01 Jul 2022

Quantification of the State of Practice of Offsite Construction and Related Technologies: Current Trends and Future Prospects

Rayan H. Assaad

Islam H. El-adaway
Missouri University of Science and Technology, eladaway@mst.edu

Makarand Hastak

Kim Lascola Needy

Recommended Citation

R. H. Assaad et al., "Quantification of the State of Practice of Offsite Construction and Related Technologies: Current Trends and Future Prospects," *Journal of Construction Engineering and Management*, vol. 148, no. 7, article no. 04022055, American Society of Civil Engineers, Jul 2022.
The definitive version is available at https://doi.org/10.1061/(ASCE)CO.1943-7862.0002302

Quantification of the State of Practice of Offsite Construction and Related Technologies: Current Trends and Future Prospects

Rayan H. Assaad, A.M.ASCE[1]; Islam H. El-adaway, F.ASCE[2]; Makarand Hastak, M.ASCE[3]; and Kim LaScola Needy[4]

Abstract: Although some researchers and practitioners have perceived that the current reliance on offsite construction methods is high, other studies have hypothesized that the use of offsite construction techniques is still considered to be somehow limited. To this end, this paper aims to quantify the state of practice of offsite construction in terms of current trends and future prospects for the overall industry as well as the following main sectors: industrial, building and commercial, and infrastructure. First, a questionnaire was formed, pilot-tested, distributed, and completed by 100 construction practitioners. Second, the questionnaire's internal and external validity and reliability were examined using statistical analysis. Third, the research findings were validated. The results showed that the future offsite construction operations will be different from the current operations by shifting from single-trade fabrication to modularization, shifting from customized offsite construction components to standardized offsite construction components, shifting from permanent offsite construction structures to relocatable or portable offsite construction structures, and shifting the reliance on single-skilled labor to multiskilled labor. In addition, 87% of industry practitioners perceive that the future offsite construction growth rate in the coming decade will be higher than that of the previous decade. This research also showed that offsite construction will become the norm rather than the exception because (1) the current average offsite construction percentage of 33.64% will substantially grow to reach an average of 54.9% in the future, (2) the offsite construction industry will grow 4.33 times, on average, in the coming decade, (3) companies are planning to increase their offsite construction utilization rate by an average of 5.03-fold, and (4) the offsite construction automation percentage will increase by 7% in the future. The research outcomes also provided guidance on the key technologies that the industry shall currently invest in and consider leveraging in the future.
DOI: 10.1061/(ASCE)CO.1943-7862.0002302.

Introduction

The construction industry is one of the key contributors to the growth of economies and is currently subject to many disruptions (Assaad and El-adaway 2021), one of which is offsite construction. Offsite construction provides a game-changing approach that transforms fragmented site-based construction into the integrated manufacturing-like production (Pan and Hon 2020; Yang et al. 2021). Compared with traditional stick-built construction, offsite construction consists of building or fabricating construction components and modules in a controlled environment, transporting them to the site, and assembling or installing them onsite. Thus, offsite construction techniques allow for faster onsite construction and reduced construction costs and time (Lim et al. 2021).

The use of offsite construction has shown to enhance construction project performance on multiple levels, including improved predictability, lower labor and soft costs, shorter schedules, better quality, enhanced safety standards, reduced waste management, and lower demand for labor (O'Connor et al. 2013; Baldwin et al. 2009; Jaillon and Poon 2008; O'Connor et al. 2016). In fact, modular structures provide advantages because components can be prefabricated and mass produced, which compounds the benefits of offsite construction, especially when the same module can be used for many structures (Tumbeva et al. 2021).

Some construction researchers and practitioners have perceived the potential benefit of transferring construction activities to offsite locations where they can have better control of the work environment (Zaalouk and Han 2021). On the other hand, some other studies have hypothesized that the level of using offsite construction methods and techniques in the US construction industry is still considered to be somehow limited (Lu 2009). This could be attributed to the fact that the construction industry is facing many challenges with the implementation of various offsite construction methods (Choi et al. 2016). Both viewpoints, beliefs, or perceptions could benefit from further research and empirical evidence to dig deeper into their claims. In fact, Ahn et al. (2020) emphasized this by stating that previous research showed mixed,

[1]Assistant Professor of Construction and Civil Infrastructure, John A. Reif, Jr. Dept. of Civil and Environmental Engineering, New Jersey Institute of Technology, Newark, NJ 07102. Email: rayan.hassane.assaad@njit.edu

[2]Hurst-McCarthy Professor of Construction Engineering and Management, Professor of Civil Engineering, and Founding Director of Missouri Consortium for Construction Innovation, Dept. of Civil, Architectural, and Environmental Engineering and Dept. of Engineering Management and Systems Engineering, Missouri Univ. of Science and Technology, Rolla, MO 65409 (corresponding author). ORCID: https://orcid.org/0000-0002-7306-6380. Email: eladaway@mst.edu

[3]Dernlan Family Head and Professor, Div. of Construction Engineering and Management, Professor, Lyles School of Civil Engineering, Purdue Univ., West Lafayette, IN 47907. Email: hastak@purdue.edu

[4]Dean of the College of Engineering, Professor of Industrial Engineering, and Irma F. and Raymond F. Giffels Endowed Chair in Engineering, Univ. of Arkansas, 4183 Bell Engineering Center, Fayetteville, AR 72701. Email: kneedy@uark.edu

Note. This manuscript was submitted on September 14, 2021; approved on March 2, 2022; published online on May 9, 2022. Discussion period open until October 9, 2022; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, © ASCE, ISSN 0733-9364.

and sometimes contradicting, results in relation to different aspects of offsite construction.

Therefore, further studies are strongly warranted to investigate different aspects of offsite construction in a more detailed manner. Hence, it would be beneficial for both practitioners and researchers to have an in-depth understanding where the current offsite construction operations and trends stand as well as the potential future prospects so as to better assess the degree of utilization of offsite construction techniques. Therefore, this research study addresses this research need and knowledge gap. It is worth mentioning that there has been an increasing research interest in studying the state of practice for different construction management–related aspects such as the work of Pocock et al. (2006) on constructability, Hanna et al. (2013) on building information modeling (BIM) in the North American (US and Canada) mechanical and electrical construction industries, Yussef et al. (2020) on front-end engineering design for industrial construction, and Bayraktar et al. (2004) on warranty practices in the US, to name a few.

Research Objectives

The goal of this research is to quantify the state of practice of offsite construction in terms of current trends and future prospects. The research objectives include (1) investigating the geographical distribution of offsite construction projects and the offsite construction fabrication shops; (2) examining the current and expected future reliance on different offsite construction characteristics, including offsite construction typologies or methods, type of offsite construction components, type of offsite construction structures, labor skillset for offsite construction, and labor skill level for offsite construction; (3) determining the current use and future potential of offsite construction–related technologies; (4) providing better understanding of the distribution of work between onsite and offsite locations; (5) exploring the future offsite construction growth trend and growth rate; (6) evaluating the offsite capacity utilization rate; and (7) assessing the distribution of work between human labor and automated offsite construction activities.

It is worth mentioning that the scope of this paper is limited to the state of practice of offsite construction in the US rather than worldwide; thus, all results and findings are framed into this context. Furthermore, the results reported in this paper constitute one focus area of a broader research project carried out by the authors as part of the research team formed by the Construction Industry Institute (CII) and named RT-371. More specifically, this paper is centered on the quantification of the state of practice of offsite construction in relation to current industry trends and future prospective directions, whereas the results of another paper (Assaad et al. 2022) targeted a different aspect, which is the implications of offsite construction methods on the workforce involved in offsite construction projects.

Background Information

This section offers a background information on previous related research efforts.

Previous Research Work on Offsite Construction

The literature reports on previous research studies that were conducted to explore various offsite construction–related aspects. Previous studies focused on investigating the industry perspective regarding the adoption of offsite strategies and providing an understanding of the development of the offsite construction industry over time (Razkenari et al. 2020). Existing literature was also directed to measuring the prefabricated construction product complexity and developing a scoring system for the different types of complexities, as well as to identifying schedule delay factor precursors, inherent project characteristics, organization-related factors, and precast concrete (a type of offsite construction) implementation-related factors (Ji et al. 2018; Cho et al. 2021). Previous research work also identified the management approaches being used in real-life standardized programs and modular projects and determined problems related to unstable stacks and reshuffling effort and their causes found in construction projects that use offsite construction techniques (Choi et al. 2020; Lee et al. 2021).

Other studies were directed to examine the critical decision-making criteria and the success factors of modularization in key projects to better leverage offsite construction methods (O'Connor et al. 2014; Sharafi et al. 2018). Existing studies also tackled the manufacturing aspects and logistics considerations of offsite construction including scheduling-relating issues, resources requirements in offsite construction projects, uncertainties that can affect the success of offsite construction methods, and the applicability of the Last Planner System to modularization (Lee and Hyun 2019; Yang et al. 2021; Lerche et al. 2020). Previous offsite construction studies examined the business models of industrialized companies and analyzed the primary characteristics of different as well as developed an evolution framework for weighted interorganizational diffusion network of prefabricated construction technology (Lessing and Brege 2018; Dou et al. 2020).

There were also efforts to assess the state of electrical construction prefabrication and to propose best practices and improvement opportunities for offsite construction as well as to define and categorize offsite modules to help in having an integrated view of modularity across the project life cycle phases and an effective collaboration between designers and site operators (Said 2015; Gosling et al. 2016). Finally, existing research also focused on the smart and intelligent aspects of offsite construction by developing a theory of an intelligent planning unit to standardize the complex physical entities and processes at a modular scale through planning in scalable modules or units that are carefully designed and optimized (Hastak and Koo 2016).

Existing Research Efforts Directed to Study the State of Practice for Different Construction Management and Civil Engineering Aspects

Many research efforts were conducted to study the state of practice for different construction management and civil engineering applications and to translate industry information into a quantification process. In relation to management-related studies, previous research work quantified the state of practice of constructability in the US architecture, engineering, and construction (AEC) industry and found that the industry has considerably accepted constructability, realized that constructability efforts should start in the early project phases, recognized the important of implementing different constructability methods and new technologies, and perceived that there are still obstacles to improving constructability; however, they can be addressed (Pocock et al. 2006).

Furthermore, a survey on warranty practices in the US was developed to quantitatively measure the state of practice of the impact of warranty implementation on highway projects (Bayraktar et al. 2004). Another survey was implemented to evaluate the state of practice of front-end engineering design (FEED) for industrial construction, and it was found that the industry lacks a consistent agreed-upon FEED definition, which causes industry misunderstandings (Yussef et al. 2020). Existing studies were also directed to measure the state of practice of BIM in the North American (US and Canada) mechanical and electrical construction industries and provided industry guidance on overall BIM use at the company level, the current reliance on BIM, the future implementation of BIM, and the value generated from BIM implementation (Hanna et al. 2013, 2014).

Continuing with the North American (US and Canada) industry, the literature also quantified the state of BIM practice in the mechanical construction industry specifically to help contractors allocate proper resources for BIM implementations and reduce its problems (Boktor et al. 2014). More recently, the state of professional practice for water infrastructure project delivery was quantified to examine the alternative project delivery methods (APDM) implementation practices for water infrastructure projects (Feghaly et al. 2020).

Moving to the broader civil engineering domain, many research studies were also directed to translate industry information into a quantification process of the state of practice. In relation to that, the US state of practice for the design of the load-transfer platform used in column-supported embankments was quantified to provide guidance on the determination of the geosynthetic properties based on the method used to design the platform (Collin 2007). Further research efforts were conducted to measure the state of practice for road safety and to provide descriptions of road safety initiatives and applications (Spring 2005). Previous literature also quantitatively studied the state of practice for the geo-seismic design in the Eastern US and examined engineering approached followed to address common geoseismic problems such as seismic hazard assessment, site response analysis, and liquefaction potential evaluation (Nikolaou et al. 2012).

Existing research work evaluated the state of practice and future prospects of the roles of stated preference methods in planning for sustainable urban transportation and examined the theoretical and methodological advances in the stated preference surveys (Loo 2012). The state of practice for offshore geotechnical practices, from geohazards assessment in the early stages of a project to the design of shallow and deep foundations, with a focus on deep-water applications and conventional siliceous sediments, was also gauged by previous research efforts (Jeanjean 2012). Finally, the state of practice of the management of ancillary transportation assets was quantified to assess the needs for their successful implementation by highlighting data collection strategies and costs, data analysis tools, and data use in decision making (Akofio-Sowah et al. 2014).

Knowledge Gap

It could be concluded from the aforementioned extensive review of the literature that there is a lack of research work that studied the current and expected future state of practice of offsite construction. However, previous offsite construction studies shed some light on different aspects of offsite construction, such as critical success factors, opportunities for modularization augmentation, lean construction implications on the sustainability of offsite constructed home buildings, prefabrication feasibility, and decision-making factors affecting the use of offsite construction, among others. Furthermore, many of the previous studies that focused on the offsite construction market followed a qualitative approach, which—despite being valuable—has many limitations, such as lack of statistical representation, being more prone to researcher subjectivisms, and having an element of uncertainty in terms of data collection and analysis.

