Benefits evaluation of design for excellence in industrialized construction projects

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Abstract

The leaders of construction innovation in China promote the integration of production best practices such as design for Excellence (DfX) in industrialized construction (IC) projects as a strategic path to leverage radical performance improvements in productivity, cost, quality, circularity, and sustainability. Despite its maturity in the manufacturing industry, the implementation of DfX methods in China's IC projects remains low. One widely cited reason for the sluggish interest is a poor understanding of the holistic business benefits that DfX methods could offer in IC projects. This study identified and evaluated 23 perceived benefits of DfX methods in IC projects in China. Quantitative data was collected using structured questionnaires administered to 229 IC academics and industry practitioners in China. Statistical analysis showed that all the benefits were perceived as significant. Based on mean significance indices, the top five perceived significant benefits include improves component design and production efficiency", "facilitates standardization and customization", "reduces labor requirements and improves productivity", "reduces labor, inventory and development costs", and "reduces material and construction wastes". The study grouped the benefits into 4 clusters, namely improved project design productivity, efficiency and management; shortened design and construction time; lifecycle cost savings; and improved flexibility, adaptability, and circularity. This study constitutes the first holistic evaluation of the benefits of DfX methods in IC projects. The evaluated benefits may serve as a basis for measuring the business benefits to justify investments in DfX in IC projects. The outcome constitutes a starting point for developing evidence based DfX performance measurement metrics, indicators, and tools in the future.

Keywords: benefits; design process; design for excellence; industrialized construction; China

Please Cite As: Wuni, I.Y., Wu, Z., Shen, G.Q.P., Bugri, J. T., and Frimpong-Asante, J. (2021), “Benefits evaluation of design for excellence in industrialized construction projects”. ASCE Journal of Architectural Engineering, Vol. 27, No.4, pp.05021015.

Introduction

The long-standing ills, pervasive market failures, increasing skills shortages, rapidly changing clients' needs, and expanding complexity of construction projects are compelling construction innovations (Farmer 2016). Industrialized construction (IC) is disrupting construction ecosystems and increasingly becoming mainstream in the construction industry. IC re-engineers the traditional construction process and leverages manufacturing principles, where projects are designed to facilitate offsite factory production and onsite assembly of building components (Wuni and Shen 2020a). It moves significant construction activities to a controlled offsite factory environment and reduces the need to work from height, resulting in shortened construction time, improved quality control, minimal site accidents and fatalities, increased labor productivity, and enhanced sustainability (Blismas et al. 2006).

However, it has been recognized that IC alone cannot deliver the documented performance improvements unless it is considered early upfront in the project lifecycle and leverage integrated design processes (KPMG 2016; Wuni and Shen 2020b). The integrated design is required because some of the most difficult downstream delivery challenges, constraints, and problems are usually traced to the quality of the design information and key decisions are the early stages (Sutrisna and Goulding 2019). IC projects are also delivered by multidisciplinary teams and organizations, with the risk of an ephemeral shifting coalition of stakeholders with disparate goals, value systems, and objectives, where adversarial relationships between relevant participants can complicate their collaboration working to deliver optimal design solutions. Integrated project design enables relevant project partners to work together during the design phase to consider lifecycle issues, downstream aspects, regulatory requirements, and trade-offs in stakeholder expectations (Gibb 2001).

The considerable similarities between IC and manufacturing offer unprecedented opportunities for cross-industry learning and technology transfer. Thus, IC Industry practitioners and researchers in China have turned to the manufacturing industry as a reference point and a potential innovation source to address IC project design optimization challenges and requirements. Consequently, an integrated design process, methodology, and philosophy known as design for Excellence (DfX) has emerged as a focal point of IC design research in China. DfX constitutes a suite of goal-specific design methods that enables designers to implement rules to realize specific design goals (Kuo et al. 2001). The DfX concept is better understood as design for 'X,' where the variable X denotes one of many interchangeable design aspects and goals, including productivity, manufacturability, assemblability, maintainability, flexibility, and adaptability. DfX is a matured concept in the manufacturing industries but constitutes an emerging design methodology in the construction industry (Gao et al. 2019; Lu et al. 2020). DfX methods such as design for manufacture and assembly (DfMA) have leveraged radical manufacturing product performance improvements in productivity, cost, development times, and quality (Fox et al. 2001). Similarly, the Chinese IC industry is implementing DfX methodologies to improve IC project performances (Yuan et al. 2018).

Despite the widely documented benefits derived from such a design approach in the manufacturing industry, there is limited application of DfX methods in IC projects in China. A major reason posited for the reluctance among industry practitioners to apply DfX methodologies in IC projects is that they have difficulty ascertaining the benefits that such a design approach would add to a project (Wuni and Shen 2020a). Consequently, IC project business partners have varied perspectives and understanding of the DfX concept (Gao et al. 2019). Some consider the approach a complex engineering design methodology less applicable to IC projects, while others consider DfX methodologies as the panacea to the ills of IC project performances (Tan et al. 2020; Wasim et al. 2020). Though neither of these perceptions is necessarily correct, they indicate some misunderstanding about the benefits of DfX in IC projects. Yet, IC project delivery is nearly impossible without integrating DfX methods such as DfMA (Lu et al. 2020). Thus, this paper aims to identify and evaluate the perceived benefits of DfX in IC projects in China.

Rather than focusing on a DfX method, this paper examines the holistic benefits of the approach because such evaluation outcomes can be used to make a compelling business case for implementing DfX methods in IC projects in China and elsewhere. Exploratory factor analysis is used to classify the benefits, resulting in a conceptual framework against which DfX impacts can be evaluated. The benefits framework can be used as a basis for measuring and monetizing the benefits to justify investments in DfX in IC projects. It may constitute a starting point for developing evidence-based DfX performance measurement metrics, key performance indicators, and tools in the future. The evaluated benefits may provide a valuable basis to promote the value of DfX in the AEC industry.

Theoretical and Conceptual Background

The Concept of DfX

The concept of DfX emerged in the late 1960s and early 1970s in the manufacturing industry, originating from Ford and Chrysler's weapon production processes during World War II (Tan et al. 2020). It is a goal-oriented design approach used by designers in the manufacturing industry to radically improve product performances (Bogue 2012). DfX constitutes integrated design methodology that works on the principles that project objectives can be explicitly designed into the product (Kuo et al. 2001). It employs a standard philosophy, methodologies, and tools to optimize a product design. DfX involves applying design rules, guidelines, processes, and standards to improve specific aspects of product performance (Huang 1996). It explicitly considers and incorporates all design goals, regulatory requirements, and downstream constraints in the early design stage rather than solve them later (Yuan et al. 2018).

Although DfX is a mature design methodology in the manufacturing industry, it constitutes an emerging design process in the construction industry (Gao et al. 2019). The considerable similarities between IC and manufacturing offer unprecedented opportunities for DfX applicability to IC projects (Gbadamosi et al. 2019). In IC projects, DfX entails a broader range of goal-specific design methods that allows the design team to differentiate a project in terms of performance requirements before the working drawings hit the production line. The variable X in DfX denotes several areas and aspects of design optimization in IC projects. DfX methods include design for assembly, design for manufacture, DfMA, design for technical merit, design for lean construction, design for cost, design for health and safety, design for supply chain, design for logistics, design for supply chain design for quality, design for six sigma, design for circularity (design for zero waste, design for adaptive reuse, design for deconstruction), design for robotics, design for sustainability, design for procurement, design for performance, design for productivity, design for reliability, design for resilience, design for flexibility, design for regulatory compliance, design for maintainability, design for volume, design for operability, and design for whole-life (Abueisheh et al. 2020; Huang 1996; Zhu et al. 2018). They are structured into guidelines, checklists, metrics, mathematical models, and overall procedures (Becker and Wits 2013).

