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Evaluating the critical success criteria for prefabricated prefinished volumetric construction projects

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Abstract

Purpose – Prefabricated prefinished volumetric construction (PPVC) is a game-changing construction method that transforms the fragmented site-based construction of buildings into an integrated production, integration, and assembly of value-added volumetric building components. Where circumstances merit, the effective implementation of PPVC leverages significant gains in time, cost, quality, productivity, and sustainability performance of construction projects. As PPVC is increasingly becoming mainstream, it is imperative to identify the critical success criteria (CSC) for measuring PPVC project success. The purpose of the research is to identify, rank and benchmark the CSC for measuring PPVC project success.

Design/methodology/approach – The study adopted a quantitative research design where the potential CSC for PPVC projects were evaluated. A comprehensive literature and pilot expert review identified 18 CSC for measuring PPVC project success. Based on a questionnaire survey of international PPVC experts, the 18 CSC were analysed and prioritized using mean score analysis and weighting function.

Finding – Based on mean index assessment, the top 5 CSC for PPVC projects were identified as adherence to project schedules, meeting project quality specification, meeting safety requirements, client and owner satisfaction, and cost savings and profitability. Further analysis grouped the 18 CSC into 6 principal success criteria (PSC), comprising time performance, cost performance, quality performance, environmental and safety performance, stakeholder satisfaction, and supply chain performance. Based on weighted analysis of the 6 PSCs, quality performance, time performance, and environmental and safety performance obtained the highest weights.

Research limitation/implications – The research results are limited by the following limitations. First, although adequate, the sample size was relatively smaller. Second, the generalized analysis overlooked the geospatial sensitivities of the CSC.

Originality/value – The results constitutes the first exclusive quantitative ranking and prioritization of the CSC for PPVC projects. The outputs of this study will enable practitioners to reliably and accurately evaluate the performance levels of PPVC projects. A framework of the CSC for measuring the success of PPVC projects was developed.

Keywords: critical success criteria; key performance indicators; off-site manufacturing; PPVC projects; project success

Introduction

Offsite manufacturing (OSM) is a construction method where components, elements or modules are constructed away from the building site and then brought to site to be installed in position (Goodier et al., 2019; Wuni and Shen, 2020a). OSM together with associated supply chain arrangements is widely pursued as part of the latest process panacea for the supposed ills of the construction industry (Wuni, Shen and Osei-Kyei, 2020; Wuni, Shen, Osei-Kyei, et al., 2020). For the promoters, OSM provide solutions to the multifaceted ill-performances, long-standing problems, persistent market failures, and as a means of addressing the much lamented 'skills crisis' in the construction industry (Farmer, 2016). Modular integrated construction, modular construction, industrialized building systems, system, and prefabricated prefinished volumetric construction (PPVC) constitute innovative and disruptive OSM techniques (Wuni and Shen, 2019a, 2019b). PPVC is a typical OSM technique with the highest integration of prefabricated prefinished volumetric modules (Hwang et al., 2018).

The effective implementation of PPVC projects significantly reduces construction time, improves construction quality control, minimizes lifecycle cost (Construction Industry Council, 2018), generates smaller waste footprint, improves the safety of workers, reduces neighbourhood nuisance, supports business continuity (Modular Building Institute, 2017), and minimizes toxic stratospheric gas emissions (Mao et al., 2013). However, not all implemented PPVC projects have achieved the desired level of success (Hwang et al., 2018; Wuni and Shen, 2019a). The disruptive nature of PPVC directly challenges conventional project design, procurement, construction, and management (Wuni et al., 2019; Wuni and Shen, 2019b).

Thus, the success of PPVC projects requires much more precision and management compared to the traditional projects. For instance, the partial collapse of hastily implemented 22-storey prefabricated Ronan Point Apartment Tower in East London in 1968 sufficiently demonstrated that PPVC projects are not immune to failure (Wuni and Shen, 2020b). The success of contemporary PPPVC projects are extremely essential because consistent glories of implemented projects is required to reverse and exonerate the approach from the negative image which cripples its wider adoption (Wuni and Shen, 2020c). Considering that success is the goal of all involved stakeholders in any construction project, it is imperative to identify and evaluate the key performance indicators or critical success criteria (CSC) for tracking and measuring the success of PPVC projects. Although CSC for traditional construction projects have been extensively studied, the unique requirements and standards of PPVC projects require a bespoke assessment of the CSC. As PPVC is gaining significant attention in the architecture, engineering and construction (AEC) industries, it is useful to critically evaluate the CSC and develop a systematic framework for measuring the success of PPVC projects.

As far as this research is concerned, evaluation and benchmarking of the CSC for PPVC projects is yet to be established. Therefore, this research aims to identify, benchmark and develop a systematic framework of the most relevant CSC for measuring the performance of PPVC projects. In doing so, the research seeks to accomplish the following objectives: (i) to identify and evaluate the CSC for PPVC projects; (ii) to quantify and rank the most relevant CSC for PPVC projects; and (iii) to develop a conceptual framework for measuring the success of PPVC projects. It would have been a better option to engage practitioners from a single country or territory due to the geospatial sensitivity of the CSC, but this study employed the international approach because of two main reasons: (1) there are relatively fewer bespoke PPVC experts in most countries; and (2) several different countries have made significant progress in PPVC, and the accumulated experiences of the wide-ranging experts constitute an enormous wealth of knowledge-base to evaluate the CSC for PPVC projects.

This research forms part of large project which specifically seeks to develop a best practice framework for implementing PPVC projects. The output of this study will constitute the first exclusive quantitative evaluation and modelling of the CSC for PPVC projects with useful practical, managerial and theoretical implications. Theoretically, this research will establish a generic checklist of the CSC for PPVC projects which would be useful to other OSM business models. For managerial purposes, the study will contribute to better decision-making and performance assessment in PPVC projects. Practically, the output of the research will contribute to the practice and praxis of PPVC project management and will facilitate proactive and efficient allocation of resources to improve PPVC project success.