That said, there is a critical research need and a knowledge gap in relation to quantifying the state of practice of offsite construction using quantitative and more objective research methods. Thus, this paper addresses this knowledge gap by studying the current practices and the future prospects of offsite construction in three main sectors, namely industrial, building and commercial, and infrastructure, using a quantitative approach, which helps in reaching accurate and generalizable conclusions, conducting statistical analysis which gives the outcomes greater credibility, and minimizing biases, thus leading to more objective findings.

Methodology

The researchers used an interdependent multistep research methodology based on an industry questionnaire to quantify the state of practice of offsite construction and its associated technologies.

Overview

This research was funded and supported by the CII, and the research team (RT) RT-371 was assigned to study the current use and future prospects of offsite construction and its impact on the workforce. More specifically, the RT-371 research falls under the Workforce of 2030 program, which aims to address issues envisioned for 2030 rather than reacting to issues faced today (CII 2021a). This effort was initiated by CII based on a rigorous process where the Future of the Built Environment Project engaged CII members in two workshops to identify a number of critical research areas and topics (CII 2021b), one culminating in the research to be carried out by RT-371. The year 2020 was used as the baseline marking the current state of practice for offsite construction.

Formation of a Questionnaire

A questionnaire was developed to (1) investigate the geographical distribution of the executed offsite construction projects and the offsite construction/manufacturing fabrication shops; (2) examine the current and expected future reliance on different offsite construction characteristics, including offsite construction typologies, type of offsite construction components, type of offsite construction structures, labor skillset for offsite construction, and labor skill level for offsite construction; (3) determine the current use and future potential of offsite construction–related technologies; (4) understand the distribution of work between onsite and offsite locations; (5) explore the future offsite construction growth trend and growth rate; (6) evaluate the offsite capacity utilization rate; and (7) assess the distribution of work between human labor and automated offsite construction activities. Different types of questions were used—including 5-point Likert scale questions, drop-down-menu questions, questions with a sliding scale, and text entry questions—depending on the type of data or information needed from the industry practitioners. As far as the used 5-point Likert scale is concerned, the following description of the scale points was used:

- 1 = very low: used in only exceptional projects (<10% of projects),
- 2 = low: unlikely to use in most projects (10%–35% of the projects),
- 3 = medium: likely to use in most projects (35%–65% of the projects),
- 4 = high: very likely to use in most projects (65%–90% of the projects), and
- 5 = very high: almost used in all projects (>90% of the projects).

In addition to the general demographic and background questions on the experiences of the surveyed industry practitioners, the questions that were asked to meet the previously mentioned seven objectives include the following:

1. Questions related to objective 1:
   a. For your previously (and currently) executed offsite construction projects, please specify the location [US state(s) and/or the international region] where these projects were constructed (check all that apply).
   b. For your previously (or currently) executed offsite construction projects, please specify the location [US state(s) and/or the international region] of the offsite construction facility/shop (check all that apply).
2. Questions related to objective 2:
   a. In your industry sector, what is the current (2020) and expected (2030) use of the following offsite construction characteristics:
      (1) Offsite construction typologies: single-trade prefabrication, multitrade prefabrication, preassembly, and modularization.
      (2) Type of offsite construction components: customized components and standard components.
      (3) Type of offsite construction structures: portable/relocatable structures and permanent structures.
      (4) Labor skillet for offsite construction: single skilled and multiskilled.
      (5) Labor skill level for offsite construction: low skilled, medium skilled, and high skilled.
3. Questions related to objective 3:
   a. In your industry sector, what is the current (2020) offsite use of the different technologies?
   b. In your industry sector, what do you expect the offsite use of each of the different technologies will be in 2030 as a result of the expected increase in offsite construction?
4. Questions related to objective 4:
   a. In your industry sector, please describe the distribution of work between onsite and offsite construction by specifying the following three percentages: (1) average percentage of man-hours performed only onsite; (2) average percentage of man-hours performed only offsite; and (3) average percentage of man-hours performed both onsite and offsite by the same labor.
5. Questions related to objective 5:
   a. Bearing in mind the current and expected technological advancements, and based on your previous experience, how do you expect the shape of the 2020–2030 growth trend of offsite construction will be in your industry sector [i.e., logarithmic, linear, logistic, exponential, or other (please specify)]?
   b. Do you expect the 2020–2030 growth in your industry sector to be higher, lower, or the same as compared to your observation of the growth of offsite construction in the previous 10 years (2010–2020)?
6. Questions related to objective 6:
   a. What is the current 2020 capacity utilization rate for offsite construction in your industry sector?
   b. Please specify "by how many folds" the offsite capacity in 2030 is expected to expand as compared to 2020 in your industry sector?
7. Questions related to objective 7:
   a. Out of the project offsite working hours, what is the current (2020) and expected (2030) average percentage performed only by human manual labor (rather than automated/operated by machines and equipment) in your industry sector?

Furthermore, it is worth mentioning that the surveyed industry practitioners were asked to provide their answers based on their own experiences rather than based on the company overall experience. In other words, the unit of measure is individuals rather than companies.

In the context of the developed questionnaire, single-trade prefabrication was defined by the research team to be the process that relies on one trade to produce components at a specialized controlled-environment facility, in which various materials are joined to form a component part of a final onsite installation. Examples include facades panels, prefabricated pipes, precast concrete, window frame, and curtain walls, among others. Multitrade prefabrication was defined by the research team to be the process where multitrades must be coordinated to produce components at a specialized controlled-environment facility, in which various materials are joined to form a component part of a final onsite installation. Once complete, the components are transported to the construction site for assembly. Examples include zone-valve boxes (plumbing, framing, and drywall), overhead racking (mechanical, plumbing, electrical, and fire protection), and equipment skids (mechanical and electrical), among others.

Preassembly was defined by the research team to be the process by which various materials, prefabricated components, and/or equipment are joined and assembled together by different crafts at a remote location for subsequent onsite installation as a subunit; generally focused on a system. Modularization was defined by the research team to be a major section of a plant resulting from a series of remote assembly operations and may include portions of many systems; usually the largest transportable unit or component of a facility. It is worth mentioning that the definition of modularization used in this paper is the one commonly used by researchers and practitioners, and it is in accordance with many previous research studies including those of Lopes et al. (2018), O'Connor et al. (2015), Choi (2014), Bekdik (2017), O'Connor et al. (2014).

Pilot Testing of the Questionnaire

The questionnaire was reviewed closely by the research team throughout the entire questionnaire development efforts, and it was pilot tested to eliminate any potential mistakes, confusions, or misunderstandings. The respondents of the pilot study were requested to provide their comments at the end of the questionnaire as related to the offsite construction characteristics and technologies that need to be added, modified, or deleted; questions that need to be added, modified, or deleted; clarifications that need to be performed to ensure consistency of understanding; and any other suggestions to make the questionnaire more beneficial.

The questionnaire was pilot tested by 11 industry practitioners. These 11 practitioners who piloted tested the questionnaire are members of the CII research team (RT-371) and were selected in a way to represent a wide range of experiences, such that they possess an experience with the US construction industry; have an experience with either offsite construction, the craft workforce, and/or the integration and usage of construction technologies; represent central project stakeholders; and represent key construction sectors.

According to Connelly (2008)'s recommendations, a pilot study sample should be 10% of the sample projected for the larger parent study. Therefore, the total number of 11 industry practitioners that pilot tested the questionnaire is considered satisfactory because it constitutes 11% (which is greater than the recommended 10%) of the sample size of 100 responses that was projected for the larger parent questionnaire in this research, as detailed in the next subsections of the paper. Comments received from the respondents in the performed pilot testing efforts were recorded and the questionnaire was fine-tuned accordingly. The pilot testing enabled some editing of the questions' language and descriptions, some formatting and aesthetic considerations, the removal of some duplications, and the enhancement and addition of some clarifications and items; however, nothing major was changed.

Targeted Industry Practitioners

Qualtrics was used for distributing and developing the questionnaire. Qualtrics is a cloud-based platform that is utilized to establish and distribute web-based questionnaires. Qualtrics is one of the most commonly used platforms in academic research due to its outstanding features that allow for a large range of question types, offer customizable designs and appearances for questionnaires, and provide the ability for complex experimental designs (if needed) and user-tailored questionnaire paths.

The questionnaire (written in English) was disseminated to industry practitioners using the purposive sampling method, which involves targeting representative respondents with relevant experience and thorough knowledge in the issue under investigation (Tetteh et al. 2021; Cooper and Schindler 2006), and these respondents usually fit certain research criteria or a particular profile of interest (Munvar et al. 2020). The profile of interest for this research included industry practitioners who (1) possess experience with the US construction industry rather than worldwide, (2) have experience with either offsite construction, the craft workforce, and/or the integration and usage of construction technologies; (3) represent one of the central project stakeholders: (i) owners or developers; (ii) architects, engineers, or service providers; (iii) (sub)contractors, construction managers; or fabricators; and (4) represent one of the following sectors: (a) building and commercial; (b) industrial; and (c) infrastructure.

As for the questionnaire recruiting procedure, the questionnaire was distributed to CII RT-371's member companies and their network; CII's Manufacturing and Life Sciences (MLS) sector; CII's Power, Utilities, and Infrastructure (PUI) sector; CII's Downstream and Chemicals Committee (DCC) sector; and CII RT-370's member companies; as well as posted on the CII LinkedIn page. In relation to that, the questionnaire was sent to an overall of 215 industry practitioners.

In total, 131 responses were received (which is equivalent to an overall response rate of 60.93%), but 31 industry practitioners provided incomplete and insufficient responses. To this end, a final total of 100 responses was included in the analysis of this paper (which is equivalent to a useable response rate of 46.51%). All details pertaining to the sufficiency of the sample size and the industry practitioners' demographics are provided in the "Results and Analysis" section.

Reliability Statistical Analysis

Two types of reliability measures are generally of interest: internal consistency (i.e., internal reliability) and interrater agreement (i.e., external reliability) (Park and Jung 2003). This subsection provides all details pertaining to the conducted reliability analyses.

Internal Consistency Using Cronbach's Alpha Reliability Coefficient

Examining internal reliability in questionnaires is very critical to demonstrate that tests and scales constructed or adopted for the research project are fit for purpose (Taber 2018). In other words, the internal reliability of any given questionnaire refers to the extent to which the used scale is a consistent measure of an underlying construct of interest (Singh 2017), where a higher internal reliability is associated with greater confidence in the scale and the associated conclusions made from the results (Robertson and Evans 2020). The Cronbach's alpha coefficient was calculated to check the internal reliability (internal consistency) among the collected responses. If the Cronbach's alpha coefficient is greater than or equal to 0.75, this shows that the questionnaire is reliable and valid (Christmann and Aelstb 2006). The Cronbach's alpha coefficient was used to examine the reliability of the scales used for investigating the state of practice of offsite construction characteristics and the associated technologies.

External Reliability (Rater Agreement or Consistency) Using Intraclass Correlation Coefficient

In addition to the internal consistency or reliability, it is crucial to check the external reliability (i.e., interrater consistency or agreement) among the collected responses. External reliability is defined as the degree to which different raters/observers give consistent estimates of the same phenomenon (Balasubramanian 2012). The importance of rater reliability lies in the fact that it represents the extent to which the data collected in the study are correct representations of the variables measured (McHugh 2012). Thus, this study used the intraclass correlation coefficient (ICC) due to its wide use in interrater reliability analyses because it does not only reflect the degree of correlation but also the agreement between measurements (Koo and Li 2016). The ICC value ranges between 0 and 1, with values closer to 1 representing stronger agreement or reliability. The most commonly used guidelines developed by Cicchetti and Sparrow (1981) were utilized in this research to assess the degree of reliability or agreement as follows: when the ICC is below 0.4, the level of agreement is poor; when it is between 0.4 and 0.59, the level of agreement is fair; when it is between 0.6 and 0.74, the level of agreement is good; and when it is between 0.75 and 1, the level of agreement is excellent.

Chi-Square Test

In addition to examining both internal consistency and external reliability, the authors have performed the chi-square (χ^2) statistical test, which is a hypothesis testing method. More specifically, the chi-square goodness-of-fit test was used, which is a nonparametric test conducted to find out how the observed value of a given phenomenon is significantly different from the expected value (Mehdizadeh et al. 2020). The chi-square test examines the null hypothesis that the categorical data has the given frequencies (Lima et al. 2019).

In relation to that, the χ^2 statistical test was conducted in this paper to examine the current and expected future reliance on different offsite construction characteristics including offsite construction typologies or methods, type of offsite construction components, type of offsite construction structures, labor skillset for offsite construction, and labor skill level for offsite construction. A critical value of 0.05 was used for the chi-square test.

Validation of the Findings

The final methodology step was the validation of the obtained research findings from the questionnaire. In relation to that, the research team validated the obtained research outputs by conducting interviews with 11 industry experts. These experts were identified by the RT-371 industry members and/or CII research collaborators and were selected based on the following criteria: (1) having a minimum industry experience of 10 years, (2) possessing a minimum offsite construction experience of 5 years; and (3) representing the considered industry sectors in this paper: (a) building and commercial; (b) industrial; and (c) infrastructure. The scripts of the conducted interviews were individually coded by two members of the research team to avoid any potential biases and to ensure completeness of the needed information. These 11 industry experts who validated the research's findings are not the same as those who piloted tested the questionnaire. More specifically, these 11 industry experts were external to the CII RT-371, whereas the practitioners who piloted tested the questionnaire were members of RT-371.