The most fundamental DfX method for IC projects is DfMA, a hybrid methodology of design for manufacture (DfM) and design for assembly (DfA). DfMA is a design philosophy and methodology where engineering parameters, rules, and principles are incorporated into the design of a product to ease downstream manufacturing and efficient assembly of components (Gao et al. 2019). DfA analysis estimates the cost of producing a design and offers the basis to eliminate the design aspects that are not indispensable to the product's function. Thus, it streamlines the design, reduces the part count, and simplifies components' interfaces (Banks et al. 2018). Conversely, DfM analysis guides the most economical method of creating each assembly part. It designs to enable specialist subcontractors to manufacture significant elements of the design in a factory environment. DfMA usually starts with DfA to simplify a project's structure, forming the basis for the economic selection of materials and processes and early cost estimates (Boothroyd 1994). The materials and processes selected are usually based on comparing the estimates for original and improved designs, followed by a more thorough analysis of the parts' detailed design through DfM. It is then is assisted with guidelines for standardization, component design, and component assembly to reduce total manufacturing cost (Gao et al. 2019).

The right dose of DfX in IC projects will leverage significant gains in performance, necessitating adherence to standard production design improvement rules and evaluation metrics (Fox et al. 2001). The design rules enable the designers to deliver the design with precision, whereas the metrics allows them to compute and predict the product's performance during the concept design (Baldwin and Clark 2000). These proactive strategies allow informed design changes to be made before they become intractable constraints during the manufacturing phase. The proactive nature imposes the need to engage critical players such as designers, suppliers, and manufacturers at the early stages of the project lifecycle to leverage their inputs to resolve downstream constraints. Design reviews at key stages throughout the design cycle and critical feedback collection are crucial in addressing potential problems before design freeze (Gao et al. 2019).

There are significant differences in nature, structure, and processes between the traditional design practices and DfX. For instance, traditional engineering design is less team-based with less involvement of manufacturers, suppliers, and clients at early design stages. It uses many tools to conduct several iterations of a product and mainly considers the product's functional requirements (Kuo et al. 2001). In contrast, DfX is a proactive team-based goal-driven design methodology that involves more collaboration among manufacturers, suppliers, and clients at the early stages of the design to anticipate downstream constraints and resolve these issues early. The collaborative approach of DfX in IC projects avoids the shortcomings associated with architects in traditional engineering design, such as specifying inappropriate materials, lack of knowledge of basic construction techniques, and poor understanding of buildability (Zhu et al. 2018). DfX also involves the selective use of an efficient set of standardized tools that consider the product lifecycle requirements and aims to get the design right at the first time to limit iterations (Bogue 2012). It also employs a concurrent engineering methodology in project design, allowing different design activities to be executed contemporaneously (Huang 1996).

Benefits of DfX

The potential benefits of DfX methods are commonly cited when justifying investment in a DfX method (s). Yet, a holistic evaluation of the perceived benefits of the approach in IC projects remains deficient. Despite a rapidly growing scholarly research in DfX methods, there is limited explicit empirical evaluation of the benefits of DfX in construction, especially for IC projects. Hence, the benefits of DfX, in general, can hardly be extracted from the existing literature directly**.** However, there is considerable documentation of the benefits of DfX in the manufacturing literature, which is also applicable to IC projects to a certain extent. Thus, this study comprehensively reviewed the benefits of DfX in the manufacturing and construction literature to identify benefits specific to IC projects in China. Literature review shows that several studies have done excellent work in summarizing the benefits of DfX methodologies.

For instance, the development of analytical techniques that were used to guide designers in the USA towards products that are easy to manufacture and assemble translated into a revolution in the manufacturing industry, resulting in reduced product cost, better quality, shorter time to market, lower inventory, and fewer suppliers (Boothroyd 1994). DfMA addresses design inefficiencies, reduces part counts, constructability issues early upfront, and further eliminates waste from the assembly line and wastes that may be designed into the product from the start (Yuan et al. 2018). Fox et al. (2001) conducted an extensive interview-based survey in the UK and found that construction practitioners perceived the benefits of DfX to include shortened lead time, reduced production risks, reduced production times, shorter development times, fewer quality problems, and reduced production costs. Bogue (2012) also identified the benefits of DfX methods, including improved reliability, reduced production costs, reduced purchasing and inventory costs, easier handling and assembly, reduced lead times, simplified repair and maintenance, and reduced waste.

Gao et al. (2019) found the benefits of DfX in building construction to include the fastest path to market leadership, shortened lead time, reduced lifecycle construction costs, minimized construction risks, and higher quality products. Similarly, Lu et al. (2020) discussed DfX benefits in construction, including increased product quality, shorter product development cycles, improved production yields, improved overall operational efficiencies, and enhanced customer satisfaction. Gbadamosi et al. (2019) found that DfMA and BIM optimization minimizes construction waste, program time, and production costs. Tan et al. (2020) concluded that DfMA results in early prevention of defects, continuous, ease of modules assembly, maximized testability, improved production stability and predictability, ease and efficiency of modules production, reduced labor requirements, and reduced engineering resources commitment. Wasim et al. (2020) reported that optimized DfMA based design of prefabricated construction components yields significant time and cost savings, facilitates standardization, reduces complexity, improves labor productivity, reduces resource consumption, improves safety, reduces materials wastage, and reduces carbon footprint. Though the preceding literature synthesis suggests that considerable research investigated the benefits of some DfX methods, none holistically evaluated the perceived benefits of DfX in IC projects in China and elsewhere. Nonetheless, this comprehensive review provides a useful reference for this study to identify the possible benefits of implementing DfX in China's IC projects.

Research Methodology and Data Presentation

The research process in this study was conducted in the following five phases. Phase 1 involved a comprehensive review of the literature to identify the potential benefits of implementing DfX in IC projects. Phase 2 consisted of pilot interviews with industry experts in China to verify the literature review's benefits. Phase 3 involved designing and administering questionnaires to IC academics and industry practitioners in China to measure the perceived significance levels of the verified benefits. Phase 4 involved statistical analyses of the dataset derived from the questionnaire survey. Phase 5 involved developing a conceptual framework of the benefits based on the outcome of factor analysis. These phases are shown in Figure 1 and further described below.