Research background of the CSC for PPVC projects

PPVC project success constitutes the most important performance outcome for developers, contractors, and clients. According to Chan and Chan (2004), project success denotes different performance outcomes for different stakeholders. Effectively, developers, contractors, clients, users, managers, consultants, and the general public have different expectations from a project, and thus, project success is quite complicated to measure comprehensively (Kamali and Hewage, 2017). However, best practices indicate that the success of PPVC projects can be effectively measured using the PPVC key performance indicators (Wuni and Shen, 2019a). Success criteria refers to the principles, standards, yardsticks or benchmarks against which the performance of PPVC projects can be measured (Horner et al., 2019). Unfortunately, there are very limited research studies on PPVC (Hwang et al., 2018) and hence, the bespoke success criteria for PPVC projects can hardly be synthesized from the extant literature. However, there are considerable research on the success of OSM techniques which are applicable to PPVC projects. Therefore, the research reviewed studies on the performance indicators for the different OSM techniques to synthesise those which are relevant to PPVC projects.

In the UK, Gibb and Isack (2003) concluded that a successful OSM project should result in cost savings and profitability, adhere to schedule, adhere to budget, meet quality specification, and results in owner or client satisfaction. In Australia, Blismas et al. (2006) documented that the performance requirement of OSM projects include reduced construction time, improved quality control, lower lifecycle cost, improved productivity, and improved safety of construction workers. Tam et al. (2007) concluded that successful prefabricated construction projects in Hong Kong resulted in reduced construction time, reduced overall construction cost, improved environmental performance, and quality control. Similarly, Jaillon and Poon (2008) also found that successful prefabricated housing projects in Hong Kong resulted in reduced construction cost, reduced construction waste, improved productivity, and reduced carbon emissions. Blismas and Wakefield (2009) concluded that successful OSM projects in Australia resulted in speedy construction, increased productivity, and predictability of construction cost.

Furthermore, Jaillon and Poon (2014) identified the key performance indicators of prefabricated construction projects to be reduced environmental burden, improved construction safety, improved productivity, reduced construction time, improved quality, and reduced construction noise. Zakaria et al. (2018) also concluded that a successful industrialized building project in Malaysia resulted in improved working conditions, lower construction cost, and improved construction productivity. Effectively, most of the OSM techniques share some success criteria, and thus provide useful basis for examining the success criteria for PPVC projects. Based on a comprehensive review of the relevant literature, success criteria relevant to PPVC projects were synthesised as shown in Table 1.

[**Table 1**. Potential success criteria for PPVC projects from literature and expert review]

Research methods and approach

This study adopted a quantitative research design where quantitative expert data was collected using structured questionnaires. The research process is based on a multistage methodological framework comprising a comprehensive review of relevant literature, experts review, questionnaire administration, mean score analysis, factor analysis, weighted analysis, and development of conceptual framework. The methodological framework of the research is shown in Figure 1. Major components of the research methodology employed are described below.

Identifying the success criteria for PPVC projects

A comprehensive review of literature on success criteria for OSM was conducted to identify the relevant CSC for PPVC projects. This approach is considered a best practice in quantitative evaluation of CSC for construction projects (Chan and Chan, 2004; Lim and Mohamed, 1999), as it allows the results to be discussed and situated within the wider context of OSM project success. Table 1 shows the checklists of CSC for PPVC projects identified in the literature. To ascertain the relevance of the CSC to PPVC projects, 2 experts from academia (Singapore and UK) and 1 expert (Hong Kong) from industry were invited to review the initial list and to suggest relevant criteria which were not included. The experts review resulted in the addition of three more CSC (See Table 1) which were not emphasized in the literature.

CSC measurement instrument and survey participants

The significance of the identified success criteria was measured using a structured questionnaire. An online-based international questionnaire survey was adopted to solicit international views on the relevance and significance of the success criteria for PPVC projects. Questionnaires were adopted due to the following reasons: (i) quantitative data was required to support the quantitative analytical tool adopted in the study, and questionnaires readily generates this data using a Likert scale; (ii) questionnaires is the most widely survey instrument for collecting data drawing on experts' opinions and understood in the construction management research domain (Ameyaw and Chan, 2015); and (iii) the online-based international questionnaire survey offer rich and powerful knowledge-based data within a short time frame. The questionnaires had two sections: the first section solicited background information of the respondents and section two requested the experts to evaluate the significance of the success criteria on a 5-point rating scale (i.e. 1= Least critical, 2= Fairly critical, 3= Critical, 4= Very critical, and 5= Extremely critical).

[**Figure 1**. Research framework for the study]

The research adopted the purposive sampling technique to identify the target PPVC experts because there is no central database for the global PPVC experts. This sampling techniques has been widely used in international surveys (Ameyaw and Chan, 2015; Osei-Kyei, Chan and Ameyaw, 2017; Sachs et al., 2007). An excel sheet was created where the researchers extracted the names and emails of OSM PPVC experts from published articles and high-rated conference proceedings. Industry experts were also extracted from websites of Construction/Building Industry Councils /Institutes. 400 industry and academic experts were identified as the primary sample size. As a reality check, questions regarding sector of work, experience in PPVC projects, and years of work experience constituted the first section. This allowed the experts to confirm their suitability for the survey.

By combining Microsoft Excel, Outlook, and Word packages, the researchers wrote personalized emails to each of the 400 experts. The survey link was created using "*Survey Monkey"* and was attached to the email (including a QR Code). The experts were requested to complete survey within 4 weeks. After several reminders, a total of 56 valid responses were retrieved for analysis. Although small, the sample was deemed adequate for analysis due to a number of reasons: (1) the 56 exceeded the 30 sample central limit theorem (Chan and Chan, 2004); (ii) smaller sample sizes are very characteristic of international surveys (Osei-Kyei, Chan and Ameyaw, 2017); (iii) the sample size exceeded the samples in similar studies such as 29 (Sachs et al., 2007), 42 (Zhang, 2005), and 46 (Osei-Kyei, Chan and Ameyaw, 2017); and (iv) the experts were diverse and distributed across 18 countries and all continents.