Results and Analysis

This section presents the results obtained from the questionnaire and analyzes them to provide insight on the state of practice of offsite construction and its future prospects.

Statistical and Empirical Sufficiency of the Sample Size and Response Rate

It is very important to check the sufficiency of the response rate to identify whether the data collected from the industry practitioners could be considered an adequate sample, thus ensuring a solid basis for the analysis to be conducted in this paper. Therefore, the sufficiency of the data collected from the 100 industry practitioners was examined statistically using well-established statistical formulas to determine the minimum required sample size as well as empirically by comparing it with previous similar research studies.

Statistical Justification

The authors investigated the sufficiency of the collected sample size of 100 respondents using commonly used statistical methods. In relation to that, the authors utilized Eq. (1), which was first established by Cochran (1977) and utilized later by many previous construction research studies such as Abdul Nabi and El-adaway (2021), Srour et al. (2017), and Assaad et al. (2020a), just to name a few.

Eq. (1) determines the minimum number of respondents required to ensure a valid generalization of the results

$$n = \frac{t^2 s^2}{e^2} \quad (1)$$

where n = minimum needed number of respondents; t = z-statistic for a given significant value α; s = estimated variance deviation for the scale adopted in data collection; and e = acceptable margin of error multiplied by the number of points on the primary scale.

Using the commonly used 95% level of significance; the associated value of t is 1.96. Because a 5-point Likert scale was adopted in the questionnaire, s is commonly taken as 5/6 (Randiwela and Wijayaratne 2017). Moreover, e is computed by multiplying 5 by 0.05, where 5 is the number of points on the adopted scale and 0.05 is the margin of error. The margin of error is generally taken to be 5%. Hence, the minimum needed number of respondents is computed using Eq. (1) as follows:

$$n = \frac{1.96^2 (\frac{5}{6})^2}{(5 \times 0.05)^2} = 42.684 \approx 43$$

As such, it could be concluded that the total of 100 collected responses is considered sufficient because it is greater than the needed minimum number of respondents calculated using Eq. (1).

Empirical Justification

In addition to statistically justifying the sufficiency of the sample size and/or response rate, it was empirically examined by comparing it with widely established and used guidelines in questionnaire-based construction management-related research work that quantified the state of practice of different applications. In relation to that, Boktor et al. (2014) highlighted the state of BIM practice in the North American (US and Canada) mechanical construction industry through a questionnaire of 75 complete responses (equivalent to an approximately 6.84% complete response rate out of the targeted population or sample). Yussef et al. (2020) conducted a questionnaire to determine the state of practice of FEED for industrial construction based on the input provided by 80 responses with a response rate of 37.91%. Feghaly et al. (2020) studied the state of professional practice for water infrastructure project delivery based on a questionnaire of 75 complete responses (response rate around 38%). Hanna et al. (2014) examined the state of practice of BIM in the electrical construction industry through a questionnaire and interview process based on 67 complete responses, equivalent to 8.38% complete response rate.

To this end, the obtained useable response rate of 46.51% and the total of 100 responses in this paper are considered acceptable because they are higher than the commonly used range for the response rate and the number of surveyed industry practitioners in questionnaire-based construction research studies.

Location and Years of Experience of the Respondents

As detailed in the "Methodology" section, the targeted respondents included industry practitioners who possess experience with the US construction industry. Fig. 1 shows the distribution of the location of the surveyed respondents among the different US states, which was recorded as part of the distributed questionnaire. In relation to that, 31% of the respondents were located in Texas, followed by 9% being located in Alabama. It is worth mentioning that although 6% were located internationally during the time of the questionnaire distribution, all surveyed industry practitioners possess experience with the US construction industry and offsite construction.

The distribution of the years of experience of the questionnaire respondents is given in Table 1.

In addition to the respondents' significant experience in the construction industry as well as offsite construction, most of them were also in senior management and high job position levels. Furthermore, the industry practitioners possessed wide experience in multiple major construction sectors in the US, including industrial, building and commercial, and infrastructure.

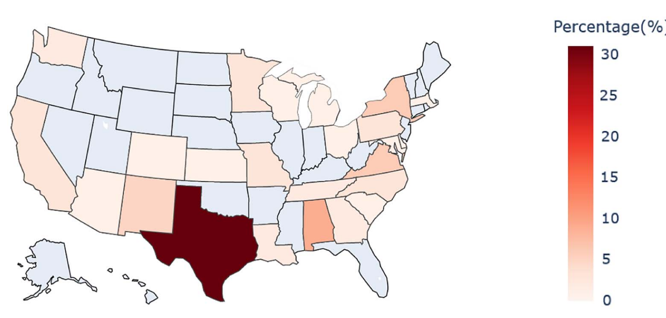

Fig. 1. Location of the surveyed industry practitioners.

Table 1. Distribution of respondents' years of experience

	Respondents (%)	
Experience	Construction industry	Offsite construction
<10 years	8	36
≥10 years and <15 years	5	16
≥15 years and <20 years	10	9
≥20 years	77	39
Average	28.05 years	13.92 years

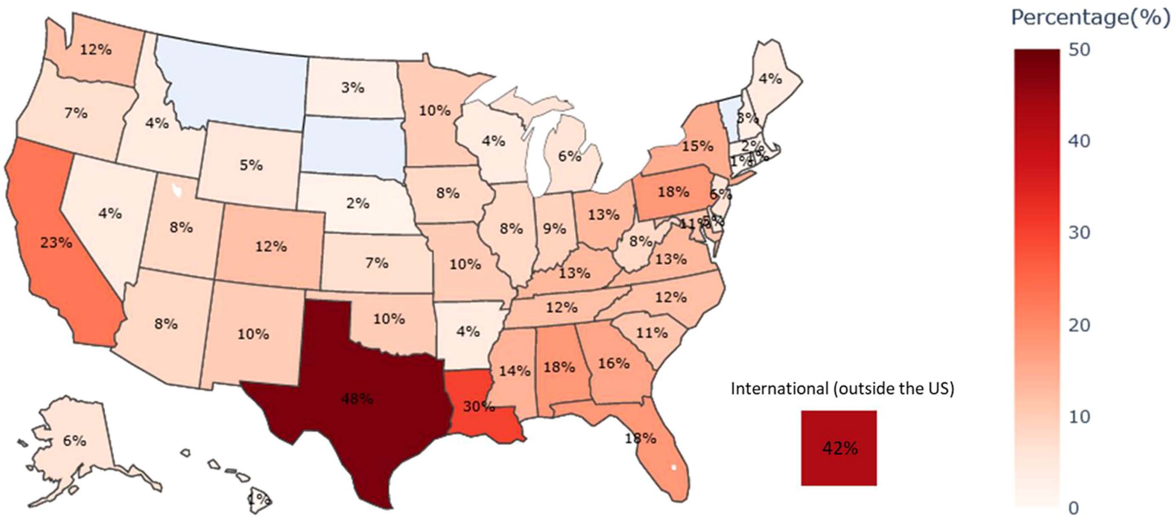

Fig. 2. Distribution of offsite construction projects.

To ensure that the respondents represented an acceptable range of experience in the industry, the average experience of the industry practitioners in this research given in Table 1 was compared with other similar questionnaire-based research studies related to the construction field. For instance, Abdul Nabi and El-adaway (2021) conducted a questionnaire for respondents with an average experience of 24.3 years in the industry and an average experience of 13.6 years with offsite construction to identify the key risks affecting cost and schedule performance of offsite construction projects. Choi et al. (2020) relied on a questionnaire data from professionals with an average experience of 21.75 years in the industry to determine the innovative technologies and management approaches that promote modularization in capital projects and higher levels of design standardization. Thus, compared with previous studies, the collected responses in this paper reflect a wide range of experience in the US construction industry as well as in the US offsite construction market. Such wide experience ensured that the collected responses are reliable enough to be considered a good representation of the US offsite construction industry.

Distribution of Offsite Construction

This subsection provides the geographical distribution of offsite construction in terms of (1) the final location of executed offsite construction projects, and (2) the location of offsite construction/ manufacturing facilities.

Distribution of the Final Location of Offsite Construction Projects

The industry practitioners were asked to specify the final locations of all their executed US and international offsite construction projects. The obtained results are shown in Fig. 2.

Fig. 2 shows that most of the US offsite construction projects are being executed in Texas (48%), Louisiana (30%), California (23%), Pennsylvania (18%), Florida (18%), and Alabama (18%). Fig. 2 also shows that the percentage for the international offsite construction projects is 42%. It is worth mentioning that these percentages reflect offsite construction projects in specific rather than the distribution of projects between offsite and stick-built construction. For instance, the 42% for the international offsite construction projects means that 42% of the respondents specified that their previously offsite construction projects were executed overseas. The detailed location distribution of the international offsite construction projects is shown in Fig. 3.

Fig. 3 shows that most of the international offsite construction projects were executed in South and Southeast Asia (including India, Indonesia, Malaysia, Philippines, Singapore, and Vietnam) as well as in Mexico, Central America, and their Islands. The percentages shown in Fig. 3 are fractional because they were not assessed based on the 100 respondents but rather based on the total number of international offsite construction locations specified by the respondents (which was 42).

Distribution of the Offsite Construction Factories

The industry practitioners were also asked to specify all locations of the national and international offsite construction factories. The obtained results are shown in Fig. 4.

Fig. 4 shows that the percentage for the international offsite construction factories was the highest with 52%, and that most of the US offsite construction factories are present in Texas (42%), Louisiana (23%), California (17%), Alabama (15%), and Mississippi (13%). The percentages specified in Fig. 4 were obtained by counting the number of times the location was specified by the respondents (where each location can be specified a maximum of one time per respondent). The detailed location distribution of the international offsite construction factories is shown in Fig. 5.

Fig. 5 shows that most of the international offsite construction factories are located in South and Southeast Asia (such as India, Indonesia, Malaysia, Philippines, Thailand, Myanmar, Singapore, and Vietnam) as well as in East Asia (including China, Korea, Taiwan, and Japan). Because the focus of this paper is the offsite construction market in the US rather than worldwide, Fig. 5 reflects the percentage of offsite construction factories overseas serving the US rather than the total number of offsite construction factories overseas in general.

Comparing the distribution of offsite construction projects (Figs. 2 and 3) as well as the distribution of the offsite construction factories (Figs. 4 and 5) on one hand with that of the location of the respondents (Fig. 1) on the other hand, it could be seen that there was no strong relationship between these locations. In fact, the offsite construction projects and factories are more distributed among the different states in the US because most of the surveyed respondents had the freedom to select as many US state locations as they

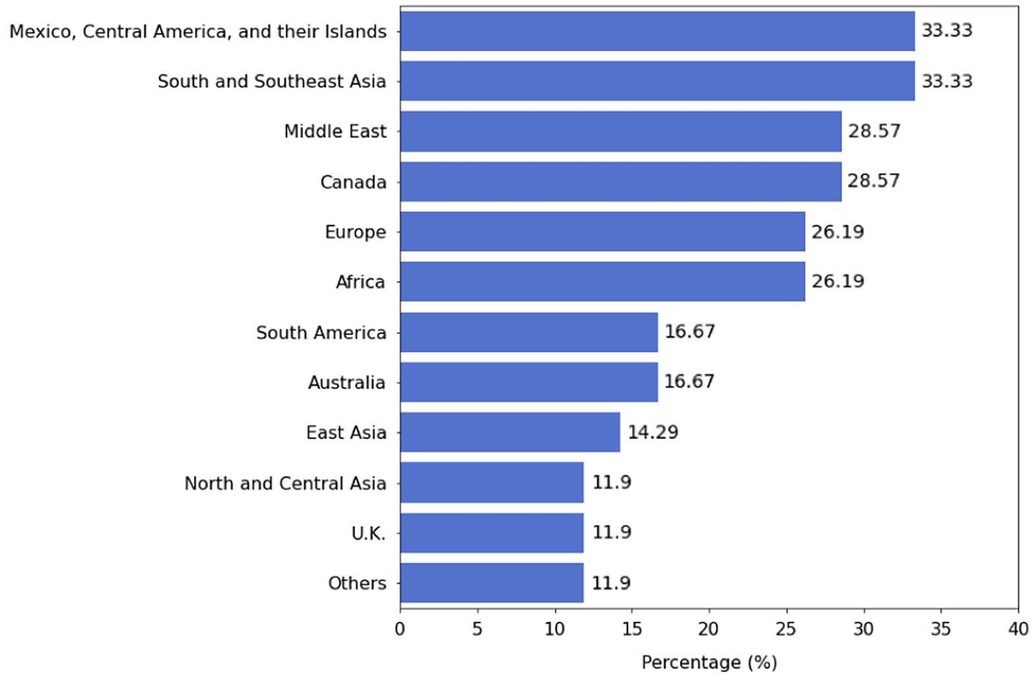

Fig. 3. Distribution of the final location of international offsite construction projects.

