PRINCIPLES FOR THE ADOPTION OF OFFSITE CONSTRUCTION IN DESIGN AND CONSTRUCTION COMPANIES

by

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A Dissertation

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Doctor of Philosophy

Department of Construction Management Technology

West Lafayette, Indiana

December 2021

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I dedicate this work to my beloved husband and daughter

ACKNOWLEDGMENTS

First, I would like to express my gratitude to my advisor, Dr. Luciana Debs, for being a valuable friend, for introducing me to Purdue, and for supporting me unconditionally and continuously throughout my doctorate. I am honored to be her first Ph.D. student. Thanks to her mentoring and valuable suggestions, this research brings significant contribution to research and practice.

I would also like to thank my committee members, Dr. Zeljko Torbica, Dr. Bryan Hubbard, and Dr. David Jae Hoon Yu, for their valuable suggestions and support when I needed them.

In particular, I am grateful to all professionals from the architecture, engineering, and construction industry who participated in this study, contributing with their expertise and providing valuable information.

I would also like to thank my colleagues, the staff and faculty from the School of Construction Management Technology who have provided support along the way.

Thanks also to my colleagues at Purdue's Campus Planning, Architecture and Sustainability office, who allowed me to develop a very special work for Purdue, but also offered me time and peace of mind when I needed them most.

I am immensely grateful to my family and friends in Brazil and around the world for always listening to me and encouraging me in difficult times. Special thanks to my mother who, despite being a very simple person, always encouraged me to study and think big.

Last but not least, my appreciation to my lovely husband Rogerio and daughter Eva, who changed their lives to be by my side during this journey, always dedicated, always patient, and always supporting me unconditionally.

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ABBREVIATIONS

AEC	Architecture, Engineering, and Construction
A/E	Architect and Engineer
AHS	American Housing Survey
BIM	Building Information Modeling
CM	Construction Manager
DB	Design-Build
DfMA	Design for Manufacturing and Assembly
HUD	U.S. Department of Housing and Urban Development
IPD	Integrated Project Delivery
GC	General Contractor
OSC	Offsite fabrication, prefabrication, and modularization
SME	Small and Medium Enterprises
UN	United Nations
US	United States
WEF	World Economic Forum

ABSTRACT

The United States presents the appropriate conditions for a wider adoption of offsite construction (OSC): steady growth in the construction industry, high construction wages, shortage of labors, and demand for housing – especially multifamily housing. The multifamily housing market is overheated, but many design and construction companies are still struggling to stay strong in this market, marked by tight profit margins, high competitiveness and inefficiencies. OSC presents itself as a solution to help design and construction companies to become more efficient and resilient to potential market crises. However, the architecture, engineering and construction (AEC) industry is hesitant to move to higher levels of OSC adoption, mainly because stakeholders, including owners, developers, designers, and construction companies, are not aware of the potential benefits resulting from OSC and are not prepared to promote the changes necessary for the successful adoption of OSC or for the engagement in modular construction, which would represent an important move towards industrialized construction. This study focused on how to implement strategic changes in design and construction companies, particularly small and medium-size enterprises, interested in successfully using OSC in multifamily housing projects, considering the need for more affordable and sustainable multifamily housing in the United States. Using mixed methods, the study involved five phases of data collection and data analysis and had the contribution of professionals from the AEC industry. Focusing only on the AEC industry of the United States, the researcher first identified the main factors affecting the use of OSC in multifamily projects, as well as the most important changes that design and construction companies need to adopt for the successful use of OSC in multifamily projects. The factors and the changes helped to structure and shape the scope of the principles, which were later consolidated and validated through research with professionals from design and construction companies. The final set of eight principles was divided into four topics: (1) strategy and business model, (2) people, organization, and culture, (3) technology, materials, and tools, and (4) processes and operations. In addition to helping to shape more efficient and resilient construction companies, the application of the proposed principles contributes to building more affordable and sustainable housing in the United States.

CHAPTER 1. INTRODUCTION

Chapter 1 provides an overview of the problem and presents the purpose and significance of this research study. Included in this chapter are also the research questions, assumptions, limitations, and delimitations. The chapter concludes with definitions of the key terms used in the research and a brief summary of chapter 1.