Reliability analysis, mean scoring and importance indices

The data was analysed using the Statistical Package for the Social Sciences (SPSS v.25). The reliability of the survey instrument was measured using the internal consistency assessment indicator. Based on the recommendations of Tavakol and Dennick (2011), the Cronbach's Alpha was used to measure the internal consistency of the responses on a scale of 0 to 1, where 0 means no reliability and 1 means absolute reliability. A Cronbach's Alpha value of 0.7 constitutes the acceptable reliability threshold (Tavakol and Dennick, 2011). Reliability analysis of the dataset generated a Cronbach's Alpha value of 0.880 which is higher than the threshold, indicating that the responses are highly reliable. Mean score analysis was conducted to ascertain the average evaluation of the success criteria on the 5-point grading scale adopted. The mean score (MS) for each performance indicator was computed using the formula:

$$MS = \frac{\sum(S \times F)}{N}, \qquad (1 \leq MS \leq 5) \tag{1}$$

Where, S denotes a score given to each performance indicator by an expert, ranging from 1 to 5 (1=least critical and 5=extremely critical); F denotes the frequency of each rating (1-5) for each performance indicator; and N represents the total number of responses for a given performance indicator. The mean scores were used to establish the list of CSC which served as input variables in the weighted analysis.

Feasibility of using factor analysis for the CSC

The dataset was analysed for its suitability for factor analysis. The necessary conditions for factor analysis are shown in Table 2. The dataset did not satisfy the 1: 5 indicator to sample size ratio required for exploratory factor analysis (Lingard and Rowlinson, 2006). This criterion has proven difficult to be satisfied in previous studies which employed exploratory factor analysis (Ameyaw and Chan, 2015; Osei-Kyei, Chan, Javed, et al., 2017). As a result, the dataset was further tested for other overriding statistical conditions required for factor analysis. The research first examined the distribution of the dataset for normality using the Shapiro – Wilk test (Wuni and Shen, 2020b) and the results shown in Table 4 indicate that the data was not normally distributed and imposed the use of non-parametric techniques to further examine the data.

[**Table 2**. Common favourable conditions for factor analysis]

The Kruskal-Wallis test; an ordinal rank-based non-parametric statistical tool was used to investigate whether there are statistically significant variations in the responses between experts from the different working backgrounds and professional specializations. The results in Table 4 revealed no statistically significant variations. Thus, the dataset was treated holistically. The Kaiser-Meyer-Olkin (KMO) test of sampling adequacy (Table 2) generated a value (0.63) less than the acceptable range of 0.8 – 1.0 (Cerny and Kaiser, 1977) and did not support factor analysis. As shown in Table 2, results of the Bartlett's test of sphericity revealed that the correlation matrix of the CSC was significantly different from an identity matrix and supported factor analysis. The high Cronbach's Alpha of 0.880 (Table 2) and results of the anti-image correlation coefficients of the CSC further supported factor analysis. Overall, the dataset was deemed unsuitable for factor analysis because of the overriding results of the KMO test (Cerny and Kaiser, 1977). However, the success criteria were grouped based on existing groupings of the CSC for traditional projects and other OSM projects in previous studies. The groupings of the CSC were referred to as principal success criteria (PSC).

Data analysis and results

Background information of the surveyed PPVC experts

Table 3 also shows that 51.8% of the experts had over 5 years of working experience in PPVC or related OSM projects. This indicates that the experts had adequate working experience to comment on the PPVC success criteria. The experts were working in 18 countries and distributed across all continents, but majority worked in the United States, Canada, China, Hong Kong, Australia, Malaysia, and the United Kingdom.

[**Table 3**. Relevant information of the experts]

The geospatial distribution of the experts highlights the quality and reliability of the research because most of these countries (Table 3) are the early adopters and front liners in the OSM disruption. The experts had worked on different types of PPVC projects. Table 2 shows that the PPVC technology is used in different construction projects. However, most of the experts had worked on housing/real estate projects (71.43%), commercial/office projects (30.35%), school projects (26.79%), industrial projects (23.21%) and health projects (17.86%) where PPVC was applied. This reinforces the reliability and relevance of the results because these project types lend themselves to modularization and repetitive design (Mao et al., 2016). Thus, the evaluation of the success criteria in the current research may be applicable to different project types and territories.

Mean scoring and ranking of the CSC for PPVC projects

The statistical mean constitutes the most fundamental statistical tool for assessing the average evaluation of the success criteria. It is widely used in the construction management research domain to the average assessment of a performance indicator on a grading point scale (Ameyaw and Chan, 2015; Osei-Kyei, Chan and Ameyaw, 2017; Sachs et al., 2007). Table 4 shows the mean scores (MS), standard deviation (Std.), weightings (normalized means) and other statistical evaluation of the success criteria. The mean score analysis generated some compelling results. From Table 4, it can be observed that all the success criteria obtained mean scores above the critical threshold of 3.0 on the 5-point grading scale used.

[**Table 4**. Results of the relevant statistical indices of the CSC for PPVC projects]

This indicates that all the success criteria are relevant and significant for measuring the success of PPVC projects. Based on the 5-point rating scale, CSC1 to CSC9 were evaluated as "very critical" and remaining success criteria are considered "critical". The top 5 most important success criteria for PPVC projects include CSC1 – adherence to project schedules (4.13), CSC2 – meeting project quality specification (4.02), CSC3 – meeting safety requirements (4.00), CSC4 – client and owner satisfaction (3.84), and CSC5 – cost savings and profitability (3.71). It is fascinating to observe that the top 3 CSC is not consistent with the popular triple constraint of time, cost and quality. Adherence to budget (3.55) and reduced project lifecycle cost (3.39), although critical, ranked 7th and 10th respectively. However, these success criteria are intertwined with CSC5. The higher ranking of CSC3 over CSC7 and CSC10 suggest that safety is a more prioritized performance indicator in PPVC projects. Table 4 also shows the normalized means of the 18 success criteria. The normalized means (weightings) were computed using equation (5). For example, considering that CSC1 obtained a mean score of 4.13, its weighting or normalized mean (N.mean) is computed as:

$$\text{CSC1}_{(\text{N.mean})} = \frac{4.13}{4.13+4.02+4.00+\cdots+3.30+3.30+3.25+3.23+3.21} = 0.065$$

Similar approach was used to normalize the means of all the success criteria. Table 4 further shows that Shapiro-Wilk test of normality was statistically significant for all success criteria. Therefore, the distribution of the dataset was not normal and dictated the use of nonparametric statistical techniques for further analysis. The Kruskal-Wallis test at 95% confidence interval was statistically insignificant for all success criteria, indicating that there were no significant variations between the ratings of the experts. Thus, it offered a legitimacy to treat the responses as a unified whole.