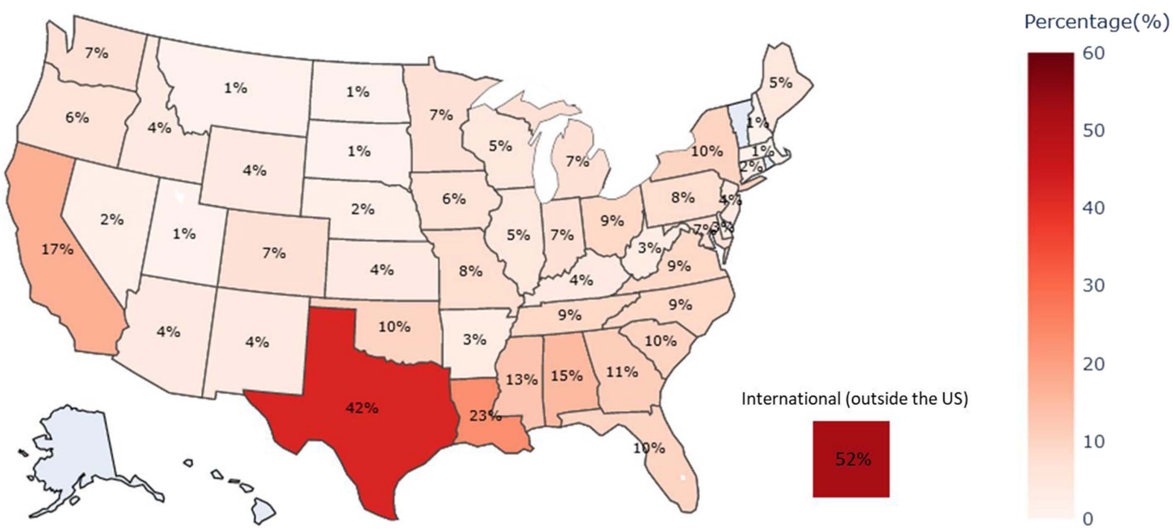

Fig. 4. Distribution of offsite construction factories.

wanted for their executed offsite construction projects as well as offsite construction factories. This was implemented in the questionnaire design to ensure a better and more accurate representation of the offsite construction market.

The only commonality among the locations of the surveyed industry practitioners, the offsite construction projects, and the offsite construction facilities is that Texas had the highest percentage among the different US states. This could be justified due to the fact that Texas actually possesses the highest estimated percentage use of offsite construction in the US (FMI 2018), with the state's total construction pipeline worth more than $425 billion (Slowey 2019). This means that it would be anticipated that many offsite construction projects and facilities are based in Texas, which also reflects that many offsite construction industry practitioners are also based in Texas, as seen in the obtained results.

Offsite Construction Characteristics

The measure of internal reliability (internal consistency) was assessed using the Cronbach's alpha and the interrater agreement (external reliability) was assessed using the ICC. For the offsite construction characteristics, the Cronbach's alpha for the 2020 data is 0.829 with a 95% confidence interval of [0.775, 0.874], and the Cronbach's alpha for the 2030 data is 0.815 with a 95% confidence interval of [0.757, 0.864]. The ICC for the 2020 data is 0.881 with a 95% confidence interval of [0.770, 0.960], and the ICC for the 2030 data is 0.958 with a 95% confidence interval of [0.920, 0.980]. Because all Cronbach's alpha coefficients are higher than 0.75, it was concluded that the established questionnaire is valid and reliable (Christmann and Aelstb 2006). Also, because all obtained ICC were greater than 0.75, it was concluded that there is an excellent

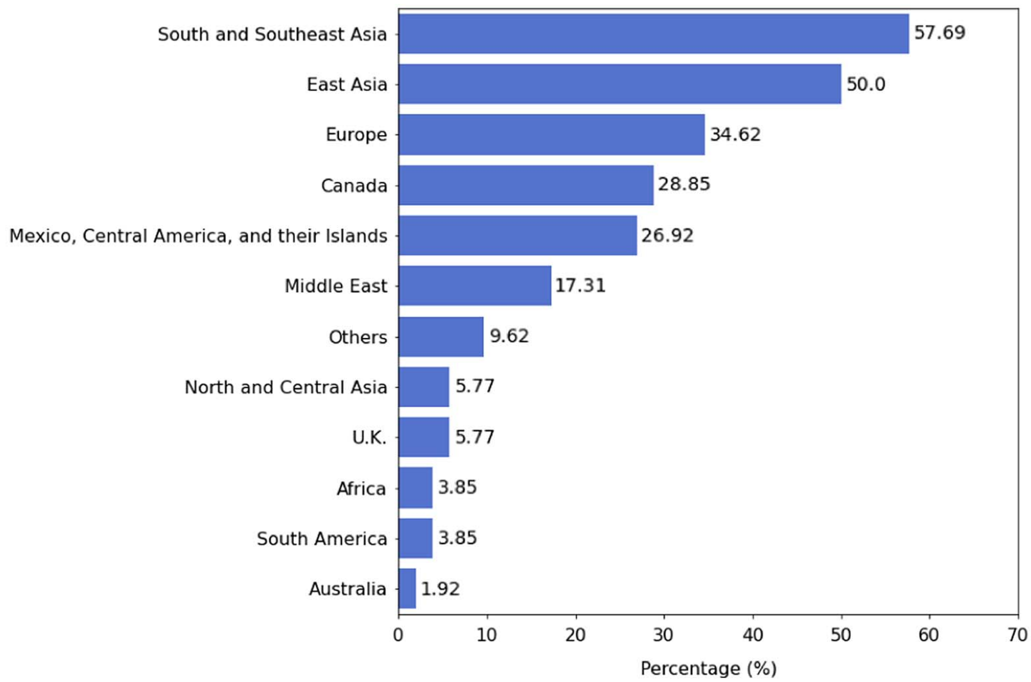

Fig. 5. Distribution of the location of international offsite construction factories.

agreement and consistency among the 100 surveyed industry practitioners (Cicchetti and Sparrow 1981).

The next subsections detail the obtained results as related to the following offsite construction characteristics: offsite construction typologies, type of offsite construction components, type of offsite construction structures, labor skillset for offsite construction, and labor skill level for offsite construction.

Offsite Construction Typologies

The following offsite construction typologies or methods were considered: single-trade prefabrication, multitrade prefabrication, preassembly, and modularization. Table 2 provides the results for the current and expected degree of use for the different offsite construction typologies.

Table 2 reflects that single-trade prefabrication is currently the most used offsite construction typology or method in the industry, with an average percentage of projects relying on such method falling within the range of [41.20%, 64.60%]. However, it is predicted that modularization will be the most used method in the future, with around 64.85% to 86.35% of the projects relying on such typology.

Type of Offsite Construction Components

The following types of offsite construction components were considered: customized components and standard components. Customized components refer to components design and specifications that are unique to each offsite construction project, whereas standardized components refer to components design and specifications that are considered the industry standard and thus they are usually used on multiple offsite construction projects. The results are given in Table 3.

Table 3 reflects that customized components are currently the most used type of offsite construction components in the industry, with an average percentage of projects relying on such components falling within the range of [37.50%, 61.90%]. However, it is predicted that standardized components will be the most used type of components in the future, with around 55.50% to 79.10% of the projects relying on such components.

Type of Offsite Construction Structures

The following types of offsite construction structures were considered: portable or relocatable structures and permanent structures. Relocatable, or portable, structures or buildings are not fixed to the ground once delivered to the construction site from the offsite shop; thus, they are often used for a short-term period (few months/years). That is, the structure can be relocated and repurposed when needed. For example, a portable building that once served as labor housing can quickly be repurposed as an office. Permanent buildings or structures are attached to a permanent foundation once delivered to the construction site from the offsite

Table 2. Results for the degree of reliance on offsite construction typologies

Offsite construction typology	2020 Mean[a]	2020 Standard deviation	2020 Number of projects (%)	2020 Rank	2030 Mean[a]	2030 Standard deviation	2030 Number of projects (%)	2030 Rank
Single-trade prefabrication	3.12	1.15	[41.20, 64.60]	1	3.54	1.13	[52.15, 74.35]	4
Multitrade prefabrication	2.90	1.13	[35.65, 59.25]	3	3.90	0.83	[61.20, 83.70]	3
Preassembly	2.95	0.95	[35.75, 61.30]	2	3.97	0.78	[62.95, 85.20]	2
Modularization	2.84	1.06	[33.75, 58.05]	4	4.04	0.79	[64.85, 86.35]	1

[a]Based on 100 responses and on the 5-point Likert scale described in the "Formation of a Questionnaire" subsection.

Table 3. Results for the degree of reliance on the type of offsite construction components

Type of offsite construction components	2020				2030			
	Mean[a]	Standard deviation	Number of projects (%)	Rank	Mean[a]	Standard deviation	Number of projects (%)	Rank
Customized	3.00	1.06	[37.50, 61.90]	1	3.47	0.97	[49.70, 73.95]	2
Standard	2.88	0.89	[33.80, 59.80]	2	3.68	0.91	[55.50, 79.10]	1

[a]Based on 100 responses and on the 5-point Likert scale described in the "Formation of a Questionnaire" subsection.

Table 4. Results for the degree of reliance on the type of offsite construction structures

Type of offsite construction structures	2020				2030			
	Mean[a]	Standard deviation	Number of projects (%)	Rank	Mean[a]	Standard deviation	Number of projects (%)	Rank
Portable or relocatable	2.49	0.99	[25.05, 48.90]	2	3.47	1.07	[49.60, 72.85]	1
Permanent	2.62	1.11	[28.85, 52.05]	1	3.21	1.09	[43.20, 67.15]	2

[a]Based on 100 responses and on the 5-point Likert scale described in the "Formation of a Questionnaire" subsection.

Table 5. Obtained results for the degree of reliance on the labor skillset for offsite construction

Offsite construction labor skillset	2020				2030			
	Mean[a]	Standard deviation	Number of projects (%)	Rank	Mean[a]	Standard deviation	Number of projects (%)	Rank
Single-skilled	2.92	1.13	[35.90, 59.50]	1	3.08	1.15	[40.40, 63.80]	2
Multiskilled	2.67	0.97	[28.75, 53.50]	2	3.74	0.85	[56.70, 80.40]	1

[a]Based on 100 responses and on the 5-point Likert scale described in the "Formation of a Questionnaire" subsection.

Table 6. Results for the degree of reliance on the skill level for offsite construction

Offsite construction labor skill level	2020				2030			
	Mean[a]	Standard deviation	Number of projects (%)	Rank	Mean[a]	Standard deviation	Number of projects (%)	Rank
Low-skilled	2.26	1.01	[20.55, 42.75]	3	2.57	1.18	[28.70, 50.85]	3
Medium-skilled	2.77	0.85	[30.90, 57.05]	2	3.29	0.88	[44.70, 70.45]	2
High-skilled	3.17	0.96	[41.75, 67.00]	1	3.83	0.9	[59.35, 81.90]	1

[a]Based on 100 responses and on the 5-point Likert scale described in the "Formation of a Questionnaire" subsection.

shop. They are often used for a long-term period (decades) because the structure is designed to remain permanently in place. The results are given in Table 4.

Table 4 indicates that permanent offsite construction structures are currently the most used in the industry, with an average percentage of projects relying on such components falling within the range of [28.85%, 52.05%]. However, it is predicted that portable or relocatable offsite construction structures will be the most used in the future, with around 49.60% to 72.85% of the projects relying on such structures.

Labor Skillset for Offsite Construction

The following labor skillsets in offsite construction projects were considered: single-skilled and multiskilled. Single-skilled workers master one specific craft trade, whereas multiskilled laborers master multiple craft trades. The obtained results are presented in Table 5.

Table 5 reports that offsite construction activities are currently performed mostly by single-skilled laborers on an average percentage of projects falling within the range of [35.90%, 59.50%]. However, it is predicted that multiskilled laborers will have the most demand in the future, with around 56.70% to 80.40% of the projects relying on such labor skillset.

Labor Skill Level for Offsite Construction

The following labor skill levels in offsite construction projects were considered: low-skilled labor, medium-skilled labor, and high-skilled labor. A low-skilled workforce has a limited skill set and possesses minimal economic value for the work performed. A medium-skilled workforce possesses the basic knowledge, experience, or training to complete the work successfully. In general, the needed skills are not highly specialized but require more complexity than low-skilled tasks. A high-skilled workforce includes considerably trained, educated, or experienced labor that can complete more complex works. High-skilled labor is specialized and usually requires a prolonged period of training and experience. The results are presented in Table 6.

Table 6 indicates that offsite construction activities are currently performed mostly by high-skilled laborers on an average percentage

Table 7. Results for the degree of reliance on offsite construction typologies

Offsite construction characteristic	Aspect	χ^2 statistic	p-value
Offsite construction typology	Single-trade prefabrication	4.30	0.038*
	Multitrade prefabrication	25.07	<0.0001*
	Preassembly	26.13	<0.0001*
	Modularization	35.52	<0.0001*
Type of offsite construction components	Customized	5.88	0.015*
	Standard	16.88	<0.0001*
Type of offsite construction structures	Portable or relocatable	25.23	<0.0001*
	Permanent	9.00	0.003*
Offsite construction labor skillset	Single-skilled	0.78	0.378
	Multiskilled	31.06	<0.0001*
Offsite construction labor skill level	Low-skilled	3.05	0.081
	Medium-skilled	7.51	0.006*
	High-skilled	10.64	0.001*

Note: $^*p \leq 0.05$, which reflects that there is enough evidence to reject the null hypothesis (H_0: the 2030 data have the same frequencies as the 2020 data).

of projects falling within the range of [41.75%, 67.00%]. It is predicted that high-skilled laborers will also have the most demand in the future, with around 59.35% to 81.90% of the projects relying on such labor skill level.