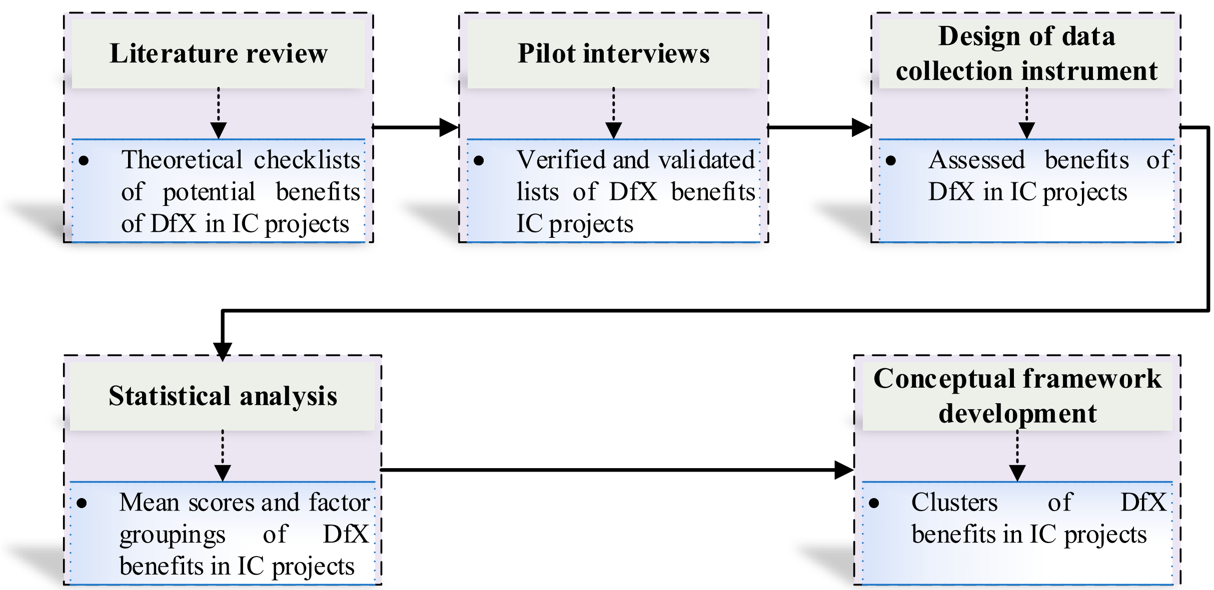

Figure 1. A flowchart of the overall research process

First, the study reviewed relevant literature to identify the potential benefits of implementing DfX methods in IC projects. A synthesis of the benefits documented in prior literature is presented

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in the previous section. A checklist of the 23 potential benefits of implementing DfX methodologies in IC projects was extracted from the literature review. Subsequently, the study conducted pilot interviews with three IC experts in China with practical experiences and theoretical knowledge of DfX methods to verify the recruited benefits. The experts confirmed the relevance and applicability of all the benefits recruited from the literature but suggested modifications which were implemented. Table 1 summarizes the 23 verified potential benefits along with their sources. The verified list of 23 benefits formed the basis for the questionnaire design.

Table 1. Verified potential benefits of DfX in IC projects

Code	Benefit	Source
B1	Efficient management and reduction of complexity	Baldwin and Clark (2000)
B2	Reduces engineering resources commitment	Fox et al. (2001)
B3	Economies of scale in component design and production	Banks et al. (2018)
B4	Increases feasibility of project functional change	Bogue (2012)
B5	Creation of variety and differentiation of final product	Boothroyd (2005)
B6	Improves durability and flexibility in use and maintenance	Zhu et al. (2018)
B7	Reduces product order lead-time	Lu et al. (2020)
B8	Enables decoupling of product design and production tasks	Baldwin and Clark (2000)
B9	Improves component design and production efficiency	Tan et al. (2020)
B10	Eases component verification and testing	Yuan et al. (2018)
B11	Facilitates standardization and customization	Wasim et al. (2020)
B12	Reduces development costs in the long run	Gbadamosi et al. (2019)
B13	Speeds up design turnaround	Gao et al. (2019)
B14	Accommodates future uncertainty and risks of product use	Bogue (2012)
B15	Early prevention of defects and increased project quality	Zhu et al. (2018)
B16	Enables and supports parallel works	Sassanelli et al. (2020)
B17	Efficient client requirement consideration	Peltokorpi et al. (2018)
B18	Reduces material and construction wastes	Vranson (2011)
B19	Steeper learning curve effect	Peltokorpi et al. (2018)
B20	Reduces assembly time	Gao et al. (2019)
B21	Ease of re-working of incorrect assemblies	Lu et al. (2020)
B22	Reduces labor requirements and improves productivity	Yuan et al. (2018)
B23	Reduces labor, inventory, and development costs	Banks et al. (2018)

The study developed a structured questionnaire to gather the opinions of Chinese industry practitioners and academics. The questionnaires consisted of two sections. The first section requested some background information of the respondents, including years of experience in IC projects, sector of work, and the types of IC projects that they have previously worked on. The second section requested the respondents to evaluate the significance of the benefits of implementing DfX methods in IC projects, using a 5-point Likert scale (i.e., 1 = very insignificant, 2 = insignificant, 3 = slightly significant, 4 = significant, and 5 = very significant). Based on the fuzzy linguistic variables assigned to the grades of the 5-point rating scale, the significance of each benefit is described using an interval scale, where a benefit with mean significance index (μ) $\leq$ 1.4, $1.5 \leq \mu \leq 2.4$, $2.5 \leq \mu \leq 3.4$, $3.5 \leq \mu \leq 4.4$, and $\mu \geq 4.5$ are considered "very insignificant", "insignificant", "slightly significant", "significant", and "very significant", respectively.

This study identified emails of IC practitioners and academics in China as potential respondents in the survey. Given the absence of a centralized database of all IC experts in China, it was impractical to employ probabilistic sampling techniques such as random sampling. Thus, the study used expert or purposive and snowball sampling techniques. The authors emailed the questionnaires to 300 IC academics and practitioners for the data collection. The authors also requested the respondents forward the email, including the questionnaires to other experts interested in participating in the research. After several weeks of reminders, a total of 229 valid responses were received and considered adequate for statistical analysis. This overwhelming response rate could be due to the questionnaire's simplicity or because DfX and IC are hot construction issues in China.

Table 3 summarizes relevant background information of IC academics and industry practitioners who participated in the questionnaire survey. It is noteworthy in Table 3 that the respondents worked in both academia and industry. The majority of the respondents worked in the industry and may have a full commitment to real-world IC projects in China. The fair distribution of the respondent panel across academia and industry provided an opportunity to capture both IC academics and industry practitioners' perceptions. This diversity is known to improve the responses' representativeness, quality, and reliability, leading to more reliable findings (Hwang et al. 2018b). As shown in Table 3, the respondents had worked on different types of IC projects that implemented DfX methods. A majority had worked on housing, real estate, schools, education, transportation, commercial, and office projects that incorporated industrialized offsite solutions and DfX methods.

Table 3. Profile of the respondents

Attribute	Sub-attribute	No. of Responses	% of Responses
Sector of Work	Academia	104	45.41
	Industry	125	54.59
	Total	229	100
Years of relevant IC work experiences	Below 5yrs	215	93.89
	6 -10yrs	10	4.37
	11 - 15yrs	4	1.75
	Total	229	100
Project types	Housing/ real estate	133	58.08
	Schools/education	79	34.50
	Transportation (roads, bridges, rails, tunnels, etc.)	39	17.03
	Commercial/Office projects (banks, hotels, castles, headquarters)	32	13.97
	Health/hospital projects	25	10.92
	Industrial Projects	16	6.99
	Energy/ Power projects	13	5.68
	Prisons/ defense	8	3.49
	Water treatment plant/ Sewage projects	7	3.06

This distribution lends further credence to the quality of the dataset because these project types lend themselves to modularization and constitute the project types where industrialized offsite solutions are widely applied worldwide (Wuni and Shen 2019). Though Table 3 shows that the majority of the respondents had limited years of experiences in IC projects that applied DfX methods, it could be explained by the fact that IC was only recently formalized and became a central consideration for construction projects within China's National New Urbanization Plan 2014-2020 (Jiang et al. 2017).