Weightings of the CSC and PSC for PPVC projects

The CSC for PPVC projects shown in table 4 were grouped to facilitate effective analysis and development of a performance evaluation framework. Although the pretesting showed that the dataset and sample were not suitable for factor analysis, the researchers conducted principal component analysis to identify the clusters of the success criteria within the dataset. A six-factor solution was generated and formed the basis for clustering the success criteria. Some criteria were wrongly clustered and were re-clustered to the most suitable factor. For this reason, the research did not report the factor loading from the SPSS. A similar approach was used in Ameyaw and Chan (2015) in categorizing risk factors for PPP projects. The categorization of the success criteria was validated drawing on the works of Jaillon and Poon (2008) and Chen et al. (2010) who grouped some of these success criteria as sustainability performance criteria for prefabricated construction. Thus, the prevailing PSC were grounded on sound scientific basis. Table 5 shows the mean scores and weightings of the PSC and the associated CSC. The 6 PSC comprises PSC1 – time performance (2 CSC), PSC2 – cost performance (4 CSC), PSC3 – quality performance (2 CSC), PSC4 – environmental and safety performance (3 CSC), PSC5 – stakeholder satisfaction (4 CSC), and PSC6 – supply chain performance (3 CSC).

[**Table 5**. Weightings of the CSC and PSC for PPVC projects]

The weightings (normalized means) of the CSC are different from those reported in Table 4 because those in Table 5 are computed within each PSC. Based on the recommendations of Zafar et al. (2019), the current research employed the normalized mean method to compute the weighting functions because it uses the mean scores of the CSC which are easy to compute. The weightings were computed by normalizing the mean score of each PSC using equation (2).

$$\mathrm{W_i} = \frac{\mathrm{MS_i}}{\sum_{i=1}^{n} \mathrm{MS_i}},\ 0 < \mathrm{W_i} < 1 \text{ and } \sum_{i=1}^{n} \mathrm{W_i} = 1 \qquad (2)$$

Where Wi denotes the weighting of a CSC/PSC i, MSi constitutes the mean score of a success criteria CSC/PSC i based on the survey, and n denotes the number of CSC within a PSC. For instance, given that the mean of CSC5 - cost savings and profitability is 3.71 under PSC2, the weighting of CSC5 is computed using equation (2) as:

$$CSC5_{(N.mean)} = \frac{3.71}{3.71+3.55+3.39+3.25} = 0.267$$

Similarly, the weightings of the remaining CSC were computed as shown in Table 5. The weightings of the 6 PSCs were computed using their mean scores. The mean score for each PSC was computed as a summation of the means of all CSC under that PSC. Given that the mean score of PSC4 – environmental safety performance is 10.76, the weighting is computed using equation (2) as:

$$PSC4_{(N.mean)} = \frac{10.76}{7.63+13.90+7.70+10.76+13.62+10.09} = 0.218$$

The same approach was adopted to normalize the means of the 6 PSCs. It should be reiterated the sum of all weightings of the CSC under a given PSC is unity and a summation of all the weightings of the 6 PSC is also unity. The 6 PSC and associated CSC were used to develop a conceptual framework of the CSC for measuring the performance of PPVC projects in Figure 2.

[**Figure 2**. A framework of success criteria for measuring the performance of PPVC projects]

Discussions of research findings

Time performance (PSC1)

Time performance of PPVC projects as a PSC scored a total mean of 7.63 and total weighting of 0.120. PSC1 comprises two CSC for PPVC projects, which include CSC1 – adherence to project schedules and CSC8 – increased productivity with mean scores of 4.13 and 3.50, respectively. CSC1 and CSC8 ranked 1st and 8th, respectively among the 18 CSC for PPVC projects. Based on their mean scores, the experts evaluated CSC1 as a "very critical" success criterion and CSC8 as a "critical" success criterion for PPVC projects. Time overrun and project delays constitute a significant failure because it affects budget, business operations and triggers conflicts among key project participants (Zafar et al., 2019). The chief benefit of PPVC is reduced construction time and strict adherence to project schedules (Blismas et al., 2006; Hwang et al., 2018). The ability of the PPVC project to be completed within or ahead of schedule constitute a significant measure of success because such excellent performance results in cost predictability and continuity of business operations. The ability to meet schedule is linked to accurate drawing and early design freeze (Gibb and Isack, 2003), productivity of the labour force (McKinsey Global Institute, 2017), effective scheduling, and supply chain coordination (Wuni et al., 2019). Increased productivity (CSC8) is another widely cited benefit of PPVC projects (Blismas et al., 2006) due to the fewer workers required on site and strict schedule in the manufacturing plant. Increased labour productivity is a driver of adherence to PPVC project schedule, *Ceteris Paribus*. This is often measured based on labour productivity index which quantifies the efficiency of the labour force used in the PPVC project. According to Chan and Chan (2004), time performance of PPVC projects takes three forms comprising construction time (practical completion date minus project commencement date), speed of construction (gross floor area/construction time), and time variation (measured in percentage). Measurement of the time performance of PPVC projects should also consider the predictability design time, predictability of construction time, and predictability of the project time.

Cost performance (PSC2)

Cost performance (PSC2) scored a total mean and weighting of 13.90 and 0.218, respectively. PSC2 has 4 CSC comprising cost savings and profitability (CSC5), adherence to budget (CSC7), reduced project lifecycle cost (CSC10), and effective risk management (CSC16), with mean indices of 3.71, 3.55, 3.39, and 3.25, respectively. Cost performance of a PPVC project measures the extent to which the outturn cost adheres to the original cost estimated for the project. Although PPVC is associated with higher initial capital cost, it does generate significant cost savings from a life cycle perspective (Pan and Sidwell, 2011). The cost savings and profitability of PPVC projects emanates from different aspects. The reduced construction waste constitutes a significant cost saving (Tam et al., 2007) and the speedy construction translates into faster solvency and sooner cash flow generations (Blismas et al., 2006). In estimating the cost performance of PPVC and its adherence to budget, due consideration must be given to the tender sum and the costs associated with variations, modifications, litigations and arbitration (Chan and Chan, 2004). Effective risk management (CSC16) is grouped within cost performance because unmanaged negative risk could significantly increase PPVC project cost (Lee and Kim, 2017). The life cycle unit cost approach may be used to evaluate the cost performance of PPVC projects and the net present value technique could be used to assess the profitability of the PPVC approach (Chan and Chan, 2004).