1.1 Nature of the Problem

The fragmented AEC industry has experienced low productivity levels over the years, unlike the development and increased productivity experienced by many other industry sectors. This trend persists, even with the emergence of various technologies and processes that are being gradually introduced into the AEC industry (McKinsey Global Institute, 2017; World Economic Forum & The Boston Consulting Group, 2016). Many factors contributed to this situation, especially a historical resistance of the AEC industry from many countries to embrace innovation and industrialization into its traditional processes (Linner & Bock, 2012) and the lack of a holistic view to address the problems identified in this fragmented industry (McGraw Hill Construction, 2013; World Economic Forum & The Boston Consulting Group, 2016).

Despite this bleak scenario, efforts to improve the productivity of the AEC industry persist and are reinforced by pressure from other, more technologically advanced industries (World Economic Forum & The Boston Consulting Group, 2016). Research suggested that prefabrication, preassembly, modularization and offsite fabrication techniques have potential to enhance the AEC industry and are more efficient in the use of resources – time, materials and labor – being more cost-effective, affordable and sustainable compared to traditional construction methods (Jaillon & Poon, 2009; R. M. Lawson et al., 2012; Luther, 2009; McGraw-Hill Construction, 2011; McGraw Hill Construction, 2013; Nahmens & Ikuma, 2012). Recent industry reports focused on modular construction and prefabrication presented encouraging numbers for the AEC industry, based on the experience of countries where offsite construction is already successfully established, such as Japan and Sweden (Bertram et al., 2019) and the experience of the United States, where offsite construction still advances timidly (Dodge Data & Analytics, 2020b).

The growing demand for housing and the labor shortage within the construction sector have been drivers for OSC over the years, especially in countries like the United States and the United Kingdom (Bertram et al., 2019). However, in the United States the use of OSC has not been consistent over the years, since factors such as poor quality, safety and aesthetics, negatively impacted the OSC reputation (Bertram et al., 2019). After some years slowly growing, OSC is again gaining traction in many countries and apparently in a more consistent and sustainable way. Partly this is due to socioeconomic and labor shortage (Bertram et al., 2019), in part because of the movement towards digitalization, including the growing use of building information modeling (BIM) capabilities, which is making it possible to integrate design, manufacturing, and construction in a revolutionary way, which ultimately drives OSC (Dodge Data & Analytics, 2020b; World Economic Forum & The Boston Consulting Group, 2016). Thus, countries such as Singapore, Australia, the United Kingdom, and the United States, which have these "ideal conditions," are experiencing remarkable growth in the adoption of OSC technologies (Bertram et al., 2019; Blismas & Wakefield, 2009).

Currently, the United States present the appropriate conditions for a sharper adoption of OSC: steady growth in the construction industry, high construction wages, shortage of labors, and demand for housing – especially affordable housing (Bertram et al., 2019). Such conditions have become more accentuated due to the advent of the COVID-19 pandemic (Jones & Grigsby-Toussaint, 2020). Still, the American AEC industry is reluctant to switch to an OSC model, mainly because many of the stakeholders, including owners, developers, designers and construction companies are unaware of the potential benefits resulting from the adoption of OSC and are not prepared to promote the necessary changes for the successful implementation of OSC in construction projects (Dodge Data & Analytics, 2020b; McGraw-Hill Construction, 2011; World Economic Forum & The Boston Consulting Group, 2016). Since not all strategies adopted so far have been successful, it is important to develop principles to help the AEC stakeholders – owners, developers, designers, and contractors – to implement the structural changes that will promote the increasing use of OSC. However, the strategies to adopt OSC may vary according to the market, building types, and company sizes. A study developed by Dodge Data & Analytics (2020b) reveals that in the United States, multifamily buildings present great potential for using OSC. These data, associated with the current scarcity of housing affordable for different income groups in the country (Airgood-Obrycki & Molinsky, 2019; U.S. Census Bureau, 2018b), demonstrate an urgent need to encourage the use of OSC in multifamily projects. An approach focused on increasing sustainability's triple bottom line in multifamily housing, which comprises social, environmental and economic dimensions (being affordability an inherent part of these dimensions), coupled with strategies to adopt OSC, would allow to achieve the goal of producing high-quality housing at a reduced cost (Dave et al., 2017; Wang et al., 2018).