The study then statistically analyzed the questionnaire dataset with the Statistical Package for the Social Sciences (IBM SPSS v.26) through a series of stages. First, the study pretested the dataset for reliability, distribution, and agreement among the responses to guide the selection of suitable analytical techniques. Based on the recommendations of (Norusis 2008), the questionnaire's internal consistency and reliability were tested using Cronbach's Alpha. The analysis generated a very strong Cronbach's Alpha of 0.953, higher than the minimum acceptable value of 0.7 (Tavakol and Dennick 2011). This indicated excellent internal consistency and validity of the responses. Typically, parametric, and non-parametric statistical tests are the two main groups of techniques for analyzing survey-based data, but the suitability of a test depends on the dataset's distribution (Kim 2015). Parametric statistical tests are suitable when the dataset follows a normal distribution, whereas non-parametric statistical test has no such requirement. As Chou et al. (1998) recommended, the study used the Shapiro-Wilk test to verify the normality of the dataset's distribution. It is conducted based on the null hypothesis that the population is normally distributed. Thus, the null hypothesis is rejected when the p-value is less than the chosen significance level (e.g., 0.05 at 95% CI), and a conclusion is made that the tested data are not normally distributed (Chou et al. 1998). The study conducted the Shapiro-Wilk test at a 95% confidence interval (i.e., $\alpha = 0.05$). As shown in the results section, the Shapiro-Wilk test generated p-values less than 0.05 for all benefits. This outcome indicated that responses for all benefits were not normally distributed (Chou et al. 1998), instructing non-parametric statistical tests for further analysis of the dataset.

Considering that respondents from academia and industry responded, it was essential to conduct an inter-group comparison to verify whether there were statistically significant variations in their perceptions, based on the sector of work. Based on the normality test results, two ordinal-based non-parametric statistical techniques - the Kruskal-Wallis test and Mann-Whitney U test are suitable for conducting the inter-group comparison (Norusis 2008). Whiles the Mann-Whitney U test is ideal for checking potential differences between only two groups, the Kruskal-Wallis test is suitable for testing the possible differences among two or more different groups of respondents (Hwang et al. 2018b). Thus, both tests tend to provide the same results when the groups are two, such as the case of the dataset in this study. This study used the Mann-Whitney U test to check whether there are statistically significant differences between academics and industry practitioners' responses.

Subsequently, the statistical arithmetic mean was used to compute each benefit's mean significance index to inform the benefits' overall ranking. Further, the study conducted an exploratory factor analysis to detect the structure and clusters of the benefits. Before the factor analysis, the study tested the suitability of the dataset for factor analysis. The suitability of data for exploratory factor analysis can be verified using test statistics such as internal consistency, benefit/factor to sample size ratio, anti-image correlation matrix, Kaiser-Meyer-Olkin Measure of Sampling Adequacy, and Bartlett's Test of Sphericity (Pett et al. 2003). Results of these test statistics for the dataset are summarized in Table 4 below.

Table 4. Test statistics for verifying the suitability of the dataset for exploratory factor analysis

Test statistic		Study data	Acceptable range	Reference
Benefit to sample size ratio		1:10	≥ 1: 5	(Lingard and Rowlinson 2006)
Cronbach's Alpha		0.953	0.70 – 1.0	(Tavakol and Dennick 2011)
Anti-image correlation (coefficient) matrix		>0.50	>0.5	(Pett et al. 2003)
Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.951	0.8 – 1.0	(Cerny and Kaiser 1977)
Bartlett's Test of Sphericity	Approx. Chi-Square	3590.1	N/A	(Norusis 2008)
	df	253	N/A	
	Sig.	0.000	<0.05 @95% CI	

As shown in Table 4, the benefit/factor to sample size ratio of 1:10 (229/23) exceeded the minimum acceptable ratio of 1: 5 (Lingard and Rowlinson 2006). This condition has proven challenging to satisfy in previous studies (Hwang et al. 2018a; Wuni et al. 2020) and lends further credence to the suitability of the data for factor analysis. The Cronbach's Alpha value of 0.953 was within the acceptable range (Tavakol and Dennick 2011). Similarly, the Kaiser-Meyer-Olkin test statistic of 0.951 exceeded the minimum value of 0.8 (Norusis 2008), indicating the sample size's

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adequacy for factor analysis. Bartlett's Test of Sphericity checks whether the benefits' correlation matrix is significantly different from an identity matrix. A Pearson Chi-Square, $\chi^2 = 3590.1$, and $p < 0.000$ showed that the benefits' correlation matrix is significantly different from an identity matrix. Lastly, the anti-image correlation coefficients between the benefits exceeded the minimum threshold of 0.5 (Pett et al. 2003). Although there are other conditions for testing the suitability of a dataset for factor analysis, these conditions are considered adequate (Pett et al. 2003). The results, as shown in Table 3, indicates that the dataset was suitable for factor analysis. The exploratory factor analysis was conducted with the aid of IBM SPPS v.25. The analysis employed principal component analysis as the extraction method and varimax with Kaiser Normalization as the rotation method. The rotation converged in 11 iterations and generated a 4-factor solution with eigenvalues greater than 1.0.

Data Analysis and Results

Frequency and Agreement among the Responses

The frequency of the responses to the significance levels of the 5-point rating scale, Shapiro-Wilk test, and Mann-Whitney U test results for the benefits of DfX in IC projects are summarized in Table 5. As shown in Table 5, significant proportions of the responses were assigned to the significance levels 3, 4, and 5, suggesting that the respondents generally perceived the benefits as at least 'slightly significant.' Shapiro-Wilk test results in Table 5 indicate that data of the 23 benefits of DfX in IC projects are non-normally distributed.

Table 5. Frequency distributions, Shapiro-Wilk test, and Mann-Whitney U – test results

Code	Benefit	No. of responses					Shapiro – Wilk test	Mann – Whitney test
		1	2	3	4	5		
B1	Efficient management and reduction of complexity	5	6	61	73	84	0.000**	0.720
B2	Reduces engineering resources commitment	6	7	52	86	78	0.000**	0.846
B3	Economies of scale in component design and production	7	4	57	76	85	0.000**	0.251

B4	Increases feasibility of project functional change	6	14	64	76	69	0.000**	0.335
B5	Creation of variety and differentiation of final product	7	32	69	68	53	0.000**	0.036
B6	Improves durability and flexibility in use and maintenance	4	14	62	79	70	0.000**	0.346
B7	Reduces product order lead-time	3	13	62	77	74	0.000**	0.734
B8	Enables decoupling of product design and production tasks	5	18	64	89	53	0.000**	0.426
B9	Improves component design and production efficiency	5	6	49	80	89	0.000**	0.420
B10	Eases component verification and testing	4	10	61	91	63	0.000**	0.060
B11	Facilitates standardization and customization	4	7	57	76	85	0.000**	0.488
B12	Reduces development costs in the long run	5	7	57	76	84	0.000**	0.532
B13	Speeds up design turnaround	3	12	64	90	60	0.000**	0.015
B14	Accommodates future uncertainty and risks of product use	4	14	74	79	58	0.000**	0.650
B15	Early prevention of defects and increased project quality	2	12	64	102	49	0.000**	0.848
B16	Enables and supports parallel works	2	5	62	93	67	0.000**	0.115
B17	Efficient client requirement consideration	3	11	67	89	59	0.000**	0.275
B18	Reduces material and construction wastes	4	5	60	78	82	0.000**	0.315
B19	Steeper learning curve effect	4	11	72	73	69	0.000**	0.216
B20	Reduces assembly time	4	9	56	96	64	0.000**	0.587
B21	Ease of re-working of incorrect assemblies	3	15	62	88	61	0.000**	0.276
B22	Reduces labor requirements and improves productivity	3	5	54	94	73	0.000**	0.476
B23	Reduces labor, inventory, and development costs	2	7	53	94	73	0.000**	0.974

** The Shapiro-Wilk test was significant at the significance level of 0.05, suggesting the data were not normally distributed.