Quality performance (PSC3)

Quality performance of PPVC projects scored a total mean score of 7.70 and total weight of 0.121. PSC comprises 2 CSC which include CSC2 – meeting project quality specification with a mean score of 4.02 and CSC6 – reduced dimensional variabilities and minimal defects with a mean score of 3.68. Poor quality is a critical driver of increased life cycle cost and dissatisfaction of clients in construction projects (Chan and Chan, 2004; Mbachu and Nkado, 2006). PPVC project quality measures the extent to which the final product (project) satisfies the regulatory, aesthetic, and functional requirement of the client or customer. Although very subjective, quality is a sustainability performance indicator in construction projects (Chen et al., 2010; Jaillon and Poon, 2008) and constitutes a critical indicator of success in PPVC projects. From a modest perspective, a successful PPVC project should meet the engineering, technical, architectural, and functional specification of the developer and clients. However, a comprehensive quality performance considers the extent to which the processes, services, people, environment, and final product meets or exceeds the expectations of the customer or client. A high quality PPVC project is fit-for-purpose from the perspective of a client. From Table 4, the ability of a PPVC project to meet project quality specification was assessed as a "very critical" indicator of quality performance. In PPVC project, dimensional and geometric variabilities are problematic and costly due to the complex module interfacing and on-site assembly (Shahtaheri et al., 2017). The accumulative effective of dimensional variabilities in PPVC project include increased fabrication cost, project risks, defects and the requirement for reworks (Wuni et al., 2019). Site-fit-rework in PPVC project require expensive rectification of errors and hence, it was not coincidence that CSC6 – reduced dimensional variabilities and minimal defects was assessed by the experts as a "very critical" indicator of PPVC project quality performance. According to Chan and Chan (2004), quality of the PPVC project may be subjectively measured using a grading scale.

Environmental and safety performance (PSC4)

Environmental and safety performance of PPVC projects comprises 3 CSC, which include *CSC3 – meeting safety requirements (4.00)*, *CSC11 – reduced construction waste footprint (3.38)*, and *CSC13 – reduced carbon emissions (3.38)*, with a total mean score of 10.76 and a weighting of 0.169. Environmental and safety performance of PPVC projects was weighted higher than PSC1, PSC3 and PSC6. This is both shocking and interesting because it highlights the increasing relevance of environmental and social sustainability performance in measuring the success of PPVC projects. The traditional site-based construction approach is usually criticized for being too dangerous (McGraw Hill Construction, 2013), wasteful, and one of the seven aggressive contributors to climate change (Intergovernmental Panel on Climate Change, 2007). In the sustainable construction transition, the higher construction waste footprint, higher carbon emissions and poor safety of construction workers are considered very significant threats to the realization of sustainable modern society and competitive construction industry (Kibert, 2007). PPVC is considered as a sustainable construction approach because it reduces construction waste (Tam et al., 2007), improves the health and safety of construction workers (Blismas et al., 2006; McGraw Hill Construction, 2013) and reduces greenhouse gas emissions(Mao et al., 2013). The experts evaluated *meeting safety requirements (CSC3)* as a “very critical” performance indicator in PPVC projects and ranked it 3rd among the 18 CSC. The higher ranking of CSC3 highlights the improved corporate social responsibility performance in PPVC projects and suggests that construction safety regulations are becoming more stringent. The number of major accidents, incidents, injuries, and accident rates during the PPVC project reflects its safety performance. PPVC projects generally improves the safety of construction workers due to the reduced need to work from heights, more organized and leaner work environment, and the fewer workers on site (McGraw Hill Construction, 2013). Safety of the construction workers is directly linked to higher productivity because lost time injury (LTI) and lost time accident (LTA) significantly reduces construction productivity. Moreover, the reduced construction waste in PPVC projects denotes a significant savings in construction cost (Tam et al., 2007). Reduced carbon emissions in PPVC projects constitute a significant avoided social cost which contributes to a more sustainable built environment and modern society. The reduced carbon emissions in PPVC may be computed using the input-output method, process-based method or a hybrid of the two. The total carbon footprint or embodied carbon may then be compared with the regulatory requirement to ascertain the total reduction.

Stakeholder satisfaction (PSC5)

Stakeholder satisfaction with PPVC projects scored a total mean score and total weight of 13.62 and 0.214, respectively. PSC comprises 4 CSC, which include client and owner satisfaction (CSC4), long-term relationship and partnership (CSC14), effective stakeholder management (CSC15), and reduced litigation and conflicts (CSC17), with mean scores of 3.84, 3.30, 3.25, and

3.23, respectively. PPVC projects involve multiple stakeholders including clients, contractors, building authorities, engineers, subcontractors, designers, assembly companies, manufacturers/fabricators, suppliers, project managers, and construction workers (Wuni et al., 2019; Wuni and Shen, 2019a). These multidisciplinary stakeholders have their unique requirements, interests, motives and value systems in the PPVC projects (Luo et al., 2019). A successful PPVC project should not only meet or exceed the expectation of the client or developer but the aspirations of the other involved stakeholders. A successful PPVC project should satisfy the functional, engineering and aesthetic requirements of the end-user (Chan and Chan, 2004). Client and owner satisfaction (CSC4) ranked 4th among the 18 CSC for PPVC projects and ranked 1st within PSC5. CSC4 was evaluated as a "very critical" performance indicator in PPVC projects and ranked higher than *adherence to budget*. This is entirely justifiable because meeting the needs of clients include delivering the project within budget (Mbachu and Nkado, 2006). The multidisciplinary stakeholders and players may be more satisfied if the project is delivered without litigations and conflicts (CSC17), which can be achieved through effective stakeholder management (CSC14). Wuni and Shen (Wuni and Shen, 2019a) explained that long-term relationship and partnership (CSC14) is a critical success factor for effective stakeholder collaboration and management in PPVC projects. Thus, the success of PPVC project requires an assessment of the satisfaction of the involved stakeholders.