Considering that the multifamily housing market in the US is overheated at this time due to persistent problems of housing shortage and housing affordability (Airgood-Obrycki & Molinsky, 2019; Joint Center for Housing Studies of Harvard University, 2018), which has been aggravated by the COVID-19 pandemic (Jones & Grigsby-Toussaint, 2020), and also taking into account that even with the growth of the multifamily market, many design and construction companies face serious difficulties to survive in a market that, although overheated, is marked by tight profit margins and low efficiency (Rice, 2013; Thompson, 2019), this study investigates and proposes strategic changes to be implemented in design and construction companies, especially small and medium-sized enterprises (SMEs), working with multifamily projects, so that they can use OSC to become more efficient and resilient, while also contributing to building more affordable and sustainable housing in the United States.

1.1.1 Statement of the Problem

This study addressed the problem of adapting the AEC industry to the increasing use of OSC in multifamily housing projects in the United States. More specifically, the study focused on the identification of strategic changes to be implemented in design and construction companies, particularly SMEs, interested in successfully using OSC in multifamily housing projects, considering two important aspects: first, the need to improve the companies' performance and resilience to potential crises that periodically affect the AEC industry and the multifamily housing market; second, the need to build more affordable and sustainable multifamily homes in the United States.

1.2 Statement of Purpose

The purpose of this research was to develop principles on how to implement structural changes in design and construction companies aiming at the successful use of OSC for delivering more affordable and sustainable multifamily buildings in the United States. To achieve this purpose, the research comprised the following steps:

- Identify and rank the factors that influence the feasibility of using OSC in multifamily projects.
- Identify and rank the changes that design and construction firms need to adopt to successfully use OSC in multifamily projects.
- Analyze the relationship between the factors and the changes.
- Develop principles to implement strategic changes in design and construction firms interested in successfully using OSC in multifamily projects.
- Validate the developed principles with AEC industry professionals.

1.2.1 Research Questions

Considering OSC's potential to make design and construction companies more efficient and resilient, while considering the need to build more affordable and sustainable multifamily buildings in the United States, the study investigated the following questions:

1. What are the most relevant factors affecting the adoption of OSC in multifamily projects in the United States?
2. What are the most relevant changes to be implemented in design and construction firms focused on successfully using OSC in multifamily projects in the United States?
3. How to implement strategic changes in design and construction companies aiming at the successful use of OSC for delivering more affordable and sustainable multifamily buildings in the United States?

1.3 Significance

Many researchers acknowledged OSC as a way to add value to the product and reduce waste, aligned with lean construction principles and even considered as part of lean construction approach (Olsen & Ralston, 2013). The practical meaning of this is that OSC can increase productivity (Fenner et al., 2017), efficiency (McGraw-Hill Construction, 2011), product quality (Linner & Bock, 2012) and sustainability (Jaillon & Poon, 2009; Luther, 2009; Nahmens & Ikuma, 2012; Quale et al., 2012) while reducing waste (Tam et al., 2007), cost (Pan & Sidwell,

2011) and construction time (Arashpour et al., 2016). In countries such as the UK, Singapore, Hong Kong, and Sweden the use of OSC has been encouraged as part of policies to meet the growing demand for housing, especially for low-income families (Jaillon & Poon, 2009; Steinhardt & Manley, 2016). However, the participation of OSC in the AEC industry worldwide is still incipient, and this fact is not different in the United States, a country that has adequate conditions for the growth and consolidation of modular construction (Bertram et al., 2019). This is due to several factors, one of the main ones being that for AEC industry professionals the rise of OSC is still new and they are not sure of the benefits it can bring to a project (Olsen & Ralston, 2013). In fact, depending on the strategy adopted, OSC techniques may not be as advantageous for some projects as it is for others (Gibb & Isack, 2003). Therefore, it is important for AEC industry professionals to have data and tools to adjust their organizations to successfully use OSC in their projects.