As a result, the Mann-Whitney U test was recruited to conduct an inter-group comparison of the responses. The Mann-Whitney U test results in Table 5 reveal that none of the benefits were perceived to be statistically different by respondents regarding their sector of work. This outcome implies that the respondents' assessments are statistically unanimous and can be treated holistically for statistical analysis.

Significant Benefits of implementing DfX in IC Projects

Table 6 summarizes the mean significance indices, standard deviations, and overall rankings of the 23 benefits of DfX in IC projects. The mean scores of all the benefits exceeded 3.50 on the 5-point rating scale, indicating that each of the documented benefits were perceived as at least 'slightly significant'. The assessment results in Table 6 show that B9 "improves component design and production efficiency", B11 "facilitates standardization and customization", B22 "reduces labor requirements and improves productivity", B23 "reduces labor, inventory and development costs", B18 "reduces material and construction wastes", and B3 "economies of scale in component design and production" are top six perceived significant benefits of implementing DfX methods in IC projects. As shown in Table 6, B3, B18, B22, and B23 scored the same mean significance index of 4. 0 on the 5-point rating scale. These were ordered according to their standard deviations. Due to the journal's space limitation, only the top five significant benefits were discussed in detail in this study.

Table 6. Mean significance indices of the benefits of DfX in IC projects

Code	Benefit	Mean (μ)	SD	Rank
B9	Improves component design and production efficiency	4.06	0.95	1
B11	Facilitates standardization and customization	4.01	0.95	2
B22	Reduces labor requirements and improves productivity	4.00	0.87	3
B23	Reduces labor, inventory, and development costs	4.00	0.87	3
B18	Reduces material and construction wastes	4.00	0.93	3
B3	Economies of scale in component design and production	4.00	0.99	3
B12	Reduces development costs in the long run	3.99	0.97	7
B1	Efficient management and reduction of complexity	3.98	0.97	8
B2	Reduces engineering resources commitment	3.97	0.96	9
B16	Enables and supports parallel works	3.95	0.85	10
B20	Reduces assembly time	3.90	0.91	11
B7	Reduces product order lead-time	3.90	0.97	11
B10	Eases component verification and testing	3.87	0.93	13
B6	Improves durability and flexibility in use and maintenance	3.86	0.98	14
B13	Speeds up design turnaround	3.84	0.92	15
B19	Steeper learning curve effect	3.84	0.97	15
B17	Efficient client requirement consideration	3.83	0.91	17
B21	Ease of re-working of incorrect assemblies	3.83	0.94	17
B4	Increases feasibility of project functional change	3.82	1.02	19
B15	Early prevention of defects and increased project quality	3.80	0.86	20

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B14	Accommodates future uncertainty and risks of product use	3.76	0.96	21
B8	Enables decoupling of product design and production tasks	3.73	0.98	22
B5	Creation of variety and differentiation of final product	3.56	1.09	23

Receiving the highest assessment of 4.06, B9 "improves component design and production efficiency" were perceived as the most significant benefit of implementing DfX methods in IC projects. In contrast to traditional engineering design, DfX methods adopt more proactive and structured approaches to engineer designs and working drawings of IC projects (Gao et al. 2019). The proactive and collaborative approaches generate high-standard design information, resulting in the incorporation of suitable materials and production constraints into the detailed design (Bogue 2012). This approach results in the production and use of detailed working drawings and design models that reflect the 'as-planned' and 'as-manufactured' industrialized components without wasting production materials, energy, resources, money, and time.

B11 "facilitates standardization and customization" were assessed as the second most significant benefit of implementing DfX methods in IC projects, with a mean significance index of 4.01. Standardization 'is the extensive use of components, methods, or processes in which there is regularity, repetition, and a background of successful practice and predictability' (Gibb 2001, pp.308). It is still a problematic engineering challenge to achieve full standardization of IC project components in China because the practice is considered a restrictive sentence to architectural design and innovation (Wasim et al. 2020; Wuni and Shen 2020a). Thus, the emphasis is far from mass standardization because such practice demands significant changes in construction design policy and industry-wide constraints on resource consumption or construction costs (Gibb 2001), which are obscure and perhaps unforeseeable. However, it is no longer esoteric that DfX methods such as DfMA and design for reconfiguration can deliver standardized components to produce customized solutions that meet the highly individualized and diversified needs of construction clients (Richard 2005). DfX methods such as DfMA and design for modularization allow IC designers to deliver variations in final projects through the principles of modularity; an engineering design concept that offers customized solutions through mixing and matching standardized components (Baldwin and Clark 2000). The core principles of standardization include accurate fit and interchangeability of parts. It is fundamental to consider the interfaces between the

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components rather than the components themselves (Gibb 2001). The greatest challenge in the standardization of components is effective resolutions of the tension between uniformity and variation, between optimum standardization and flexibility. DfX resolves this design importance of traditional design through standardization of the interfaces between the IC components (Peltokorpi et al. 2018). As Yuan et al. (2018) noted, DfX facilitates standardization and customization because it allows designers select from quantified comparisons of different materials, processes and components through referencing standard design improvement rules and evaluation metrics contained in the DfX manuals.

B22 "reduces labor requirements and improves productivity" were assessed as the third most significant benefit of implementing DfX methods in IC projects, with a mean significance index of 4.0. As indicated previously, DfX methods employ more systematic guidelines, standards, and metrics. Although DfX adopts a collaborative approach, the design labor requirement is minimal because of the precisely defined design tasks. Additionally, the early prevention of defects and downstream reworks through a more proactive approach has favorable cascading implications on the overall labor required for correcting errors due to faulty design (Zhu et al. 2018). By leveraging concurrent engineering strategies, DfX enhances design tasks' parallelization (Huang 1996). The associated improved efficiency of the design team results in improved design productivity, and the minimal requirements for reworks at downstream segments improve the overall productivity of the IC process.

B23 "reduces labor, inventory, and development costs" were assessed as the fourth most significant benefit of implementing DfX methods in IC projects, with a mean significance index of 4.0. Decisions made at the design stage determine over 70% of the manufacturing cost of a product or project (Bogue 2012). By identifying and resolving downstream construction issues such as manufacturing and assembly difficulties, DfX methods avoid the associated costs of such delivery challenges. The structured approach and associated minimal labor requirements of DfX methods result in reduced design labor cost, especially at the highest learning curve stages and maturity (Wasim et al. 2020). Relative to traditional engineering design, the incorporation of lean and circularity principles in DfX methods results in the efficient selection, use, and management of materials, leading to waste minimization during assembly and lower inventory costs (Gbadamosi et al. 2019). Put differently, DfX methods guide cost reduction efforts early in the design process in IC projects through the elimination of downstream manufacturing problems and assembly constraints, selection of suitable materials, and reduction of construction wastes. Additionally, DfX methods significantly shorten design time and leverage the fastest path to market leadership in product development. The shorter development cycles and times translate into lower development costs since it avoids the delay-related costs inherent in modifying the production process or the initiation of iterative design due to errors.