Chi-Square Test for Offsite Construction Characteristics

As detailed in the "Methodology" section, the χ^2 statistical test was conducted in this paper to examine the current and expected future reliance on different offsite construction characteristics, including offsite construction typologies or methods, type of offsite construction components, type of offsite construction structures, labor skillset for offsite construction, and labor skill level for offsite construction. The obtained results of the conducted χ^2 statistical test are given in Table 7.

Table 7 reflects that only two offsite construction aspects (reliance on single-skilled labor and reliance on low-skilled labor) have a p-value greater than the critical value of 0.05, which reflects that there is not enough evidence about rejecting the null hypothesis (H_0: the 2030 data have the same frequencies as the 2020 data). On the other hand, all other aspects of offsite construction have a p-value less than the critical value of 0.05 (Table 7), which reflects that there is enough evidence to reject the null hypothesis. Thus, the results of the chi-square test show that the future offsite construction operations will generally be different from the current operations.

Offsite Construction Technologies

The industry practitioners were asked to rate on a 5-point Likert scale the level of reliance or use of different offsite construction–related technologies. The measure of internal reliability (internal consistency) was assessed using the Cronbach's alpha and the interrater agreement (external reliability) was assessed using the ICC. For the offsite construction technologies, the Cronbach's alpha for the 2020 data is 0.925, with a 95% confidence interval of [0.901, 0.944], and the obtained Cronbach's alpha for the 2030 data is 0.931, with a 95% confidence interval of [0.910, 0.949]. The ICC for the 2020 data is 0.985, with a 95% confidence interval of [0.980, 0.990], and the obtained ICC for the 2030 data is 0.986, with a 95% confidence interval of [0.980, 0.990]. Because all obtained Cronbach's alpha coefficients were higher than 0.75, it was concluded that the established questionnaire is valid and reliable (Christmann and Aelstb 2006). Also, because all obtained ICC values were greater than 0.75, it was concluded that there is an excellent agreement and consistency among the 100 surveyed industry practitioners (Cicchetti and Sparrow 1981). The results are presented in Table 8.

As detailed in the last column of Table 8, the top 10 technologies with the most potential to be of greater use and benefit in the future as compared with their current use include (1) drones and remote monitoring; (2) smart sensors; (3) artificial intelligence (AI), cognitive learning, and computer/machine vision; (4) extended reality (XR) which includes augmented reality (AR), virtual reality (VR), and mixed reality (MR); (5) integrated real-time project management information systems (PMIS) (cloud-, web-, or mobile-based); (6) wireless technology and 5G/*n*G networks; (7) big data, data analytics, and data ecosystem; (8) robotics; (9) internet of things (IoT); and (10) three-dimensional (3D)/four-dimensional (4D)/*n*-dimensional (*n*D) printing and additive manufacturing.

These top 10 technologies were ranked based on the mean difference between the 2030 data (reported in Column 5 in Table 8) and the 2020 data (reported in Column 2 in Table 8), where the higher the mean, the lower the rank number (i.e., a higher mean value reflects a higher use of the associated technology, which indicates that the technology should be within the top list that includes ranks 1 to 10). As an example, the technology referred to as drones and remote monitoring has a 2020 mean of 2.39 (Column 5 in Table 8) and a 2030 mean of 4.09 (Column 2 in Table 8), which reflects that the difference is $4.09 - 2.39 = 1.70$ (Column 8 in Table 8). This process was done for all 24 technologies. Because the 1.70 is the highest difference in Column 8 of Table 8, the drones and remote monitoring technology was assigned a rank of 1 (i.e., being the top technology). This was performed until all 24 technologies had been ranked from 1 to 24.

Cognitive learning is a self-learning programmed system that is based on a combination between AI and cognitive science (Furbach et al. 2019). This automated system can perform or augment tasks, improve its own performance, help better inform decisions, and achieve objectives that have traditionally needed human intelligence (Schatsky et al. 2015).

Although the list of 24 technologies in Table 8 was provided in the questionnaire so that all industry practitioners would assess the use of each one of these technologies, the industry practitioners were given the freedom to add any other technologies they believe are missing from the list.

Table 8. Results for the degree of reliance on offsite construction technologies

Technology	2020 Mean (A)	2020 Standard deviation	2020 Rank based on (A)	2030 Mean (B)	2030 Standard deviation	2030 Rank based on (B)	Difference between 2030 and 2020: Mean difference [(B)–(A)]	Difference between 2030 and 2020: Rank based on mean difference
3D/4D/*n*D laser or light scanning and photo/videogrammetry	2.64	0.93	10	3.94	0.84	11	1.30	15
Artificial intelligence, cognitive learning, and computer/machine vision	1.63	0.71	20	3.15	0.88	18	1.52	3
Big data, data analytics, and data ecosystem	2.26	0.91	14	3.67	0.96	13	1.41	7
3D/4D/*n*D printing and additive manufacturing	1.57	0.79	21	2.91	0.92	21	1.34	10
Extended reality (XR), which includes augmented reality (AR), virtual reality (VR), and mixed reality (MR)	1.76	0.81	19	3.28	1.01	16	1.52	4
Internet of things (IoT)	2.13	1.00	15	3.48	1.16	15	1.35	9
Nanotechnology	1.47	0.70	23	2.37	1.06	24	0.90	24
Blockchain	1.52	0.73	22	2.46	1.10	22	0.94	23
Cyborg (cybernetic organism) crew and wearables	1.43	0.70	24	2.43	1.18	23	1.00	22
Automation	2.35	0.88	13	3.59	0.99	14	1.24	16
Robotics	1.84	0.84	17	3.21	0.97	17	1.37	8
Instrumentation and control	2.99	1.04	3	4.01	0.88	10	1.02	21
Digital twin	1.84	0.88	18	3.14	1.15	19	1.30	14
Drones and remote monitoring	2.39	0.93	12	4.09	0.94	8	1.70	1
Geographic information system (GIS)	2.70	0.96	9	3.94	0.90	12	1.24	17
Material technology (such as smart, intelligent, and responsive materials)	1.87	0.80	16	3.08	1.11	20	1.21	18
Global positioning system (GPS), geofencing, and radio-frequency identification (RFID)	2.77	0.90	7	4.08	0.85	9	1.31	13
Predictive maintenance	2.78	0.93	6	4.10	0.78	6	1.32	12
Integrated real-time project management information systems (PMIS) (cloud-, web-, or mobile-based)	2.89	0.86	5	4.36	0.70	3	1.47	5
3D/4D/*n*D information modeling and rendering (such as BIM)	2.91	1.09	4	4.25	0.88	4	1.34	11
Wireless technology and 5G/*n*G networks	2.77	0.99	8	4.22	0.94	5	1.45	6
Computer modeling, simulation, and visualization	3.40	0.95	1	4.58	0.68	1	1.18	19
Cybersecurity	3.27	1.06	2	4.37	0.87	2	1.10	20
Smart sensors	2.57	0.97	11	4.10	0.93	7	1.53	2

Distribution of Work between Onsite and Offsite Construction

The industry practitioners were asked to specify the distribution (in terms of percentages) of the total worker hours in their offsite construction projects between worker hours performed only onsite, worker hours performed only offsite, and worker hours performed both onsite and offsite by the same labor. To avoid any possible biases and ensure reliable quantification and results, the respondents were only asked to rank their perceptions of the industry sector to which they belong rather than for all sectors. The results are shown in Fig. 6.

Fig. 6 shows that the current average percentage of the offsite construction scope as related to the overall project scope is 23.40% for pure offsite construction activities and 33.64% (23.40% + 10.24%) for offsite construction–related activities; whereas the average percentage of the onsite or stick-built construction scope is 66.36%. However, it is expected that the offsite construction–related scope will substantially grow to reach an average of 54.90% (40.51% + 14.39%) in the future, the pure offsite construction scope will reach an average of 40.51%, and the onsite or stick-built construction scope will decrease to an average of 45.1%. This trend of an increasing offsite construction percentage and a decreasing onsite percentage was seen for all the considered industry sectors in this paper: industrial sector, building and commercial sector, and infrastructure sector.

Comparing the industry sectors among each other in Fig. 6, the current average percentage of offsite construction is the highest in the industrial sector, followed by the building and commercial sector, and then by the infrastructure sector. However, Fig. 6 shows that all construction sectors can capitalize on the benefits of offsite construction in the future where the percentage use and reliance on the offsite construction scope is perceived to substantially increase in the future.

Future Offsite Construction Growth Trend and Growth Rate

The industry practitioners were asked to provide their perceptions on the future offsite construction growth trend. More specifically, the industry practitioners were provided with possible functions for the future offsite construction growth as shown in Fig. 7, and they were also given the option to specify any other trend that they saw appropriate. The results are presented in Fig. 8.

Fig. 8 shows that most industry practitioners (44%) perceived that the future offsite construction growth trend will be logistic. This is also seen in all industry sectors where most of the industry practitioners in each of these sectors perceived that the future trend will be similar to a logistic growth.

The logarithm growth is considered the inverse of the exponential growth in the sense that whereas the exponential growth starts slowly and then speeds up faster and faster, the logarithm growth starts fast and then gets slower and slower. In addition, the logistic growth could be thought of as a combination of the logarithmic growth and exponential growth because in the logistic growth, the

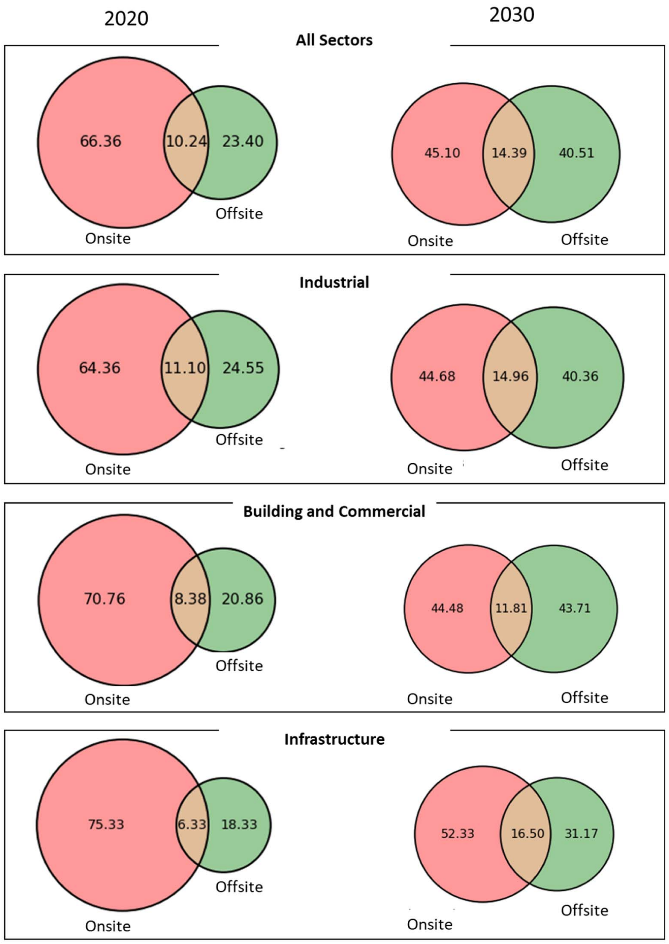

Fig. 6. Distribution of work (in %) between onsite and offsite construction.

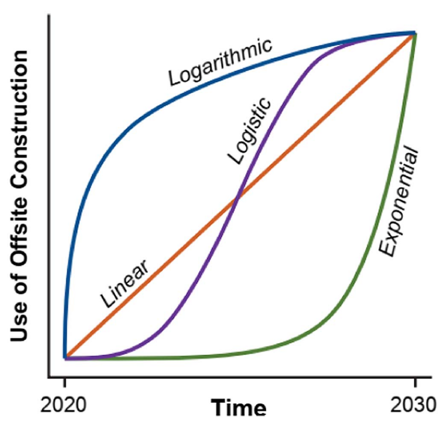

Fig. 7. Possible trends for the future offsite construction growth.

growth rate is slow at the beginning, quick in the middle, and then it begins to slow down later on. Furthermore, the linear growth has a constant growth rate throughout the entire period. Finally, the Others category in Fig. 8 included answers provided by the industry practitioners who opted to specify their own perception of the trend, and they included responses such as "a predicted growth trend which is a step function that is similar to the logistic but based on industry improvements and culture acceptance" as well as "a predicted growth trend which is flat with bumps as technology increases while trending in a linear fashion."

The industry practitioners were also asked to specify their perception of the future offsite construction growth rate in the coming decade compared with its growth rate in the previous decade. The obtained results are shown in Fig. 9.