Industry and government reports have highlighted the benefits of OSC in construction (Bertram et al., 2019; Dodge Data & Analytics, 2020b; McGraw-Hill Construction, 2011; McKinsey Global Institute, 2017; World Economic Forum & The Boston Consulting Group, 2016), and research has shown the benefits of OSC adoption and barriers and challenges as well (Gibb & Isack, 2003). There is also research identifying factors that affect the use of OSC (Sharafi et al., 2018), but it is important to adopt a holistic approach to this type of decision (Blismas et al., 2006; Kamali & Hewage, 2017; Zakaria et al., 2018). Thus, this study had an approach based on the three widely accepted dimensions of sustainability: economic, environmental and social (World Commission on Environment and Development, 1987), which have been applied to recent research on the adoption of OSC in construction (Hammad et al., 2019; Kamali & Hewage, 2016, 2017; Yunus & Yang, 2012).

Considering the lack of research addressing strategies to support design and construction firms on the adoption of OSC, this study proposed principles to implement strategic changes that would make design and construction companies, especially SMEs, more efficient and resilient by using OSC in multifamily projects in the United States. Other indirect benefits include (1) foster the adoption of higher levels of OSC in multifamily projects in the US; (2) contribute to the construction of more affordable and sustainable multifamily housing projects in the United States; and (3) support stakeholders in managing the factors that affect the adoption of OSC in multifamily housing projects in the United States.

1.4 Assumptions

Assumptions are intrinsic to research, and the following assumptions were initially identified as part of this research:

- The sample for the Delphi survey would be a significant representation of the United States' AEC industry involved with the use of OSC in multifamily housing projects.
- Professionals with eight or more years of full-time industry experience accurately represented expert professionals.
- Participants answered the Delphi survey, the online survey, and the interview questions truthfully and unbiased.
- Professionals with five or more years of full-time AEC industry experience and working in design and construction firms that use OSC in their projects would accurately provide their perceptions regarding the changes required to successfully adopt OSC in multifamily housing projects in the US.

1.5 Delimitations

Delimitations are intrinsic to research, and the following delimitations were initially identified as part of this research:

- This study focused on companies and professionals from the AEC industry working or that have already worked with multifamily housing projects in the US and with knowledge of OSC.
- Only professionals from the AEC industry or AEC industry-related organizations with experience in multifamily projects and OSC were invited to participated in the Delphi Survey and in the online survey.
- Only designers and construction professionals with previous experience in multifamily projects and OS were invited to participate in the interviews.
- The proposed principles focused only on strategies to support design and construction firms to implement changes to successfully use OSC in multifamily projects in the US.

1.6 Limitations

Limitations are intrinsic to research, and the following limitations were initially identified as part of this research:

- Phase 1: only one researcher conducted the thematic analysis to identify and categorize the factors, thus results can be susceptible to subjectivity and potential bias.
- Phase 2: the validation and the ranking of the factors that affect the decision on the use of OSC in multifamily projects, and the identification and ranking of the changes required to adjust design and construction firms to successfully use OSC in multifamily projects depended on the perceptions of the experts from the AEC industry.
- Phase 4: only one researcher conducted the thematic analysis to generate the principles to implement changes in design and construction firms to successfully use OSC in multifamily projects, thus the results could be susceptible to subjectivity and potential bias.
- Phase 5: only one researcher conducted the content analysis to code and interpret the interviews material, which was used to validate the principles, hence the results were susceptible to subjectivity and potential bias.
- The study was limited by the AEC industry experts' willingness to cooperate.

1.7 Definitions

Delphi technique: is "a method for the systematic solicitation and collation of judgements on a particular topic through a set of carefully designed sequential questionnaires interspersed with summarized information and feedback of opinions derived from earlier responses" (Delbecq et al., 1975, p. 10).

Multifamily Housing: "Residential buildings containing units built one on top of another and those built side-by-side which do not have a ground-to-roof wall and/or have common facilities (i.e., attic, basement, heating plant, plumbing, etc.)" (U.S. Census Bureau, n.d.)

Modularization: "Modularization involves breaking up a system into discrete chunks, which communicate with each other through standardized interfaces, rules, and specifications" (Gosling et al., 2016, p. 1).

