Relevant results of such early analyses must be shared with the design team to enable the designers to receive rapid feedback on their design decisions' consequences at the conceptual stage where changes in the decisions count. Given the shortage of DfX specialist designers in China, the bespoke technical requirements of DfX methods stifles their rapid diffusion. Also, though standardized design improvement rules and evaluation metrics are the core principles of DfX methods (Fox et al., 2001), a third layer and perhaps the most essential principle of standardization is the interface between the systemic components, rather than the elements themselves (Gibb, 2001). An intentional and conscious commitment are required to ensure that interface or connections design ensure interchangeability and fit (ibid). As part of modularization, design engineers often manage and reduce complexity in IC through using abstraction to hide the complexity of the components and interfaces to specify how the component interconnect in the building system. Once the components and interfaces are standardized, it becomes simpler to attach one part to another to improve efficiency in the components' onsite assembly (Gao et al., 2018). Effectively, DfX methods require a paradigm shift from traditional linear design to dynamic lifecycle-based design thinking. However, veteran designers may find it obscure to adjust to new processes. As the transition demands acceptance of manufacturing and assembly inputs into the design, they could be perceived as trespassing their responsibilities.

Discussion and implications

This study has demonstrated that multifaceted challenges stifle DfX application in IC projects in China. Consistent with existing studies (Gao et al., 2019; Tan et al., 2020; Zhu et al., 2018), the study found that the persistent issue of insufficient collaboration, coordination, and trust among relevant stakeholders in the IC industry constitutes a major challenge. As an integrated design process, Zhu et al. (2018) corroborated that the collaboration problem suffocates and

threatens DfX because it relies on effective communication, information sharing, and coordination among multidisciplinary project participants to deliver value. Unlike automotive manufacturing, relevant and complementary IC project team members (e.g., production engineers, assemblers, designers, contractors) seldom collaborate during project design to generate optimal DfX solutions in IC projects due to some unsupportive modes of procurement (Che Ibrahim et al., 2020). It is usually not mandatory that these project partners are brought together at the conceptual design stage when implementing DfX methods in IC projects, but their collaboration constitutes a best practice in delivering optimal benefits. Given the near-impossibility of collaborative working among some project participants (e.g., design professionals and maintenance team) during the design stage, a plausible solution involves bringing the knowledge of the downstream parties (e.g., facility management team) up to the design stage to break the persistent 'over-the-wall' approach to building design. This knowledge management and sharing approach is widely used in the automotive manufacturing industry (Venables, Barlow, & Gann, 2004).

Currently, the designer-centric practices in China, where architects play leading roles in the design process and without manufacturers' inputs, is problematic. Manufacturers have adequate technical expertise in the production and installation of modules. Hence, the designer-centric approach results in insufficient details in components and interfaces, an unfit split of parts, and complex component design that render reiterative design improvement in the production phase obscure (Lu et al., 2020). Like the automotive manufacturing modes (Venables et al., 2004), it is imperative to promote integrated project delivery methods to enable a multidisciplinary team of design, production, and assembly experts to form a DfX community of practice in China to enhance optimal DfX solutions in IC projects in China. Based on lessons from automotive manufacturing, a useful complementary strategy to improve DfX implementation in IC projects is development of knowledge-based and data-driven decision support systems to guide

decisions throughout the design process (Gann, 1996) instead of the dictated directions of the most forceful project partner.

Moreover, the Chinese IC industry's predominant use of design guidelines constitutes a less desirable practice because they can guide the design team in the wrong direction. For instance, as Fox et al. (2001) and Bogue (2012) noted, DfMA rules attempt to force the designer to engineer shaped parts that are easier to manufacture and meet a performance requirement. However, this can lead to a more complicated project structure that increases total construction costs. Hence, IC designers must fully understand the associated penalties of not adhering to design rules, especially when considering a novel design of components that perform several functions. Additionally, when using the generic guidelines, meaningful design solutions are achieved when the DfX methods are implemented individually but can be easily contradictory if applied together (Tan et al., 2020). Hence, like the practice of automotive design, the IC industry must develop and use systematic DfX procedures that guide the designer to simpler project structures. A practical strategy is for the IC industry to develop and communicate formal DfX reference materials containing systematic design rules, guidelines, procedures, and practices to building designers. Additionally, design engineers should work closely with factory production engineers, suppliers, contractors, and project managers to develop systematic DfX rules and evaluation metrics that can be digitally incorporated into 3D models to provide building designers with powerful information to evaluate design alternatives.