Fig. 9 shows that most industry practitioners (87.0%) perceived that the future offsite construction growth rate in the coming decade will be higher than that in the previous decade. This is also seen in all industry sectors, where most of the industry practitioners in each of these sectors perceived that the future offsite construction growth rate in the coming decade will be higher than that in the previous decade. To better understand how comparable these two offsite construction growth rates are, the industry practitioners were asked to specify their perceptions on the magnitude of the 2020–2030 offsite construction growth rate compared with 2010–2020 growth rate. The results are given in Table 9.

The magnitude of the 2020–2030 offsite construction growth rate compared with the 2010–2020 growth rate was assessed based on an interval data where the surveyed practitioners were asked to enter any number they want. That being said, the mean reported in Table 9 is the average value of the entered numbers by the practitioners, which was obtained for the entire practitioners/respondents as well as for the individual sectors. Also, Q1, Q2, and Q3 in Table 9 represent the first (lower), second (median), and third (upper) quartiles, respectively.

Table 9 demonstrates that the industry practitioners perceived that offsite construction will grow 4.33 times, on average, in the coming decade compared with its growth in the last decade. Also, Table 9 indicates that all industry sectors perceived that the magnitude of the 2020–2030 offsite construction growth rate will be higher than that of the 2010–2020 growth, with the building and commercial sector being the most optimistic. The higher value for the building and commercial sector could be attributed to the fact that this sector has a great potential for offsite construction compared with other sectors because projects in the building and commercial sector usually have repetitive components and systems, which make them fit for offsite construction methods (Said 2015).

Offsite Capacity Utilization Rate

The industry practitioners were asked to provide the current offsite construction utilization rate in their offsite construction projects. In other words, they were asked to provide the current production capacity percentage that is being allocated to offsite construction compared with the overall potential capacity that the offsite facility can deliver. The results are given in Table 10.

Table 10 reveals that the current average offsite construction utilization rate ranges between 39.50% and 49.50%, which is not considered to be particularly high. Table 10 also indicates that the infrastructure sector currently has the highest average offsite construction utilization rate with a range between 60.0% and 70.0%, which is considered to be somehow high. Possible reasons behind not having a particularly high offsite construction utilization could be the lack of suitably skilled labor that can perform the offsite construction works, discrepancy between demand and supply, logistics-related constrains, lack of investment in offsite development, and the capacity of the offsite sector where offsite construction builders are generally relatively small players in the industry and some contractors have not wholly embraced offsite construction (Watson 2018).

The industry practitioners were also asked to specify "by how many folds" their company is willing to expand and invest in offsite

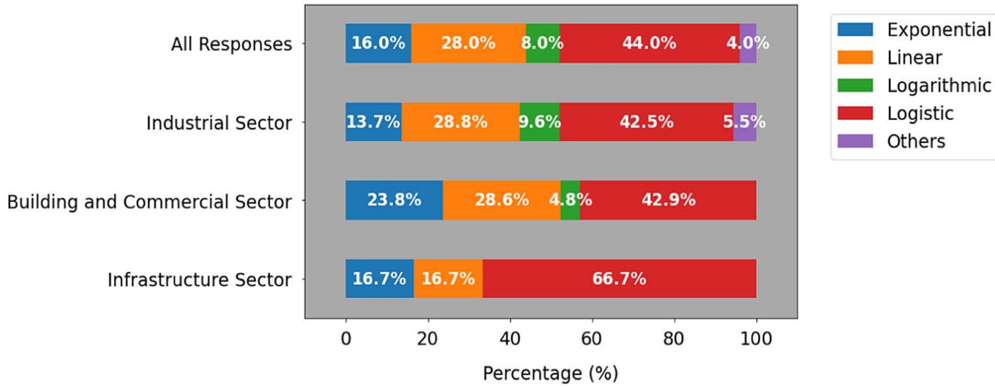

Fig. 8. Results for the future offsite construction growth.

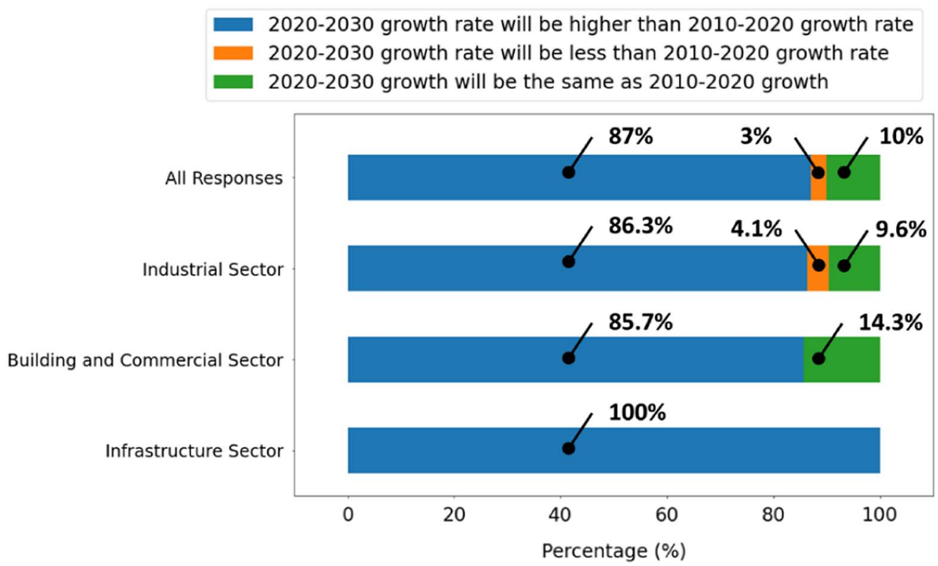

Fig. 9. Offsite construction growth rate for 2020–2030 compared with the 2010–2020 growth rate.

Table 9. Results for magnitude of 2020–2030 offsite construction growth rate compared with 2010–2020 growth rate

Sector	Mean	Q1	Q2	Q3
All sectors	4.33	1.62	2.00	3.00
Industrial	2.49	1.50	2.00	3.00
Building and commercial	10.61	2.00	3.00	4.00
Infrastructure	2.67	2.50	3.00	3.00

Table 10. Obtained results for the range for the average offsite construction utilization rate

Sector	Range for the average offsite construction utilization rate (%)	Mean (%)
All sectors	]39.50, 49.50]	44.50
Industrial	]38.90, 48.90]	43.90
Building and commercial	]35.71, 45.71]	40.71
Infrastructure	]60.00, 70.00]	65.00

Table 11. Results for the magnitude of the 2030 offsite construction capacity utilization rate compared with that of 2020

Sector	Mean	Q1	Q2	Q3
All sectors	5.03	1.50	2.00	3.00
Industrial	4.22	1.50	2.00	3.00
Building and commercial	8.50	2.00	3.00	4.00
Infrastructure	2.08	2.00	2.00	2.00

construction by increasing its offsite capacity in the future. The obtained results are presented in Table 11.

Table 11 indicates that companies are planning to increase their offsite construction utilization rate by an average of 5.03-fold, with the building and commercial sector being the most optimistic. The obtained results for the offsite construction utilization rate are in conformity with the previous findings showing that the current reliance on offsite construction methods is not particularly high; however, the future offsite construction market is perceived to be huge where the reliance on offsite construction will substantially increase. Also, the deviation between the values in Table 11 for the different industry sectors is similar to those obtained previously in Table 9, where the building and commercial sector has the highest value, which could be attributed to the fact that offsite construction manufacturers and organizations are becoming knowledgeable and skilled across the array of different project types in the building and commercial sector (Smith 2016), which makes them specifically focusing on using offsite construction methods in this sector due to its a great potential to repetitive components and systems suited for offsite construction methods.

Table 11 reflects that the future offsite construction market is perceived to grow in all the various sectors but in a nonuniform way, where different sectors have different prospective offsite construction developments.

Distribution of Work between Human Labor and Automated Activities

Finally, industry practitioners were asked to provide the distribution of the offsite construction work hours (in terms of percentages) between human labor and completely automated activities. The obtained results are presented in Table 12.

Table 12 demonstrates that the current range for the average percentage of automated offsite worker hours is between 34.60% and 44.60% and that it will increase by an average of 7.00% in the future. The results also show that the infrastructure sector was perceived to have the highest average increase of 15.00% in the automation percentage, followed by the building and commercial sector, with an average increase of 13.33% in the automation percentage, and then by the industrial sector, with an average increase of 4.52% in the automation percentage.

Discussion and Contributions

This section discusses the obtained findings and highlights the contributions of this paper.

Distribution of Offsite Construction

The findings of this research illustrate that there is a considerable reliance on the international market in terms of both the location of the executed offsite construction projects (42%) as well as the location of the offsite construction facilities or shops (52%). Although this might provide some benefits in terms of offering industry practitioners the opportunity to learn from the international, and in some instances more advanced, offsite construction professionals as well as to be exposed to the latest offsite construction methods worldwide, this also poses some concerns or challenges related to the displacement of the workforce. The displacement of the workers could further exacerbate the shortage in skilled labor in the construction industry (Wong et al. 2017).

In fact, current laborers already face risks of being displaced from their jobs and ultimately being replaced by workers that are experienced with the offsite construction–related skills (OECD 2018). To avoid being displaced, the onsite construction laborers must be willing to acquire the needed skills for offsite construction, should not be resistant to shift toward performing offsite construction–related activities, and should possess the right mindset that offsite construction is the future of the industry. Also, the construction companies should help the craft onsite workforce by designing and implementing proper training programs and plans.

Furthermore, there is some consensus that the geographic distribution of offsite construction is uneven or irregular, with some regional hubs of expertise and activity and a large concentration of offsite construction is some locations compared with others (Vokes and Brennan 2013), mostly on large-scale construction projects such as infrastructure projects, building and commercial projects, and industrial facilities. Another point worth mentioning is that the distribution of offsite construction might even be different depending on the nature of the area being urban or rural. Although previous literature has acknowledged that the provision of offsite fabricated facilities may particularly benefit rural locations by delivering a completed house or house-part to underresourced locations (Blismas et al. 2010), this does not necessarily imply that the businesses serving these locations would not base themselves in a central urban location (Steinhardt et al. 2014).

Changes in Offsite Construction

The findings and contributions of this paper also show that the future offsite construction operations will be different from the current operations in many aspects, such as shifting from single-trade fabrication to modularization, shifting from customized offsite construction components to standardized offsite construction components, shifting from permanent offsite construction structures to relocatable or portable offsite construction structures, and shifting the reliance on single-skilled labor to multiskilled labor. In fact, this shift is believed to be beneficial for the overall industry as well as for the construction companies. For instance, the reliance on modular construction provides a faster speed of build because entire preassembled and integrated modular construction systems require very minimal onsite works compared with prefabrication or other offsite construction typologies or methods, which could help in better avoiding and minimizing tolerance and interface issues (O'Connor et al. 2014). Also, the reliance on standardization rather than customization provides many added benefits or advantages, including lower production and procurement costs through economies of scale, easier and less expensive repair and replacement, and faster and more efficient processes, among many others (Liu and Ramakrishna 2021). Moreover, relocatable or portable offsite construction structures provide more flexibility compared with permanent offsite construction structures in terms of repurposing the intended use of the structure, carrying it to various construction sites, having the potential to be onsite and ready to use within weeks (rather than the months required for permanent structures), being ideal for situations that demand quick construction and future relocation, and being easier to transport or reinstall (Modular Building Institute 2021). Finally, the multiskilled labor used in offsite construction could provide

Table 12. Obtained results for the range for the percentage of automated offsite workhours

Sector	2020 Range	2020 Mean (%)	2030 Range	2030 Mean (%)	Change between 2020 and 2030 (%)
All sectors	[34.60, 44.60[	39.60	[41.60, 51.60[	46.60	7.00
Industrial	[36.44, 46.44[	41.44	[40.96, 50.96[	45.96	4.52
Building and commercial	[30.48, 40.48[	35.48	[43.81, 53.81[	48.81	13.33
Infrastructure	[26.67, 36.67[	31.67	[41.67, 51.67[	46.67	15.00

J. Constr. Eng. Manage., 2022, 148(7): 04022055

many benefits and opportunities, as listed by Kelchner (2021), including increased productivity, reduced labor costs, fewer idle work hours, efficiency in planning workers, better workers' job satisfaction, consistently in learning new skills to adapt to changes in production, providing the flexibility to move workers where they are needed from one moment to another by having the ability to schedule and arrange workers to best suit the needs, and maintaining production levels under many circumstances that would otherwise leave workers idled or profits left on the table. The results also showed that offsite construction needs high-skilled labor in the future.

Construction Technologies

The contributions also touched upon the key technologies that construction companies shall invest in and consider leveraging in their operations in the future. However, the construction industry is known for its limited technology-related budget and scope allocated by construction companies because firms are spending less than 1% of their annual revenues/sales on technology, thus making the construction industry lag behind all other industries (JBKnowledge 2018). A study conducted by Construction Dive showed that 61% of contractors in North America cited worries over field worker acceptance as the biggest hurdle to adopting technologies (Biggs 2018). In fact, the construction industry's hesitancy to adopt new technologies created a $1.6 trillion gap in potential earnings (Fish 2019).