Offsite construction: “offsite [construction] is defined as the manufacture and pre-assembly of components, elements or modules before installation into their final location” (Goodier & Gibb, 2007, p. 586).

Prefabrication: “[is] the production of components under factory conditions, and their assembly on-site, aimed to reduce costs, to increase speed of construction processes, and to improve quality” (Gann, 1996, p. 439).

Small and Medium-Sized Enterprise (SME): in the United States, there is no distinct way to identify small and mid-size enterprises (SMEs), so the term small business and SME many times are used interchangeably. The U.S. International Trade Commission defined SMEs as enterprises with fewer than 500 employees, but acknowledged that there is not a straightforward definition for SME across all sectors of the U.S. economy. (United States International Trade Comission, 2010).

Sustainable housing: refers to residential buildings that promote minimized resource consumption, quality of life and satisfying the needs of residents, and affordability (Sullivan & Ward, 2012).

Resilience: is “the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks” (Walker et al., 2004, p. 2)

1.8 Related published research journal articles

The researcher worked on two studies related to the current research, which were accepted and published in peer-reviewed research journals.

1.8.1 Research article 1

- A review on the factors affecting the use of offsite construction in multifamily housing in the United States (Gusmao Brissi, Debs, et al., 2021)

The study, lead-authored by Sara Gusmao Brissi, identified specific factors that affect use of OSC in multifamily housing in the United States.

Focusing on the sustainability dimensions of construction – social, environmental, and economic—the authors reviewed literature that was published

> between 2000 and 2019 and identified factors that are related to OSC adoption in general construction, in housing construction, and, more specifically, in multifamily housing construction in the US. (Gusmao Brissi, Debs, et al., 2021, p. 1)

The part of the results of this study focused on the factors affecting the adoption of OSC in multifamily in the US correspond to a large portion Phase 1 of the current research and was used as a basis in the Delphi survey to validate and rank the most relevant factors affecting the adoption of OSC in multifamily projects in the United States.

1.8.2 Research article 2

- A review on the interactions of robotic systems and lean principles in offsite construction (Gusmao Brissi, Wong Chong, et al., 2021)

The study, lead authored by Sara Gusmao Brissi, explored the interactions of robotic systems and lean construction in the context of OSC that were addressed in the literature published between 2008 and 2019.

In the present research, the results of this study were important for the development, of the principles to support the implementation of changes in design and construction firms interested in successfully using OSC in multifamily projects in the US, more specifically the principles focused on (1) technology, material and tools, (2) processes and operations, and (3)

1.9 Summary

This chapter provided an overview of the research, including the nature of the problem, statement of purpose, research questions, and significance. Assumptions, limitations, and delimitations for the study were also indicated in this chapter, as well as the main definitions of terms that will be used across this dissertation. Related published studies lead-authored by the researcher were presented, given their relevance to the current research. The next chapter features a review of the relevant literature that sustain the main concepts used in the theoretical framework of this study.

CHAPTER 2. LITERATURE REVIEW

This chapter presents an overview of the literature related to four topics of great relevance for this study: multifamily housing in the United States; offsite fabrication (OSC); how OSC is transforming the AEC industry; resilience in AEC companies; and the use of Delphi technique in research. The researcher focused on more up-to-date literature published in the following sources: (1) high ranked peer-reviewed journals; (2) conference proceedings; (3) theses and dissertations from well-reputed institutions; (4) reports from government agencies and industry organizations; (5) data from the U.S. Census Bureau; (6) reliable websites from the industry, and from private/ public/ government organizations, and (7) the author's previous publications related to this subject: Research Article 1 (Gusmao Brissi, Debs, et al., 2021) and Research Article 2 (Gusmao Brissi, Wong Chong, et al., 2021).

2.1 Multifamily Housing in the United States

The multifamily housing market in the United States is large, with nearly 22 million units in 2019, and has been growing steadily in recent years with a growth of over 16% between 2009 and 2019 (Table 2.1). Recent studies indicate that by 2030, it will be necessary to build about 4.6 million new rental units in the US, to meet the demand of households from different income groups (Fannie Mae, 2020; Hoyt Advisory Services, 2017).