Furthermore, even though there are many similarities between IC and manufacturing, directly transplanting the DfX guidelines from manufacturing to IC constitutes a poor practice because of the subtle differences between the processes and products of the two industries. For instance, as Tan et al. (2020) noted, there is little consideration of downstream logistics and supply chain in DfMA guidelines from the manufacturing industry, which has critical importance in IC projects. Thus, an indiscriminate adaptation of manufacturing design

guidelines to IC projects is a recipe for risks and anomalies. It is laudable that lessons are learned from the manufacturing industry for IC project delivery, but it is also fundamental that houses are not cars (Gibb, 2001). Hence, close comparisons between the two industries must be treated with the greatest caution. With the added DfX, there are blurred differences between industrial production of complete buildings and automotive manufacturing. Existing case studies show that effectively adapting, optimizing, and managing manufacturing-based DfX guidelines and standards in IC projects could overcome some of the pricey unpredictabilities and inefficiencies of traditional design practices (Gbadamosi et al., 2019). However, an obvious shortcoming is that manufacturing DfX guidelines do not consider essential attributes such as site conditions, cultural contexts, the flexibility of building forms, logistics, and supply chain issues in IC projects. Hence, it is imperative for research & development departments of construction organizations to consider localized characteristics and uniqueness of IC projects to develop DfX operational strategies, solutions, frameworks, and guidelines that can link general guidelines with company-specific requirements.

Finally, concerns that DfX solutions are relatively more expensive than traditional design solutions reflect the limited consideration of lifecycle cost performance (Blismas et al., 2006). The practice of prioritizing lower upstream costs when reaching optimal design can lead to expensive mistakes because downstream costs could be significant multipliers of upstream costs (Wübbenhorst, 1986). The damage of incorrect design decisions based on the short-range actions is severe and sometimes cannot be compensated during subsequent phases of the IC project lifecycle. DfX leverages LCC principles to reduce the total IC project costs through reducing downstream costs during the project design and typically makes a trade-off between comprehensive upstream costs (e.g., design cost) and reduced downstream costs (Wübbenhorst, 1986). For instance, it implements specific rules during the design to improve downstream maintainability, such as providing ease, economy, safety, and accuracy in the

performance of maintenance actions during the operations stage. However, reducing downstream recurring costs of IC projects almost automatically increases upstream costs. For instance, enhancing the reliability of IC projects during the design eventually reduces maintenance costs but generates a corresponding increase of upstream costs because increased reliability requires better quality parts, a more sophisticated design, etc. LCC proponent recommends that the trade-off between upstream costs and downstream costs should be practiced if an appropriate reduction of downstream costs compensates for any marginal increase of upstream costs (Wübbenhorst, 1986). However, advances in automotive design optimization have leveraged DfX to optimize both upstream and downstream costs (Gbadamosi et al., 2019; Yuan, Sun, & Wang, 2018). It deploys value analysis to eliminate the non-value adding and over-ambitious design functions or performance characteristics and retains the crucial components, leading to a reduction in both upstream costs and downstream costs without compromising functionality and quality. However, the varied value systems of project participants incubate a significant challenge in optimizing IC project costs during design. For instance, contractors may not have the incentive to leverage higher design costs to reduce downstream costs. Hence, IC clients should insist on lifecycle costing and provide incentive fees, such as using cost-plus contracts to promote LCC thinking during the design (Wübbenhorst, 1986).