Therefore, this research found that offsite construction provides numerous opportunities for leveraging many technologies that can improve the efficiency of the production operations. For example, offsite construction could help in better digitalization of the construction industry through continuous improvement and the emerging paradigm shifts in relation to new manufacturing techniques and production methods. As such, to ensure success and viability in the future, construction companies need to swiftly advance the adoption of offsite construction technologies and techniques. Construction companies that are more open-minded to the idea of integrating technologies are perceived to be at a competitive advantage (Biggs 2018). In fact, offsite construction is considered one of the main disruptions in the construction industry (Assaad et al. 2021, 2020b). Therefore, construction organization are recommended to invest in offsite construction technologies highlighted in this research so that they remain competitive with other companies that have already embraced or used the recent advancements in offsite construction–related technologies. The construction workforce should be prepared and well-trained for the use and implementation of the offsite construction technological developments.

Offsite Construction Potential

The findings and contributions of the paper are in alignment with other reports that shed light on the potential of offsite construction. For instance, a study conducted by Market Research Future (2017) predicted that the market for offsite/modular construction will flourish, with a compound annual growth rate of 5.95% and a global market value of $154.8 million by the end of their forecast period (i.e., 2026). Another study conducted by Frost & Sullivan (2019) established that the global market of modular/offsite construction will grow to reach $215 billion (in revenues) in 2025, with a compound annual growth rate of 6.3% as a result of the uptick in construction activities and significant cost, labor, and time savings associated with offsite construction (Limaye 2019).

Offsite Construction Automation

This research also showed that there are opportunities to increase the level of automation in the offsite construction operations and activities. In fact, it is believed that the engineering and construction industry is able to move beyond offsite construction toward true manufacturing of the built environment (FMI 2018). Such a move toward more automated processes or real manufacturing practices is an important solution to alleviate the workforce issues and labor shortage that is facing the industry because automated offsite construction operations can substantially reduce the reliance on scarce skilled labor and maximize productivity. However, the industry and the construction firms will need to find a balance between human labor–based activities and completely automated operations so as not to impact construction workforce due to an expected less demand on low-skilled laborers and higher demand for high-tech and more skilled ones.

Thus, the findings suggest that automation can facilitate offsite construction production activities through programmable computer-controlled and mechanized systems that can be integrated with other technologies. An example of such technologies is BIM, which is considered one of the main disruptions that can digitalize and automate the offsite construction–related activities in terms of planning, design, construction, and project management. In fact, BIM is vital for offsite construction to ensure transparency, traceability, and immutability throughout the entire supply chain management process (Li et al. 2022). BIM technology has shown its usefulness in facilitating effective data management and representation of sensory components of offsite construction elements and systems by rendering and visualizing different information. Ramaj et al. (2017) identified the following seven major incentives for adoption of BIM in offsite construction projects: improved module coordination, reduction in rework, reduction in repetitive errors, improved engineering analyses, improved quality, improved efficiency through reusing building information models of modules, and improved communication on complex projects.

Future Growth of Offsite Construction

Finally, this research showed that offsite construction will become the norm rather than the exception. Specifically, (1) it is expected that the offsite construction–related scope will substantially grow to reach an average of 54.90% in the future, (2) the industry practitioners perceived that the offsite construction will grow 4.33 times, on average, in the coming decade compared with its growth in the last decade, (3) companies are planning to increase their offsite construction utilization rate by an average of 5.03-fold, and (4) the offsite construction automation percentage will increase by 7.00%. Therefore, rather than viewing offsite construction as a threat or negative disruption, construction organizations that embrace it will be best positioned to win in the built environment of today and tomorrow. In conclusion, the future is bright for continued growth in offsite construction methods.

Validation of the Research Outputs

The research findings were validated by 11 experts that have an average experience of 25.45 years in the US construction industry and an average offsite construction experience of 14.55 years. These experts were asked to assess the obtained results and interpretations from the questionnaire. The experts were also requested to evaluate whether the questionnaire successfully captured the main aspects of the offsite construction market and whether the questions are indicative of the characteristics of offsite construction methods that are of particular importance to the industry.

The results from the validation efforts reflected that the interviewed experts confirmed the usefulness and benefits of the research findings by being representative of the state of practice of offsite construction in the US and its future potential. These experts also stressed the adequacy and suitability of the research outcomes in relation to the current and future prospects of offsite construction methods and the perceived changes in this market. Ultimately, these experts emphasized the value and significance of this research, its generalizability to the industry, and its applicability to industry practices.

Limitations and Future Work

Despite the research team's efforts in minimizing biases in the different methodology steps followed in this paper, this does not nullify that there are limitations in the conducted research. These limitations include potential inherent biases in the focus of this research and the sampling process of the distributed questionnaire. More specifically, the findings of this paper are limited to the offsite construction industry in the US rather than worldwide because the questionnaire's respondents were selected in a way that they had experience with the US construction industry in specific. Another limitation includes the selection or recruitment of the respondents based on accessibility and availability (i.e., purposeful sampling) identified by the RT-371 industry members and CII research collaborators. Nevertheless, the research team tried to reduce these inherent biases as much as possible by pilot testing the questionnaire before distributing it, examining both its internal and external reliability after collecting the data from the respondents, and further validating the findings and interpretations by external experts.

Future research work could be directed toward assessing the state of practice of offsite construction in different geological areas (and not only the US) so that a comparative analysis could be conducted to better understand the maturity of offsite construction methods in different countries. Further research work could also include identifying and examining best practices that would help and assist companies in leveraging offsite construction techniques and technologies to achieve the perceived increased reliance on such methods in the future (i.e., 2030 or even beyond).

Conclusion

This research studied the state of practice of offsite construction and its associated technologies. This study (1) investigated the geographical distribution of offsite construction projects and the offsite construction fabrication shops; (2) examined the current and expected future reliance on different offsite construction characteristics including offsite construction typologies or methods, type of offsite construction components, type of offsite construction structures, labor skillset for offsite construction, and labor skill level for offsite construction; (3) determined the current use and future potential of offsite construction–related technologies; (4) provided better understanding of the distribution of work between onsite and offsite locations; (5) explored the future offsite construction growth trend and growth rate; (6) evaluated the offsite capacity utilization rate; and (7) assessed the distribution of work between human labor and automated offsite construction activities.

The outcomes showed that the future offsite construction operations in 2030 will be different from the current operations in 2020 in many aspects, such as shifting from single-trade fabrication to modularization, shifting from customized offsite construction components to standardized offsite construction components, shifting from permanent offsite construction structures to relocatable or portable offsite construction structures, and shifting the reliance on single-skilled labor to multiskilled labor. The findings also provided guidance on the key technologies that construction companies shall invest in and consider leveraging in their offsite construction operations. It was concluded that offsite construction will become the norm rather than the exception and that the future is bright for continued growth in offsite construction methods.

This paper adds to the body of knowledge by quantifying the state of practice of offsite construction and its technologies in terms of current trends and future prospects. This research helps construction firms understand the evolving use of offsite construction and consequently allocate resources appropriately. Ultimately, this study is a valuable reference for both practitioners and researchers in relation to the status of offsite construction.

Data Availability Statement

All data generated or analyzed during the study are included in the published article.

Acknowledgments

This research was collaboratively carried out by the authors through funding provided by the Construction Industry Institute (CII) at the Missouri University of Science and Technology, Purdue University, and the University of Arkansas under CII RT-371. To this end, the authors are very thankful for the financial and logistical support provided by CII. Also, the authors deeply appreciate and value the efforts and the insightful guidance provided by the CII RT-371 industry team members who offered a wealth of knowledge and real-world experience with exceptional dedication.

References

Abdul Nabi, M., and I. El-adaway. 2021. "Understanding the key risks affecting cost and schedule performance of modular construction projects." *J. Manage. Eng.* 37 (4): 04021023. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000917.

Ahn, S., L. Crouch, T. W. Kim, and R. Rameezdeen. 2020. "Comparison of worker safety risks between onsite and offsite construction methods: A site management perspective." *J. Constr. Eng. Manage.* 146 (9): 05020010. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001890.

Akofio-Sowah, M. A., R. Boadi, A. Amekudzi, and M. Meyer. 2014. "Managing ancillary transportation assets: The state of the practice." *J. Infrastruct. Syst.* 20 (1): 04013010. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000162.

Assaad, R., M. O. Ahmed, I. H. El-adaway, A. Elsayegh, and V. S. Siddhardh Nadendla. 2021. "Comparing the impact of learning in bidding decision-making processes using algorithmic game theory." *J. Manage. Eng.* 37 (1): 04020099. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000867.

Assaad, R., and I. H. El-adaway. 2021. "Impact of dynamic workforce and workplace variables on the productivity of the construction industry: New gross construction productivity indicator." *J. Manage. Eng.* 37 (1): 04020092. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000862.

Assaad, R., I. H. El-adaway, and I. S. Abotaleb. 2020a. "Predicting project performance in the construction industry." *J. Constr. Eng. Manage.* 146 (5): 04020030. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001797.

Assaad, R., I. H. El-adaway, M. Hastak, and K. L. Needy. 2020b. "Commercial and legal considerations of offsite construction projects and their hybrid transactions." *J. Constr. Eng. Manage.* 146 (12): 05020019. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001948.

Assaad, R., I. H. El-adaway, M. Hastak, and K. L. Needy. 2022. "The impact of offsite construction on the workforce: Required skillset and prioritization of training needs." *J. Constr. Eng. Manage.* 175 (Feb): 121394.

Balasubramanian, N. 2012. "Likert technique of attitude scale construction in nursing research." *Asian J. Nursing Educ. Res.* 2 (2): 22.

Baldwin, A., C.-S. Poon, L.-Y. Shen, S. Austin, and I. Wong. 2009. "Designing out waste in high-rise residential buildings: Analysis of precasting methods and traditional construction." *Renew. Energy* 34 (9): 2067–2073.

Bayraktar, M. E., Q. Cui, M. Hastak, and I. Minkarah. 2004. "State-of-practice of warranty contracting in the United States." *J. Infrastruct. Syst.* 10 (2): 60–68.

Bekdik, B. 2017. "Improving productivity in building construction—By repetitions in products, processes, and organisations." Doctoral dissertation, Dept. of Management Engineering, Technical Univ. of Denmark.

Biggs, J. 2018. "Getting ahead of construction tech adoption challenges." Accessed January 16, 2020. https://jobsite.procore.com/getting-ahead-of-construction-tech-adoption-challenges/.

Blismas, N., R. Wakefield, and B. Hauser. 2010. "Concrete prefabricated housing via advances in systems technologies: Development of a technology roadmap." *Eng. Constr. Archit. Manage.* 17 (1): 99–110.

Boktor, J., A. Hanna, and C. C. Menassa. 2014. "State of practice of building information modeling in the mechanical construction industry." *J. Manage. Eng.* 30 (1): 78–85.

Cho, K., S. Ahn, K. Park, and T. W. Kim. 2021. "Schedule delay leading indicators in precast concrete construction projects: Qualitative comparative analysis of Korean cases." *J. Manage. Eng.* 37 (4): 04021024. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000915.

Choi, J. O. 2014. "Links between modularization critical success factors and project performance." Doctoral dissertation, Dept. of Civil, Architectural, and Environmental Engineering, Univ. of Texas at Austin.

Choi, J. O., J. T. O'Connor, and T. W. Kim. 2016. "Recipes for cost and schedule successes in industrial modular projects: Qualitative comparative analysis." *J. Con. Eng. and Man.* 142 (10): 04016055. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001171.

Choi, J. O., B. K. Shrestha, Y. H. Kwak, and J. S. Shane. 2020. "Innovative technologies and management approaches for facility design standardization and modularization of capital projects." *J. Manage. Eng.* 36 (5): 04020042. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000805.

Christmann, A., and S. V. Aelst. 2006. "Robust estimation of Cronbach's alpha." *J. Mult. Anal.* 97 (7): 1660–1674.

Cicchetti, D. V., and S. A. Sparrow. 1981. "Developing criteria for establishing interrater reliability of specific items: Applications to assessment of adaptive behavior." *Am. J. Mental Deficiency* 1981 (Jan): 1–9.

CII (Construction Industry Institute). 2021a. "CII research." Accessed February 23, 2021. https://www.construction-institute.org/groups/standing-committees/funded-studies-committee/cii-research.

CII (Construction Industry Institute). 2021b. "Research programs." Accessed February 23, 2021. https://www.construction-institute.org/groups/standing-committees/funded-studies-committee/research-programs.

Cochran, W. G. 1977. *Sampling techniques*. 3rd ed. New York: Wiley.

Collin, J. G. 2007. "US State-of-practice for the design of the geosynthetic reinforced load transfer platform in column supported embankments." In *Soil improvement*, 1–12. Reston, VA: ASCE.

Connelly, L. M. 2008. "Pilot studies." *Medsurg Nursing* 17 (6): 411.

Cooper, D. R., and P. S. Schindler. 2006. *Business research methods*. Boston: McGraw-Hill.

Dou, Y., X. Xue, C. Wu, X. Luo, and Y. Wang. 2020. "Interorganizational diffusion of prefabricated construction technology: Two-stage evolution framework." *J. Constr. Eng. Manage.* 146 (9): 04020114. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001904.

Feghaly, J., M. El Asmar, and S. T. Ariaratnam. 2020. "State of professional practice for water infrastructure project delivery." *Pract. Period. Struct. Des. Constr.* 25 (3): 04020018. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000500.