Between 2009 and 2019, the increase in the number of units built (starts and completions) and the reduction in vacancy rates, both for rental and owned properties, indicate that the units built were absorbed by the market (Table 2.1); such indicators were important for understanding the multifamily market trends in the United States (U.S. Department of Housing and Urban Development, 2021a). However, the indicators vary widely across the country, particularly in metropolitan areas, as demonstrated in a recent study by Freddie Mac (2020), which revealed a housing deficit in 29 states, with a total shortage of 2.5 million homes.

Table 2.1. Multifamily housing indicators 2009–2019

Index	2009	2011	2013	2015	2017	2019
Starts	97,300	167,300	293,700	385,800	342,700	388,900
Completions	259,800	129,900	186,200	310,300	346,900	342,900
Total rental units	18,786,537	19,352,228	19,696,731	20,378,207	20,692,117	21,858,442
Rental Occupied	16,614,043	17,356,162	17,899,088	18,681,706	18,837,547	19,997,161
Rented, Not Occupied	293,788	330,193	322,330	342,299	336,357	339,309
For Rent	1,878,706	1,665,873	1,475,313	1,354,202	1,518,213	1,521,972
Vacancy rates—rental units (%)	10.00%	8.61%	7.49%	6.65%	7.34%	6.96%
Total homeowner units	2,720,261	2,612,132	2,505,441	2,566,658	2,650,842	2,782,032
Owner Occupied	2,474,084	2,371,061	2,344,494	2,425,255	2,509,713	2,647,796
Sold, Not Occupied	59,439	64,037	54,989	53,414	55,020	51,161
For Sale	186,738	177,034	105,958	87,989	86,109	83,075
Vacancy rates—homeowner units (%)	6.86%	6.78%	4.23%	3.43%	3.25%	2.99%

Note. Reprinted from "A review on the factors affecting the use of offsite construction in multifamily housing in the United States", by Gusmao Brissi, Debs, et al., 2021, *Buildings, Volume 11*, p.3. Copyright retained by the authors. Creative Commons CC BY 4.0 license.

Units under construction is also important to understand the trends in the multifamily housing market. Figure 2.1 shows that in the last decade, regarding units under construction, the increase in the number of multifamily units was more significant than the increase in the number of single-family units, indicating an increasing demand for multifamily housing.