Supply chain performance (PSC6)

Supply chain performance of PPVC projects scored a total mean index of 10.09, and a total weighting of 0.158. There are 3 CSC within PSC6, including CSC9 – stable and reliable supply chain (3.50), CSC12 – information and communication technology (3.38), and CSC18 – less disruption and business continuity (3.21). According to Hausman (2004, pp.62), *"Supply chain performance refers to the extended supply chain's activities in meeting end-user requirements, including product availability, on-time delivery, and all the necessary inventory and capacity in the supply chain to deliver that performance in a responsive manner"*. Effective supply chain coordination and management is critical success factor for PPVC projects (Wuni and Shen, 2019a). The overall success of PPVC projects is driven by the stability and reliability of the entire supply chain (CSC9). It is not surprising that CSC9 was assessed as a "critical" performance indicator in PPVC projects and ranked 1st under PSC6. The effective use of information and communication technology such as building information modelling facilitates a more collaborative and coordinated management of the PPVC supply chain. Due to the speedy and less noisy nature of PPVC, business operations are not disrupted because of the construction schedule. For instance, schools do not have change the calendar due to the longer or noisy construction activities. Except CSC18 – less disruption and business continuity, both CSC9 and CSC12 are also critical success factors for PPVC projects (Wuni and Shen, 2019a). Supply chain performance of PPVC projects can be assessed using standardized indices or through development of a bespoke supply chain measurement index. The inclusion of supply chain performance as a PSC allows for a more comprehensive assessment of PPVC project performance. However, the low rating of the PSC6 given by the experts suggests that it may be less important but still useful.

Conclusions, contributions and limitations of the research

For many types of building projects, PPVC is increasingly becoming a preferred alternative method of construction over the traditional site-based construction approach. Rapid adoption and effective implementation of PPVC will leverage significant gains in the construction industry. Where favourable conditions prevail and circumstances merit, the effective implementation of PPVC improves construction project performance in terms of time, cost, quality, safety, and sustainability. However, not all implemented PPVC projects have achieved the desired level of success. As PPVC is gaining significant attention worldwide, it is crucial to establish a comprehensive framework for measuring the success of PPVC projects. This research identified and evaluated 18 critical success criteria (CSC) for PPVC projects through a structured questionnaire survey with international experts in 18 countries across 6 continents. Based on mean score analysis, the top 5 CSC for PPVC projects were identified as adherence to project schedules, meeting project quality specification, meeting safety requirements, client and owner satisfaction, and cost savings and profitability. The research also identified some unique CSC for PPVC projects such as reduced dimensional variabilities, defects and reworks; reduced construction waste footprint; reduced carbon emissions; and less disruption and business continuity. These are not traditional construction success criteria but were assessed by the experts as “critical” in measuring the success of PPVC projects. This makes a unique contribution to knowledge on the CSC for measuring construction project performance and further highlights the significant differences between the business model of PPVC and the traditional construction approach. The 18 CSC are further grouped into 6 PSC comprising time performance, cost performance, quality performance, environmental and safety performance, stakeholder satisfaction, and supply chain performance. These PSCs formed the input variables for development of the conceptual framework for measuring the success of PPVC projects. The ranking of “environmental and safety performance” higher than other PSC highlights the increasing importance of sustainability in PPVC project success assessment. The research developed a performance evaluation framework for measuring the success of PPVC projects. As a result, the research makes the following contribution. Practically, the study established a comprehensive framework for assessing and measuring the success of PPVC projects. Theoretically, the research has established an extended checklist of success criteria for PPVC projects and similar OSM techniques. Therefore, the research provides a preliminary guidance to PPVC practitioners as to what indicators are globally perceived as the most appropriate to use to determine the differences and hopefully, the improvements in performance brought about by OSM, and particularly PPVC projects. The overarching recommendation is that PPVC practitioners must choose the CSC which most closely reflect their strategic objectives and should objectively evaluate the available CSC to determine which ones and associated metrics are most suitable for their context and project. However, the study suffered the following limitations. First, although adequate, the sample size was small and may compromise the generalizability of the results. Indeed, the experts from North America and Asia dominated the participants and could affect the generatability of the results to territories such as Europe, etc. However, such generic analysis is required for the theoretical progress of the construction engineering and management research field since the geospatial and project sensitives of the CSC become essential when the analysis is conducted to inform a specific policy instrument. Second, the CSC were grouped without explicit factor analysis. Future research will develop a structural equation model of the success criteria and link them to the critical success factors for PPVC projects.

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Table 1. Potential success criteria for PPVC projects from literature and expert review

Success criteria	Reference
Meeting project quality specification	(Gibb and Isack, 2003); (Tam et al., 2007); (Jaillon and Poon, 2008)
Increased productivity	(Jaillon and Poon, 2008); (Jaillon and Poon, 2014);(Zakaria et al., 2018); (Chen et al., 2010)
Adherence to project schedules	(Gibb and Isack, 2003); (Blismas and Wakefield, 2009); (Chen et al., 2010)
Reduced project lifecycle cost	(Blismas et al., 2006); (Pan and Sidwell, 2011)
Reduced dimensional variabilities, defects, and reworks	(Enshassi et al., 2019); (Shahtaheri et al., 2017)
Reduced construction waste footprint	(Tam et al., 2007); (Jaillon and Poon, 2008)
Information and communication technology diffusion	(Wuni and Shen, 2019a)
Effective risk management	(Wuni and Shen, 2019a); (Li et al., 2013)
Adherence to budget	(Gibb and Isack, 2003); (Pan and Sidwell, 2011)
Client and owner satisfaction	(Jaillon and Poon, 2008); (Chen et al., 2010)
Meeting safety requirements	(Jaillon and Poon, 2008); (Chen et al., 2010)
Reduced litigation and conflicts	Expert review
Reduced carbon emissions	(Mao et al., 2013); (Quale et al., 2012)
Long-term relationship and partnership	Expert review
Less disruption and business continuity	Expert review
Stable and reliable supply chain	(Wuni et al., 2019); (Wang et al., 2018)
Effective stakeholder management	(Wuni et al., 2019); (Luo et al., 2019)
Cost savings and profitability	(Gibb and Isack, 2003); (Pan and Sidwell, 2011)