Fish, J. 2019. "The future of construction will be changed by technology." Accessed January 16, 2020. https://rew-online.com/2019/11/the-future-of-construction-will-be-changed-by-technology/.

FMI (Fails Management Institute). 2018. "New day, new mindset: Rethinking offsite construction." Accessed November 17, 2019. https://www.fminet.com/special-reports/2018-fmi-curt-cii-owner-survey/.

Frost & Sullivan. 2019. "Global modular and prefabricated building market set for robust CAGR of 6.3% from 2018 to 2025." Accessed February 24, 2021. https://ww2.frost.com/news/press-releases/global-modular-and-prefabricated-building-market-set-for-robust-cagr-of-6-3-from-2018-to-2025/.

Furbach, U., S. Hölldobler, M. Ragni, C. Schon, and F. Stolzenburg. 2019. "Cognitive reasoning: A personal view." *KI-Künstliche Intelligenz* 33 (3): 209–217. https://doi.org/10.1007/s13218-019-00603-3.

Gosling, J., M. Pero, M. Schoenwitz, D. Towill, and R. Cigolini. 2016. "Defining and categorizing modules in building projects: An international perspective." *J. Constr. Eng. Manage.* 142 (11): 04016062. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001181.

Hanna, A., F. Boodai, and M. El Asmar. 2013. "State of practice of building information modeling in mechanical and electrical construction industries." *J. Cons. Eng. Manage.* 139 (10): 04013009. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000747.

Hanna, A. S., M. Yeutter, and D. G. Aoun. 2014. "State of practice of building information modeling in the electrical construction industry." *J. Cons. Eng. Manage.* 140 (12): 05014011. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000893.

Hastak, M., and C. Koo. 2017. "Theory of an intelligent planning unit for the complex built environment." *J. Manage. Eng.* 33 (3): 04016046. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000486.

Jaillon, L., and C. S. Poon. 2008. "Sustainable construction aspects of using prefabrication in dense urban environment: A Hong Kong case study." *Constr. Manage. Econ.* 26 (9): 953–966.

JBKnowledge. 2018. "Construction technology report." Accessed November 17, 2019. https://jbknowledge.com/2018-construction-technology-report-survey.

Jeanjean, P. 2012. "State of practice: Offshore geotechnics throughout the life of an oil and gas field." In *Geotechnical engineering state of the art and practice: Keynote lectures from GeoCongress 2012*, 643–677. Reston, VA: ASCE.

Ji, W., S. M. AbouRizk, O. R. Zaïane, and Y. Li. 2018. "Complexity analysis approach for prefabricated construction products using uncertain data clustering." *J. Constr. Eng. Manage.* 144 (8): 04018063. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001520.

Kelchner, L. 2021. "The advantages of multi-skilled labor." Accessed February 24, 2021. https://smallbusiness.chron.com/advantages-multiskilled-labor-18280.html.

Koo, T. K., and M. Y. Li. 2016. "A guideline of selecting and reporting intraclass correlation coefficients for reliability research." *J. Chiropr. Med.* 15 (2): 155–163. https://doi.org/10.1016/j.jcm.2016.02.012.

Lee, J., and H. Hyun. 2019. "Multiple modular building construction project scheduling using genetic algorithms." *J. Constr. Eng. Manage.* 145 (1): 04018116. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001585.

Lee, Y., J. I. Kim, A. Khanzode, and M. Fischer. 2021. "Empirical study of identifying logistical problems in prefabricated interior wall panel construction." *J. Manage. Eng.* 37 (3): 05021002. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000907.

Lerche, J., H. H. Neve, G. Ballard, J. Teizer, S. Wandahl, and A. Gross. 2020. "Application of last planner system to modular offshore wind construction." *J. Constr. Eng. Manage.* 146 (11): 05020015. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001922.

Lessing, J., and S. Brege. 2018. "Industrialized building companies' business models: Multiple case study of Swedish and North American companies." *J. Constr. Eng. Manage.* 144 (2): 05017019. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001368.

Li, X., W. Lu, F. Xue, L. Wu, R. Zhao, J. Lou, and J. Xu. 2022. "Blockchain-enabled IoT-BIM platform for supply chain management in modular construction." *J. Constr. Eng. Manage.* 148 (2): 04021195. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002229.

Lim, I., J. Sawab, J. Wang, S. Fan, Y. L. Mo, and M. Li. 2021. "Characterization of ultrahigh-performance concrete materials for application in modular construction." *J. Mater. Civ. Eng.* 33 (5): 04021087. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003674.

Lima, R., D. F. de Noronha Osório, and H. Gamboa. 2019. "Heart rate variability and electrodermal activity in mental stress aloud: Predicting the outcome." In *Biosignals*, 42–51. Hampshire, UK: Science and Technology Publications.

Limaye, P. 2019. "Modular market predicted to grow to $215 billion by 2025." Accessed January 16, 2020. https://www.curt.org/modular-market-predicted-to-grow-to-215-billion-by-2025/.

Liu, L., and S. Ramakrishna. 2021. *An introduction to circular economy.* Berlin: Springer.

Loo, B. P. 2002. "Role of stated preference methods in planning for sustainable urban transportation: State of practice and future prospects." *J. Urban Plann. Dev.* 128 (4): 210–224.

Lopes, G. C., R. Vicente, M. Azenha, and T. M. Ferreira. 2018. "A systematic review of prefabricated enclosure wall panel systems: Focus on technology driven for performance requirements." *Sustainable Cities Soc.* 40 (8): 688–703.

Lu, N., 2009. "The current use of offsite construction techniques in the United States construction industry." In *Construction research congress 2009: Building a sustainable future*, 946–955. Reston, VA: ASCE.

Market Research Future. 2017. "Modular construction market research report: Forecast to 2023." Accessed February 1, 2021. https://www.marketresearchfuture.com/reports/modular-construction-market-1682.

McHugh, M. L. 2012. "Interrater reliability: The kappa statistic." *Biochem Med (Zagreb)* 22 (3): 276–282.

Mehdizadeh, M. J., N. Shariatmadari, and M. Karimpour-Fard. 2020. "Probabilistic slope stability analysis in Kahrizak landfill: Effect of spatial variation of MSW's geotechnical properties." *Bull. Eng. Geol. Environ.* 79 (5): 2679–2695.

Modular Building Institute. 2021. "Relocatable buildings vs. permanent modular construction: What's the difference?" Accessed February 24, 2021. https://www.modular.org/HtmlPage.aspx?name=MA-f-rb-v-pmc.

Munvar, C., D. G. Mengistu, and G. Mahesh. 2020. "Concurrent delay analysis: Methods, case law, and expert perception." *J. Leg. Aff. Dispute Resolut. Eng. Constr.* 12 (1): 04519035. https://doi.org/10.1061/(ASCE)LA.1943-4170.0000343.

Nikolaou, S., J. E. Go, C. Z. Beyzaei, C. Moss, and P. W. Deming. 2012. "Geo-seismic design in the Eastern United States: State of practice." In *Geotechnical engineering state of the art and practice*, 828–854. Reston, VA: ASCE.

O'Connor, J. T., W. J. O'Brien, and J. O. Choi. 2013. *Industrial modularization how to optimize; how to maximize*. Austin, TX: Univ. of Texas at Austin.

O'Connor, J. T., W. J. O'Brien, and J. O. Choi. 2014. "Critical success factors and enablers for optimum and maximum industrial modularization." *J. Cons. Eng. Manage.* 140 (6): 04014012. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000842.

O'Connor, J. T., W. J. O'Brien, and J. O. Choi. 2015. "Standardization strategy for modular industrial plants." *J. Constr. Eng. Manage.* 141 (9): 04015026. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001001.

O'Connor, J. T., W. J. O'Brien, and J. O. Choi. 2016. "Industrial project execution planning: Modularization versus stick-built." *Pract. Period. Struct. Des. Constr.* 21 (1): 04015014. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000270.

OECD (Organisation for Economic Co-Operation and Development). 2018. "Transformative technologies and jobs of the future." Accessed November 17, 2019. https://www.oecd.org/innovation/transformative-technologies-and-jobs-of-the-future.pdf.

Pan, W., and C. K. Hon. 2020. "Briefing: Modular integrated construction for high-rise buildings." In Vol. 173 of *Proc., Institution of Civil Engineers—Municipal Engineer*, 64–68. London: ICE Publishing.

Park, H. M., and H. W. Jung. 2003. "Evaluating interrater agreement with intraclass correlation coefficient in SPICE-based software process assessment." In *Proc., 3rd Int. Conf. on Quality Software*, 308–314. New York: IEEE.

Pocock, J. B., S. T. Kuennen, J. Gambatese, and J. Rauschkolb. 2006. "Constructability state of practice report." *J. Constr. Eng. Manage.* 132 (4): 373–383.

Ramaji, I. J., A. M. Memari, and J. I. Messner. 2017. "Product-oriented information delivery framework for multistory modular building projects." *J. Comput. Civ. Eng.* 31 (4): 04017001. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000649.

Randiwela, P., and S. T. Wijayaratne. 2017. "Determinants of perceived brand globalness: FMCG and airline services." In *Proc., Oxford Business and Economics Conf. 2017*. Oxford, UK: Global Conference on Business & Economics.

Razkenari, M., A. Fenner, A. Shojaei, H. Hakim, and C. Kibert. 2020. "Perceptions of offsite construction in the United States: An investigation of current practices." *J. Build. Eng.* 29 (3): 101138.

Robertson, O., and M. S. Evans. 2020. "Just how reliable is your internal reliability? An overview of Cronbach's alpha (α)." In *Psychology postgraduate affairs group*. Glasgow, UK: PsyPAG.

Said, H. 2015. "Prefabrication best practices and improvement opportunities for electrical construction." *J. Constr. Eng. Manage.* 141 (12): 04015045. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001018.

Schatsky, D., C. Muraskin, and R. Gurumurthy. 2015. *Cognitive technologies: The real opportunities for business*. New York: Deloitte University Press.

Sharafi, P., M. Rashidi, B. Samali, H. Ronagh, and M. Mortazavi. 2018. "Identification of factors and decision analysis of the level of modularization in building construction." *J. Archit. Eng.* 24 (2): 04018010. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000313.

Singh, A. S. 2017. "Common procedures for development, validity and reliability of a questionnaire." *Int. J. Econ. Commerce Manage.* 5 (5): 790–801.

Slowey, K. 2019. "Report: 60% of US construction activity concentrated in 10 states." Accessed December 2, 2021. https://www.constructiondive.com/news/report-60-of-us-construction-activity-concentrated-in-10-states/558524/.

Smith, R. E. 2016. *Off-site and modular construction explained*. Washington, DC: National Institute of Building Sciences.

Spring, G. S. 2005. "Road safety: discussion of state of practice." *J. Transp. Eng.* 131 (5): 329–332.

Srour, F. J., I. Srour, and M. G. Lattouf. 2017. "A survey of absenteeism on construction sites." *Int. J. Manpower* 38 (4): 533–547. https://doi.org/10.1108/IJM-08-2015-0135.

Steinhardt, D. A., K. Manley, and W. Miller. 2014. *Predicting Australian builders' intentions to use prefabrication*. Brisbane, Australia: Queensland Univ. of Technology.

Taber, K. S. 2018. "The use of Cronbach's alpha when developing and reporting research instruments in science education." *Res. Sci. Educ.* 48 (6): 1273–1296. https://doi.org/10.1007/s11165-016-9602-2.

Tetteh, M. O., A. P. Chan, A. Darko, A. Torku, and G. Nani. 2021. "Critical barriers to international construction joint ventures success: Multiexpert views and contextual disparities." *J. Constr. Eng. Manage.* 147 (8): 04021081. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002059.

Tumbeva, M. D., A. P. Thrall, and T. P. Zoli. 2021. "Modular joint for the accelerated fabrication and erection of steel bridges." *J. Bridge Eng.* 26 (6): 04021022. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001706.

Vokes, C., and J. Brennan. 2013. *Technology and skills in the construction industry.* London: UK Commissions for Employment and Skills.

Watson, P. 2018. "There are two main barriers to the widespread use of offsite construction." Accessed December 2, 2021. https://www.building.co.uk/comment/there-are-two-main-barriers-to-the-widespread-use-of-offsite-construction/5095454.article.

Wong, P. S., C. Zwar, and E. Gharaie. 2017. "Examining the drivers and states of organizational change for greater use of prefabrication in construction projects." *J. Constr. Eng. Manage.* 143 (7): 04017020. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001309.

Yang, Y., M. Pan, W. Pan, and Z. Zhang. 2021. "Sources of uncertainties in offsite logistics of modular construction for high-rise building projects." *J. Manage. Eng.* 37 (3): 04021011. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000905.

Yussef, A., G. E. Gibson, M. El Asmar, and D. Ramsey. 2020. "Industry survey for determining the state of practice of front end engineering design for industrial construction." *Pract. Periodical Struct. Des. Constr.* 25 (4): 04020025. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000504.

Zaalouk, A., and S. Han. 2021. "Parameterized design optimization framework for worker-friendly workplaces in modular construction." *J. Constr. Eng. Manage.* 147 (5): 04021030. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002029.