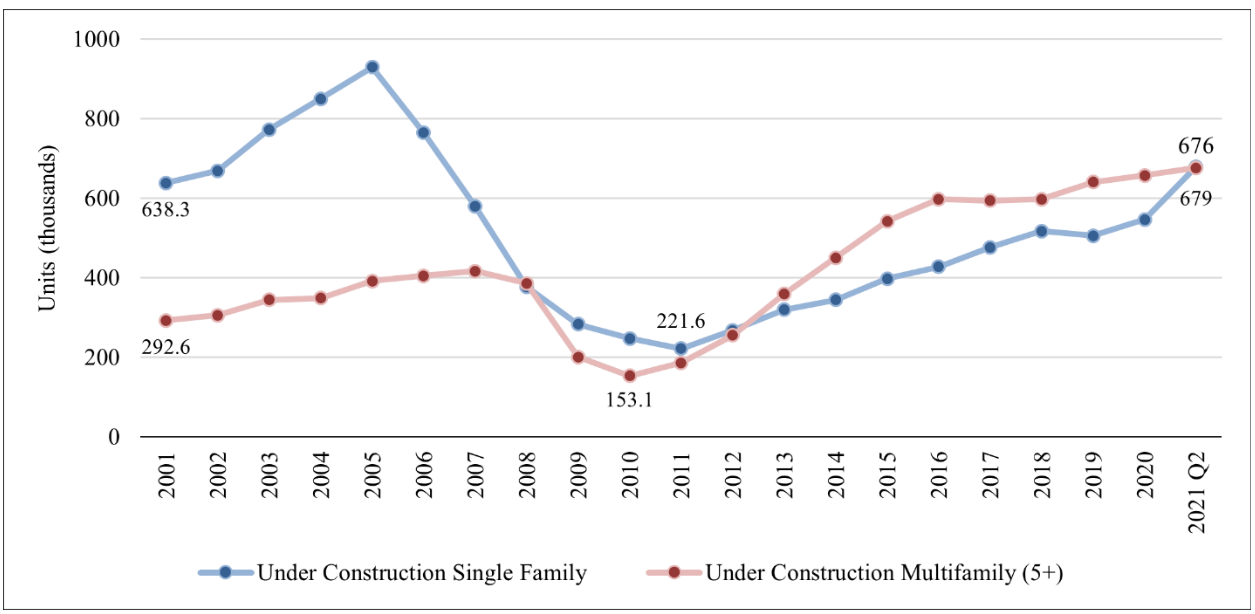


Figure 2.1. Private housing units under construction between 2001-2021 Q2. Based on data from the U.S. Department of Housing and Urban Development (2021a).

2.1.1 Multifamily housing market in the United States

In 2017, the multifamily housing market, not including for-sale builders, encompassed 3,200 multifamily general contractors and generated $47 billion (Siniavskaia, 2021). Considering the strength of this market, it is important to understand home builders' perceptions of on issues related to housing affordability and the use of innovative construction techniques in housing construction.

The study by Colton & Ahluwalia (2019) involving 290 home builders (including single-family builders, multifamily builders, and residential remodelers, among others) asked the participants to rate housing affordability in their specific market region and across the United States. The results revealed that 86% of the multifamily builders rated housing affordability as a serious or very serious issue in their market region (Colton & Ahluwalia, 2019). As for innovation and new technologies, among multifamily builders, 15% was using wall panels and 7% was using modular or factory-built modules in their projects, compared to 13% of the single-family builders using wall panels and 4% using modular or factory-built modules. About the time frame to implement changes, 46% of all participants indicated that they were planning to increase the use of innovative construction methods (including factory-built/modular, pre-cut, open wall panels, and closed wall panels) over the next 2-5 years. Table 2.2 shows that 57% of the multifamily builders were planning to increase the use of innovative construction methods in the next 2-5 years, compared to 43% of the single-family builders (Colton & Ahluwalia, 2019).

Table 2.2. Period of time in which home builders plan to change construction methods (*n*=290)

Period of time to implement changes	Multifamily Builders	Single-Family Builders
In the next 2-3 years	25%	26%
In the next 3-5 years	32%	17%
Beyond 5 years	11%	13%
Not Sure	21%	16%
Not at all	11%	28%

Source: Tabulations made by the author based on data from Colton & Ahluwalia (2019).

2.1.2 Housing affordability in the United States

The 2017 American Housing Survey (U.S. Census Bureau, 2018c) revealed that in 2017 approximately 42 million households (renters and homeowners) were spending more than 30% of their annual incomes on housing related costs. This number has increased by about 2 million households (5%) since 2007, when approximately 40 million families were cost-burdened. Considering the universe of renters, during this period, the number of cost-burdened households increased by 3 million (19%), reaching approximately 21 million households, which is almost the same number of cost-burdened owners, but unlike owners, renters situation worsens every year. (National Low Income Housing Coalition, 2019), especially with the advent of the COVID-19 pandemic (Jones & Grigsby-Toussaint, 2020).

According to scholarly literature, and recent data and reports from the U.S. government and private organizations, rental affordability in the United States remains a challenge due to rising rent costs nationwide and the low availability of rental houses affordable for lower-income households (Airgood-Obrycki & Molinsky, 2019; Colton & Ahluwalia, 2019; U.S. Census Bureau, 2018c; U.S. Department of Housing and Urban Development - Office of Policy Development and Research, 2019). The situation is even worse in some regions of the country, such as metropolitan areas, and for particular sizes of residential units, such as two-bedroom units for renters (Airgood-Obrycki & Molinsky, 2019).