Table 2. Common favourable conditions for factor analysis

Test statistic	Study	Acceptable range	Source
Factor/indicator to sample size ratio	1:3	1:5	(Lingard and Rowlinson, 2006)
Internal consistency using Cronbach's Alpha	0.880	0.70 – 1.0	(Tavakol and Dennick, 2011)
Anti-image correlation (Coefficients) matrix	>0.5	>0.5	(Cerny and Kaiser, 1977)
Kaiser-Meyer-Olkin Measure of Sampling Adequacy	0.63	0.8 – 1.0	(Cerny and Kaiser, 1977)

Bartlett's Test of Sphericity	Approx. Chi-Square	585.294	N/A	
	df	171	N/A	
	Sig.	0.000	<0.05 @95% CI	(Cerny and Kaiser, 1977)

Table 3. Relevant information of the experts

Attribute	Sub-attribute	Responses	% Responses
Years of PPVC work experience	Below 5 years	27	48.2
	5 - 10 years	13	23.2
	11 - 15 years	5	8.9
	16 - 20 years	2	3.6
	21years and above	9	16.1
	Total	***56***	***100.0***
Country	United States	10	17.9
	Canada	8	14.3
	China	7	12.5
	Hong Kong	7	12.5
	Australia	5	8.9
	Malaysia	4	7.1
	United Kingdom	4	7.2
	Brazil	1	1.8
	Finland	1	1.8
	Germany	1	1.8
	Greece	1	1.8
	Lebanon	1	1.8
	Singapore	1	1.8
	Slovakia	1	1.8
	Spain	1	1.8
	Sweden	1	1.8
	Switzerland	1	1.8
	Tanzania	1	1.8
	Total	***56***	***100.0***
Projects participated	Housing/ real estate	40	71.43
	Commercial/Office projects (banks, hotels, castles, headquarters)	17	30.36
	Schools/education	15	26.79
	Industrial Projects	13	23.21
	Health/hospital projects	10	17.86
	Energy/ Power projects	9	16.07
	Transportation (roads, bridges, rails, tunnels etc)	5	8.93
	Prisons/ Défense	3	5.36
	Water treatment plant/ Sewage projects	3	5.36

Other (please specify)	6	10.71

Table 4. Results of the relevant statistical indices of the CSC for PPVC projects

Code	**Success criteria**	**MS**	**Std.**	**Weightings**	**Rank**	**Wilk-Shapiro Test (p-value)**	**Kruskal-Wallis Test**
CSC1	Adherence to project schedules	4.13	0.63	0.065	1	0.000*	0.474
CSC2	Meeting project quality specification	4.02	0.86	0.063	2	0.000*	0.650
CSC3	Meeting safety requirements	4.00	0.99	0.063	3	0.000*	0.322
CSC4	Client and owner satisfaction	3.84	0.95	0.060	4	0.000*	0.850
CSC5	Cost savings and profitability	3.71	1.11	0.058	5	0.000*	0.934
CSC6	Reduced dimensional variabilities, defects and reworks	3.68	0.99	0.058	6	0.000*	0.393
CSC7	Adherence to budget	3.55	0.99	0.056	7	0.000*	0.807
CSC8	Increased productivity	3.50	1.04	0.055	8	0.000*	0.121
CSC9	Stable and reliable supply chain	3.50	0.93	0.055	8	0.000*	0.166
CSC10	Reduced project lifecycle cost	3.39	1.11	0.053	10	0.000*	0.061
CSC11	Reduced construction waste footprint	3.38	1.05	0.053	11	0.000*	0.509
CSC12	Information and communication technology diffusion	3.38	0.86	0.053	11	0.000*	0.708
CSC13	Reduced carbon emissions	3.38	0.86	0.053	11	0.000*	0.128
CSC14	Long-term relationship and partnership	3.30	0.99	0.052	14	0.000*	0.182
CSC15	Effective stakeholder management	3.30	0.89	0.052	14	0.000*	0.062
CSC16	Effective risk management	3.25	0.81	0.051	16	0.000*	0.795
CSC17	Reduced litigation and conflicts	3.23	1.08	0.051	17	0.000*	0.148
CSC18	Less disruption and business continuity	3.21	0.93	0.050	18	0.000*	0.161

*Shapiro – Wilk test was significant at the 0.05 significance level, indicating the data were not normally distributed.

Table 5. Weightings of the CSC and PSC for PPVC projects

Code	Success criteria	MS	Weightings for each CSC	Total Mean for each PSC	Weightings for each PSC
PSC1	**Time performance**			**7.63**	**0.120**
CSC1	Adherence to project schedules	4.13	0.541		
CSC8	Increased productivity	3.50	0.459		
PSC2	**Cost performance**			**13.90**	**0.218**
CSC5	Cost savings and profitability	3.71	0.267		
CSC7	Adherence to budget	3.55	0.255		
CSC10	Reduced project lifecycle cost	3.39	0.244		
CSC16	Effective risk management	3.25	0.234		
PSC3	**Quality performance**			**7.70**	**0.121**
CSC2	Meeting project quality specification	4.02	0.522		
CSC6	Reduced dimensional variabilities and minimal defects	3.68	0.478		
PSC4	**Environmental and safety performance**			**10.76**	**0.169**
CSC3	Meeting safety requirements	4.00	0.372		
CSC11	Reduced construction waste footprint	3.38	0.314		
CSC13	Reduced carbon emissions	3.38	0.314		
PSC5	**Stakeholder satisfaction**			**13.62**	**0.214**
CSC4	Client and owner satisfaction	3.84	0.282		
CSC14	Long-term relationship and partnership	3.30	0.242		
CSC15	Effective stakeholder management	3.25	0.239		
CSC17	Reduced litigation and conflicts	3.23	0.237		
PSC6	**Supply chain performance**			**10.09**	**0.158**
CSC9	Stable and reliable supply chain	3.50	0.347		
CSC12	Information and communication technology diffusion	3.38	0.335		
CSC18	Less disruption and business continuity	3.21	0.318		