B18 "reduces material and construction wastes" were assessed as the fifth most significant benefit of implementing DfX methods in IC projects, with a mean significance index of 4.0 on the 5-point rating scale. The collaborative and proactive approaches implemented in DfX methods guide a more informed selection of construction materials at the design stage (Vranson 2011). DfX methods effectively design out material and construction wastes before the detailed design and working drawings reach the assembly line. The consideration of constructability, buildability and several error-laden downstream constraints early upfront at the design are crucial in reducing material wastage during production and onsite assembly (Wasim et al. 2020).

Principal Benefits of implementing DfX in IC Projects

Exploratory factor analysis was conducted to group the 23 benefits into clusters, known as principal benefits (PBs). As shown in Table 7, the principal factor extraction using varimax rotation for the 23 benefits generated a 4-factor solution with eigenvalues greater than 1.0, explaining about 63.15% of the benefits' total variance. As shown in Table 7, the factor loadings for all the benefits are close to or above 0.50, with 13 of them exceeding 0.60. The four principal benefits are labeled as PB1 "improved IC project design productivity, efficiency, and management", PB2 "shortened design and construction time", PB3 "lifecycle cost savings", and PB4 "improved flexibility, adaptability, and circularity". The labels of the principal benefits were considered the best descriptions of the benefits within each cluster. These principal benefits are discussed below, and Figure 2 conceptualizes these benefits of implementing DfX in IC projects.

Table 7. Factor loadings and Eigenvalues of the principal benefits of DFX in IC projects

Code	Benefits (B)/ Principal Benefit (PB)	Factor Loading	Eigen value	% of variance explained	Cumulative % of variance explained
PB1	**Improved project design productivity, efficiency and management**		**5.001**	**21.74**	**21.74**
B22	Reduces labor requirements and improves productivity	0.785			
B1	Efficient management and reduction of complexity	0.752			
B5	Creation of variety and differentiation of final product	0.747			
B8	Enables decoupling of product design and production tasks	0.669			
B21	Ease of reworking of incorrect assemblies	0.541			
B11	Facilitates standardization and customization	0.509			
B10	Eases component verification and testing	0.508			
B9	Improves component design and production efficiency	0.487			
PB2	**Shortened design and construction time**		**4.622**	**20.09**	**41.83**
B20	Reduces assembly time	0.729			
B16	Enables and supports parallel works	0.669			
B19	Steeper learning curve effect	0.600			
B13	Speeds up design turnaround	0.568			
B7	Reduces product order lead-time	0.464			
PB3	**Lifecycle cost savings**		**3.123**	**13.58**	**55.41**
B23	Reduces labor, inventory and development costs	0.781			
B3	Economies of scale in component design and production	0.745			
B14	Accommodates future uncertainty of product use	0.602			
B17	Efficient client requirement consideration	0.588			
B15	Early prevention of defects and increased project quality	0.532			
B12	Reduces development costs in the long run	0.515			
PB4	**Improved flexibility, adaptability and circularity**		**1.781**	**7.74**	**63.15**
B2	Reduces engineering resources commitment	0.792			
B18	Reduces material and construction waste	0.726			

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B4	Increases feasibility of product functional change	0.658
B6	Improves durability and flexibility in use and maintenance	0.502

PB1 "improved IC project design productivity, efficiency, and management" accounts for 21.74% of the factor analysis variance. PB1 consists of eight sub-benefits related to improvements in productivity, efficiency, and management of the IC project design. The sub-benefits include "reduces labor requirements and improves productivity", "efficient management and reduction of complexity", "creation of variety and differentiation of final product", "enables decoupling of product design and production tasks", "ease of reworking of incorrect assemblies", "facilitates standardization and customization", "eases component verification and testing", and "improves component design and production efficiency". The most fundamental cause of low productivity is defective product design. DfX methods can reduce defects in project design to the barest minimum because of their structured, forward-looking, and collaborative nature, resulting in high-quality design and improved productivity in IC projects (Blismas et al. 2006). IC project is considered a complex system with interconnected parts, but traditional engineering design often uses producibility design rules to replicate the complexity at the design stage, limiting standardization and generating colossal cost. The very complexity of a product or process increases the costs beyond the sum of the costs of individual parts or steps (Gao et al. 2019). DfX methods such as DfMA improves the management and reduction of the complexity through simplifying the structure and geometry, reducing weights of parts, minimizing the variety of parts, and sub-assemblies, using standard parts, fitting with the specification of production facilities, and optimizing the trade-off between function and cost (Wasim et al. 2020).