Conclusion

This research offers fresh insight and a better understanding of the challenges, constraints, and problems of implementing DfX methods in IC projects. Analysis revealed at least 31 challenges stifling DfX implementation in IC projects in China. The top five were linked to inadequate systematic DfX rules, required additional commitment, code compliance complexities, higher design costs, and requirements for performance evaluation throughout the design. In addition, the study revealed four PCs, including limited knowledge and organizational readiness,

unsupportive entrenched industry practices, increased organizational financial burden, and deficits in bespoke technical requirements. The findings contribute to knowledge, practice, and policy of building design innovation and DfX optimization in IC projects.

A major contribution to knowledge is that the study constitutes the first to empirically evaluate and rank the relative significance of the challenges to implementing DfX methods in IC projects in a specific context. Thus, it addressed the research gap associated with the limited knowledge of the challenges posing the greatest hindrance to DfX implementation in IC projects. Though the study was conducted in the context of China, the findings apply to other countries because some of the challenges relate to the technical aspects of DfX methods and entrenched industry cultural practices, which are largely the same in other countries and regions.

Theoretically, the study's contributions are two folds. It constitutes the first to organize the challenges of implementing DfX methods in IC projects into a holistic framework. It exposed the multifaceted barriers between the manifesto of DfX and its full benefits design optimization in IC projects, redirecting attention to an integrated approach for improving DfX implementation in the construction industry. The identified challenges contribute to the theoretical checklist of constraints to implementing DfX methods in the construction industry and may form a useful basis for future research. Additionally, the study contributes to the ongoing debate surrounding the identity of DfX in the construction industry. It reconsidered the sweeping generalization of the applicability of DfX principles from automotive manufacturing to IC projects in the construction management literature and provided a nuanced description of the similarities and differences between the products and processes of the two industries. It established the practical need to respect the differences and contextualize the similarities between the two industries when adapting automotive manufacturing design guidelines to IC project design.

From a policy perspective, the study redefined the central role of policymakers in the DfX implementation as some major challenges are intertwined with bespoke standards, codes, guidelines, and the absence of a community of practice. The holistic diagnosis of the challenges provides an evidence base to inform policymakers and industry leaders to develop countermeasures and policies to improve the wider and successful implementation of DfX methods in the construction industry, especially IC projects in China. However, there are some limitations. First, the study was specific to China, and the relative importance of the challenges may be significantly different in countries with different or even similar industry climates and socio-cultural milieu. Second, the respondents had fewer years of experience implementing DfX methods in IC projects, and the appropriateness of their evaluation could only be as good as their experiences. Finally, the challenges evaluated in this study may not be exhaustive as the sample size was relatively modest. Hence, additional research is required to explore further the issues coming out of the questionnaire survey. Nevertheless, despite these limitations, it is possible to make some tentative recommendations.

Based on the findings, thirteen recommendations to improve DfX implementation in IC projects are proposed: (1) providing and enhancing DfX training programs, (2) establishing a DfX community of practice, (3) developing suitable ecosystem of systematic DfX codes, rules, guidelines, standards, and affordable technologies, (4) developing DfX legislative framework to codify design policies, regulations, and best practices, (5) developing DfX courses in tertiary institutions, (6) upskilling designers knowledge, capabilities, and skills in both DfX and the IC project delivery process, (7) developing systematic DfX rules and evaluation metrics, which can be digitally incorporated into 3D models to provide building designers with powerful information to assist in evaluating design alternatives, (8) developing DfX decision support systems to guide and automate optimal design decisions, (9) develop methodologies to measure the lifecycle benefits and business value of DfX methods, (10) using integrated procurement

methods and strategies such as design-build and cost-plus contracts in IC project delivery to encourage design innovations, (11) adopting a lifecycle cost criterion for DfX, (12) developing a scoring system for DfX methods, and (13) developing a shared DfX knowledge database to enhance the communication among relevant parties and share the DfX knowledge. These issues can be addressed in future research and be considered by practitioners and policymakers as IC continues to evolve.

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