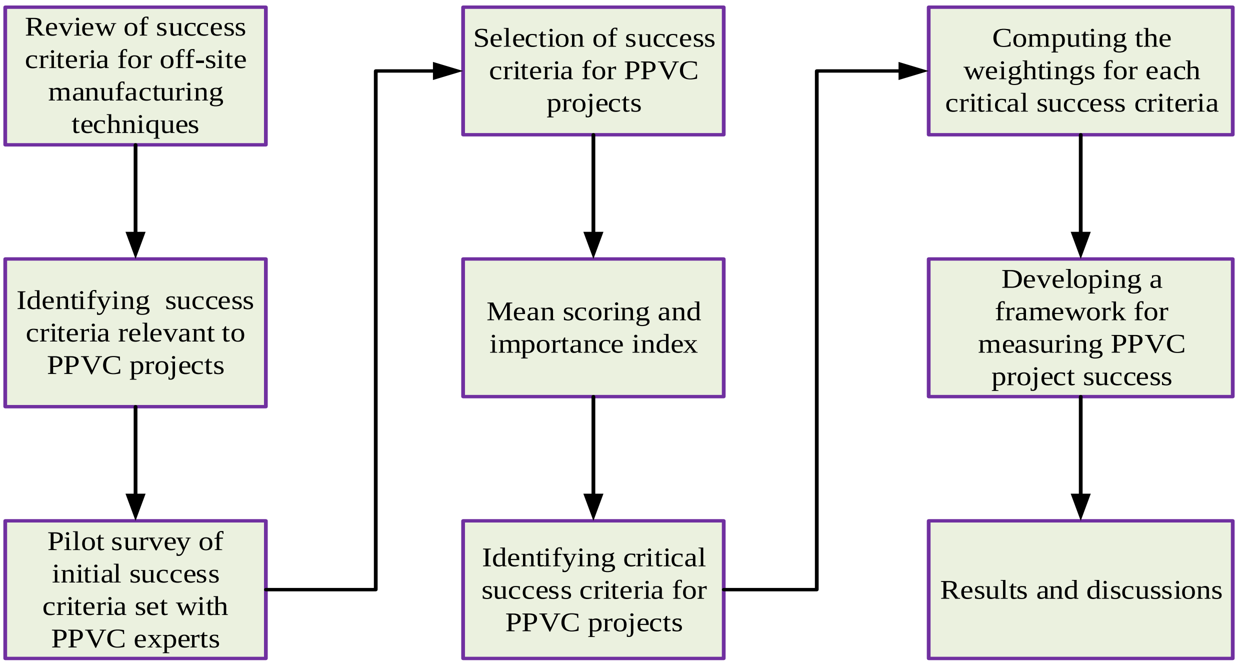

Figure 1. Research framework for the study

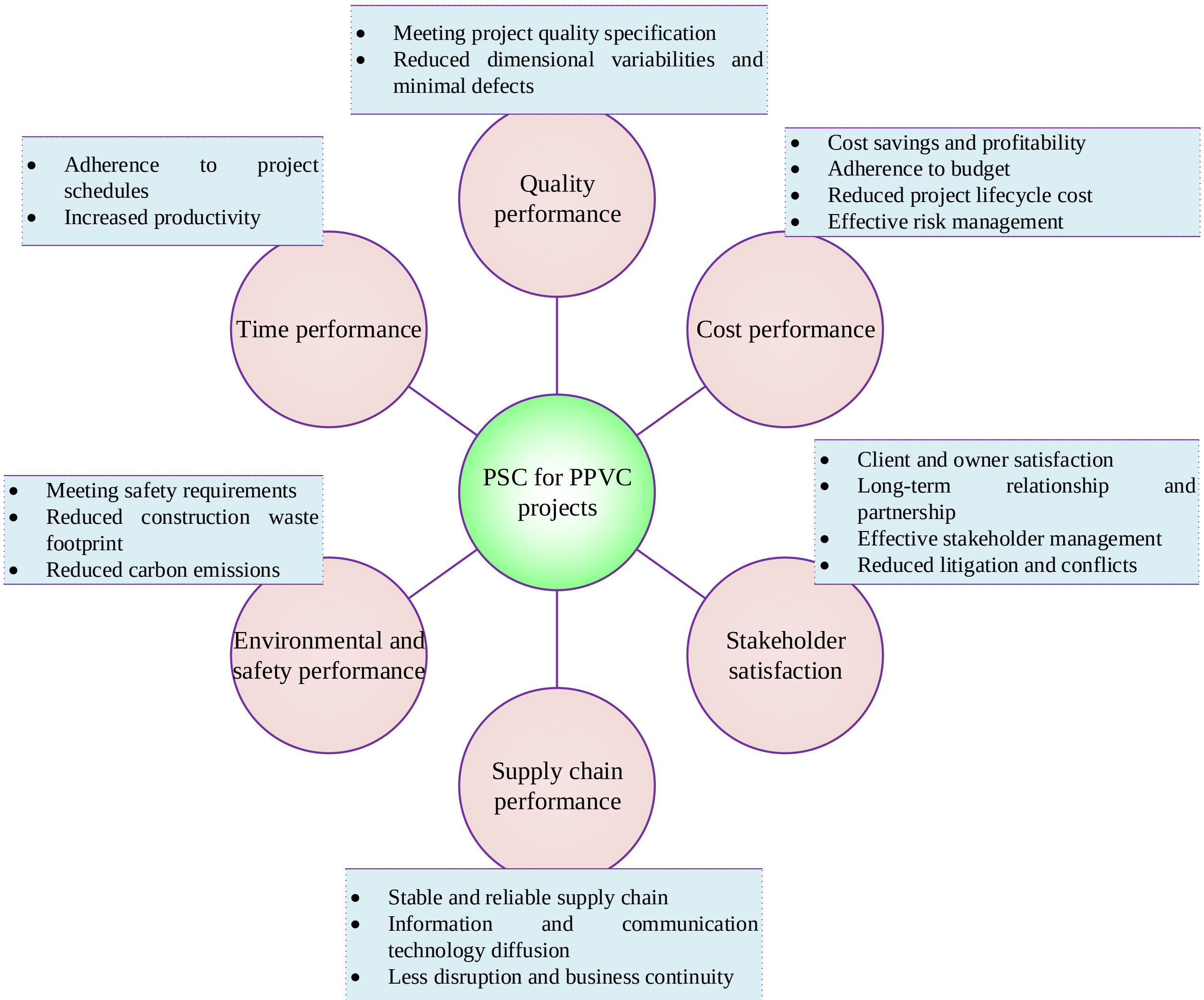

Figure 2. A framework of success criteria for measuring the performance of PPVC projects