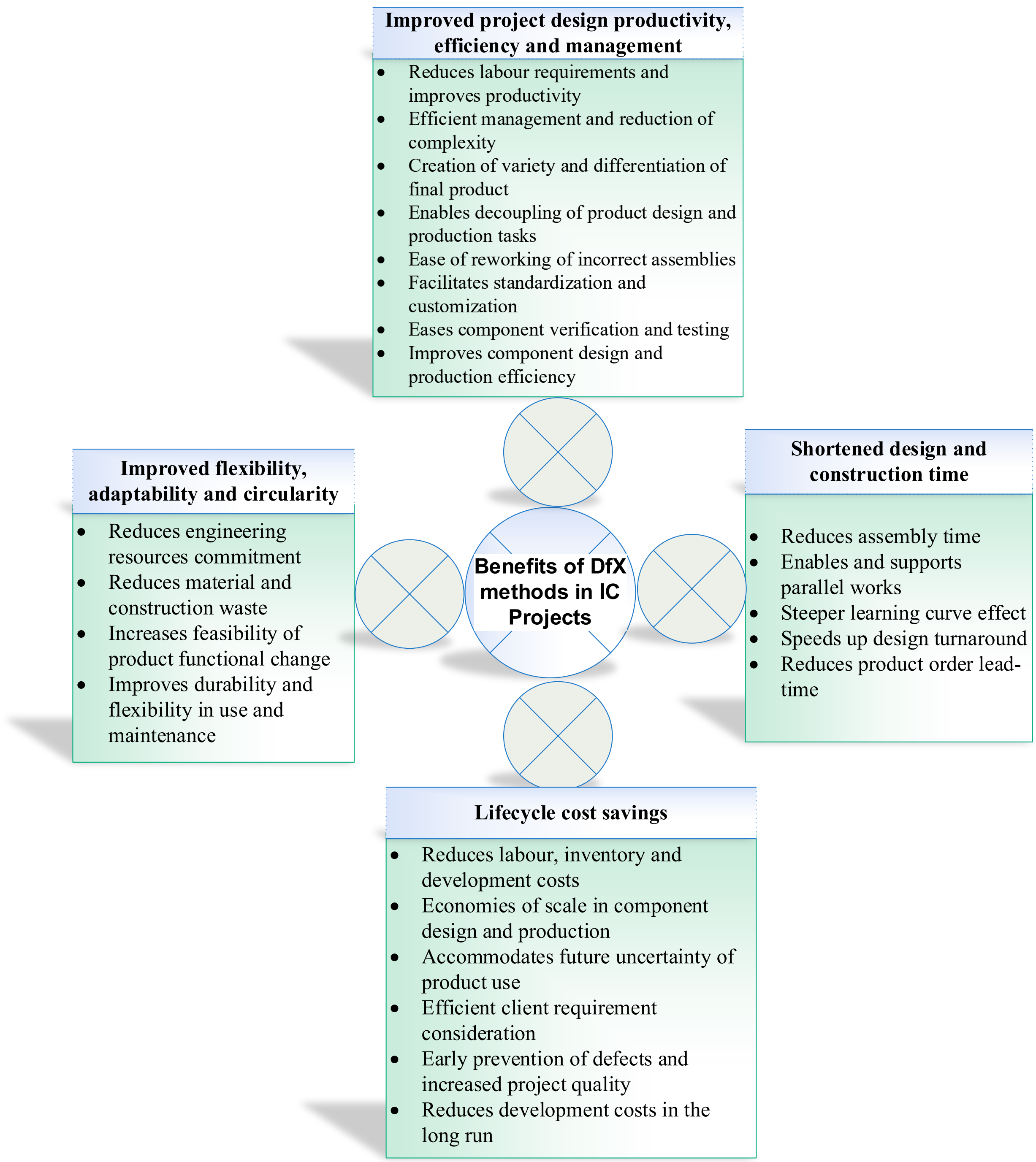

Figure 2. Conceptual framework of the perceived benefits of implementing DfX in IC projects

In DfX methods, standardization of components, removal of elements, and a reduction in overall parts help reduce manufacturing time and improve efficiency (Tan et al. 2020). These

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design rules and strategies can directly minimize time, cost, and waste in the entire project lifecycle. Although DfX methods (e.g., DfMA) share the same object as value analysis, the fundamental difference is that value analysis does not consider the structure and complexity of the project, but DfMA usually applied early in the design cycle, incorporates value analysis, and due consideration of the structure of the project and its possible simplification (Yuan et al. 2018). Additionally, unlike value engineering, usually applied in the very extreme later stage of the design process in construction, DfX methods such as DfMA are typically applied early in the design phase where decisions matter most, and maximum savings are realized (Goulding et al. 2015). DfX solutions that have enhanced project performance requirements and design goals have improved productivity, reduced risks of unforeseen problems, improved quality and safety (Abueisheh et al. 2020; Zhu et al. 2018).

PB2 "shortened design and construction time" accounts for 20.09% of the factor analysis variance. PB2 consists of five sub-benefits related to reduced design, production, and onsite assembly times. These sub-benefits include "reduces assembly time", "enables and supports parallel works", "steeper learning curve effect", "speeds up design turnaround", and "reduces product order lead-time". In traditional design, there is frequently the occurrence of 'over-the-wall approach' (Boothroyd 1994); a design practice where the designer throws the design 'over a wall' to the manufacturing engineers who have to deal with the various manufacturing problems arising because they were not part of the design team. In other words, fabrication and assembly engineers are tasked with optimizing the assembly drawings and detailed part drawings by the designers at the production stage even though they are not involved in the design effort.

Hence, the production stage is where the manufacturing and assembly problems are encountered, and requests are usually made for design changes (Banks et al. 2018). These design changes are the fundamental causes of more extended design, construction, and development cycles in construction projects with attendant cost and delay implications. DfX breaks the wall so that manufacturing and assembly engineers work with the design team early upfront in the design process to consider and resolve potential downstream manufacture and assembly challenges and constraints before the detailed design reaches the production stage (Gao et al. 2019). Similarly, unlike conventional design that usually starts from 'first principle' where the design process involves progressive layering with success levels of details until all materials are specified, and their incorporation is represented in the working drawings (Pasquire and Gibb 2002), DfX allows parallelization of the design tasks (Huang 1996). As such, the design team in DfX methods are referred to as simultaneous-engineering or concurrent-engineering team. The extra time spent early in the design process is more than compensated for by savings when prototyping occurs. This is the opportunity where DfX methods reduce delay-related project costs and shorten the entire construction time.

PB3 "lifecycle cost savings" accounts for about 13.58% of the factor analysis's total variance. The structure of PB3 comprises six sub-benefits related to reduced design, supply chain, production, and assembly costs of IC projects. The sub-benefits include "reduces labor, inventory and development costs", "economies of scale in component design and production", "accommodates future uncertainty of product use", "efficient client requirement consideration", "early prevention of defects and increased project quality", and "reduces development costs in the long run". Project design is the first step in manufacturing and constitutes the stage where the most pivotal decisions are made that affects the final cost of the product (Lu et al. 2020). Considering and resolving manufacturing and assembly constraints in the early stages of the project design in DfX methods minimize construction defects; a critical problem which could translate into over 10% of the contract sum of the project (Love and Li 2000). Additionally, the collaboration of designers, engineers, suppliers, and contractors at the early design stage means that more detailed and robust information becomes available earlier in DfX methods than in the conventional engineering design process (Lu et al. 2020). This team working strategy helps anticipate, identify, and resolve potential downstream risks and constraints using DfX guidelines. The use of evaluation standards, metrics, and knowledge bases allow the designers to precisely estimate total assembly time, assembly costs, costs of the parts and associated tooling, absolute measure of the quality of the design for ease of assembly, the minimum theoretical part-count and assembly efficiency (Bogue 2012), resulting in more informed design optimization and cost control. Notably, the ability of DfMA to reduce the number of component parts without compromising quality and functionality cascades into a snowballing effect on cost reduction (Wasim et al. 2020) due to the drawings and specifications, suppliers, and inventory that are eliminated (Yuan et al. 2018). In other words, the incorporation of design rules in DfX methods to reduce the number of modules in the IC assembly process reduces the associated assembly operations, saving parts, and operations costs. As these generate significant overheads and accounts for a considerable proportion of total construction cost (Gibb 2001), DfX methods can generate substantial cost savings. Overall, DfX methods generate cost savings due to reduced development times, requirements for fewer engineering changes, fewer parts to detail, document, and purchase, as well as a less complex project with enhanced performance, buildability, assembly, sustainability, and circularity characteristics.

PB4 "improved flexibility, adaptability and circularity" accounts for 7.74% of the total variance of the factor analysis. PB4 consists of four sub-benefits, including "reduces engineering resources commitment", "reduces material and construction waste", "increases feasibility of product functional change", and "improves durability and flexibility in use and maintenance". DfX methods aim to simplify IC projects' structure without compromising functionality and contain strategies for evaluating engineering choices and design alternatives for optimal solutions (Tan et al. 2020). They provide a strategic path to reduce engineering resources requirement in IC projects by selecting the most appropriate and cost-effective materials, processes, and techniques (Gao et al. 2018). Similarly, DfX methods such as design for lean, circularity, and sustainability incorporate design rules that allow for process-wastes and construction material wastage to be designed out before the detailed design hits the production line (Sassanelli et al. 2020; Vranson 2011). Design for deconstruction and reconfiguration rules enable designers to develop adaptable, demountable, flexible, and industrialized building systems that can meet highly diversified and individualized needs and support functional change without the need for demolition (Richard 2006). As such, DfX methods have been identified as gate-way through which designer engineers can incorporate flexibility, adaptability, circularity, constructability, transportability, 'assemblability', maintainability, and sustainability inputs at the conceptualization stage of the design process in a structured approach (Huang 1996; Zhu et al. 2018).

Discussions and Implications

This exploratory study demonstrated that IC academics and practitioners in China perceive numerous benefits of implementing DfX methods in IC projects. This corroborating evidence suggests that the effective implementation of DfX methods could offer the construction industry the opportunity to leverage radical improvement in productivity, efficiency, cost reduction, and schedule performance of building, infrastructure, and civil engineering projects. Perhaps, the most crucial promise of DfX methodologies is that they facilitate the realization of the full benefits of implementing industrialized offsite solutions in construction projects. DfX methods in IC projects' full benefits may not have been realized because current investment commitment has been devoted to mainly DfMA, with minimal considerations of other crucial methods such as design for a circular economy, health and safety, logistics, additive manufacturing, robotics, and whole life. Developing and applying systematic design improvement rules and evaluation metrics rather than generic guidelines for the wide-ranging DfX methods could significantly leapfrog IC projects' performance in the coming years. However, like other innovative and disruptive construction technologies, investment, and wider implementation of DfX methods depend on detailed and evidence-based understanding and appreciation of the documented benefits' monetary values and business benefits. At best, existing evaluation methods mainly consider the direct costs and time savings associated with DfX methods, especially DfMA. Holistic methodological assessments and evidence-based measurement of the business benefits of DfX methods in IC projects have not been well established.

More seriously, standard evaluation methods for comparing DfX methods and conventional design usually adopt a cost-comparison approach (Blismas et al. 2006; van Vuuren and Middleton 2020). The heavy reliance on elemental cost analyses, drawing on historical data in cost-comparison approaches, are themselves recipes for biases and problems when evaluating DfX and IC's business benefits in construction projects (Gibb 2001). These comparison methods are insensitive to value-adding processes of DfX and IC (Groak 1992), where a majority of the performance improvements are realized elsewhere in the construction process (Blismas et al.

2006). Through the elemental cost analysis of DfX processes, the cost-comparison approaches usually ignore significant aspects of the delivery process where DfX methods could offer prominent value in IC projects. For instance, such cost-comparison methods overlook the business benefits of softer performance improvements such as circularity benefits, health and safety improvements, early prevention of prohibitively expensive future defects, improved efficiency, among others. These intangible benefits and performance improvements often constitute the aspects where DfX methods could deliver the most prominent value in IC projects (Bogue 2012). To the extent that current evaluation methods remain deficient in providing more objective and evidence-based quantification of these benefits, it is obscure to make a strong business case for significant investment in DfX methods. Even though the evaluation of benefits through experts' opinions is relevant, it has become necessary to develop effective measurement methods to consistently evaluate the business benefits of DfX methods through analyses of several IC case studies. Some studies have measured the benefits of DfX methods (e.g., DfMA) using case studies (Gbadamosi et al. 2019; Wasim et al. 2020), but in practice, a majority of the claimed indirect benefits and softer performance improvements are rarely explicitly measured, but still primarily based on the perceptions of clients and practitioners.

Furthermore, the popular opinion that DfX methods are only worthwhile investments through economies of scale is not necessarily correct. DfX methods could be more critical when production quantities are small because an initial design is usually not reconsidered for low-volume production (Boothroyd 1994). Applying the philosophy 'do it right the first time' becomes even more critical when the production quantities are small. Similarly, the optimum benefits of standardization of components in DfX methods are achieved through continual improvement. The one-off, project-based, customer-led, highly localized, longer development cycles, customized designs, non-standardized workflows, and labor-intensive onsite processes that characterize traditional construction projects limit the full feasibility associated benefits of standardization in DfX methods. However, as IC projects are susceptible to repetition mass production of units, it offers an opportunity to leverage the benefits of the organizational-, project- and local-level optimal standardization of design and components. Finally, DfX methods increase predictability and efficiency of IC processes, but project teams need to collaborate to ensure that both DfX and IC increase design choices to exonerate them from the long-standing drawback of limiting architectural design innovations. Towards this, project teams should be upskilled to ensure that both DfX methods and IC solutions provide controlled innovation, controlled manufacturing, and improved quality, aesthetic appeal, and distinction.

Conclusions, Contributions, and Limitations

This study evaluated the perceived benefits of implementing DfX methods in IC projects in China. Based on a comprehensive literature review and pilot interviews with three experienced experts in China's construction industry, this study first identified and verified 23 benefits of implementing DfX methods in IC projects. Then, relying on the data collected by a questionnaire formed by the 23 benefits, this study statistically analyzed responses from 229 IC academics and industry practitioners in China. The statistical analysis showed that all the benefits were perceived as significant. Based on the mean significance indices, the top five most perceived significant benefits of implementing DfX methods in IC projects include "improves component design and production efficiency", "facilitates standardization and customization", "reduces labor requirements and improves productivity", "reduces labor, inventory and development costs", and "reduces material and construction wastes". Based on a factor analysis, the 23 benefits were grouped into 4 clusters of "improved project design productivity, efficiency and management", "shortened design and construction time", "lifecycle cost savings", and "improved flexibility, adaptability, and circularity".

The first contribution of this research is the holistic evaluation of 23 benefits of DfX methods in IC projects that can be used to promote the widespread adoption of DfX in the construction industry. These holistic benefits are arguably the first to be presented for the IC industry and therefore add to the existing knowledge. Second, the framework of the benefits can be used as a basis for measuring and monetizing the business benefits to justify investments in DfX in IC projects and may constitute a starting point for developing evidence-based DfX performance measurement metrics, key performance indicators, and tools in the future. Hence, this makes a useful contribution to industrial practice in IC design. Though the benefits were evaluated in China's context, they are also applicable to other countries because the evaluated benefits in this study relate more to the technical aspects of DfX methods that are not sensitive to different countries and regions. Nevertheless, while using the benefits in other countries, it is necessary to reevaluate and recalculate the weights because these benefits might be perceived differently from China.

Despite the fulfillment of the objectives, there are some limitations to the conclusions drawn from the results. First, the study was conducted in China's context, and the significance of the benefits may be perceived differently in other territories and jurisdictions. Thus, the results may not reflect the opinions of IC experts in other regions. Second, most of the respondents had fewer years of experience in IC projects. Thus, the study may have to be repeated in the future to capture more knowledge-based assessments. Third, the benefits of DfX methods in IC projects assessed in this study might not be exhaustive, even though close attention was paid to the study's research methodology to circumvent this problem. Future research would be crucial to explore further the benefits of drawing on more experienced respondents' opinions and improving the analysis using powerful techniques such as fuzzy set theory. Furthermore, it would also be necessary to measure, quantify, and monetize the business benefits using lifecycle value-based approaches to build a strong evidence-base to inform investment in DfX methods.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request (Background information of the respondents and evaluation of the benefits of implementing DfX in IC projects in China).

Acknowledgment

The authors are grateful to the three anonymous reviewers for their helpful comments and suggestions. We also extend our most profound appreciation to the academics and industry practitioners in China who participated in the questionnaire survey. The research reported in this paper received funding from the Research Grants Council of Hong Kong under the Hong Kong Ph.D. Fellowship Scheme (PF17-00649). This paper forms part of a research project investigating the challenges, benefits, and opportunities for implementing DfX in IC projects in China. Hence,

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the respondents' background presented in the data is shared in other manuscripts from the same research project.

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Please Cite As: Wuni, I.Y., Wu, Z., Shen, G.Q.P., Bugri, J. T., and Frimpong-Asante, J. (2021), “Benefits evaluation of design for excellence in industrialized construction projects”. ASCE Journal of Architectural Engineering, Vol. 27, No.4, pp.05021015.

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