Data from the United States Department of Housing and Urban Development (HUD) confirms that rental affordability is a challenge for a large portion of renter families, including middle-income households, with the HUD's Rental Affordability Index (RAI) declining nationwide as rising rents surpass income growth (U.S. Department of Housing and Urban Development, 2021b). The HUD housing market report revealed that since 2007 RAI and the homeownership affordability index (HAI) have drifted diametrically apart (Figure 2.2). While HAI increased from 115.3 to 163.2 in 2020 (+41.5%), RAI decreased from 117.0 to 108.8 in 2020 (-7%) and even less in the second quarter of 2021 (101.0) (U.S. Department of Housing and Urban Development, 2021b). This indicates that for a large portion of the population that depends on housing rentals, it is increasingly difficult to afford the rising rents.

2.1.3 Housing sustainability in the United States

The discussion on housing affordability involves the social, economic and environmental dimensions of sustainability (Golubchikov & Badyina, 2012) because sustainable housing contributes to lower utility costs, enhanced financial stability, healthier environments, lower maintenance costs, improved building performance, durability of buildings, and lower generation of waste and pollutants, ultimately benefiting owners, households, managers and communities (Pivo, 2014; Samarripas & York, 2019; U.S. Department of Housing and Urban Development - Office of Community Planning and Development, 2008; U.S. Environmental Protection Agency, 2018).

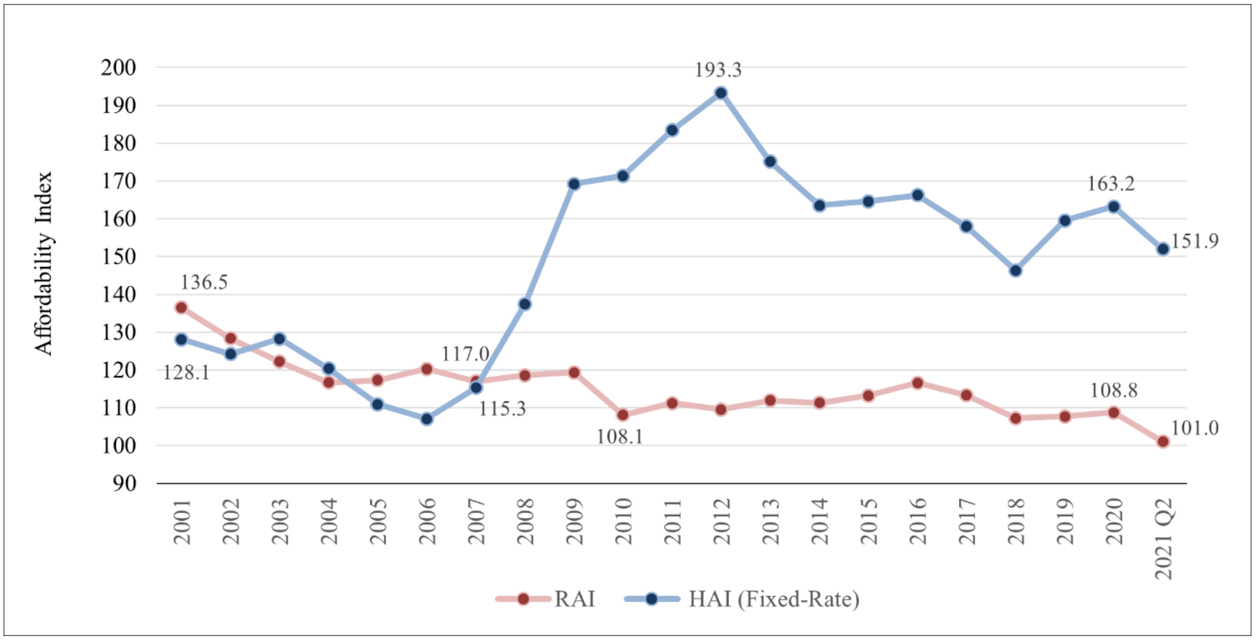


Figure 2.2. HUD's Rental Affordability Index (RAI)[1] and Homeownership Affordability (HAI)[2] variation between 2001-2021 Q2. Based on data from the U.S. Department of Housing and Urban Development (2021a)[3].

In the United States, the issue of housing sustainability is closely linked to energy efficiency (Fannie Mae, 2019; Samarripas & York, 2019). So, focusing on the energy consumption issue, it is acknowledged that the problem of energy burden is the most significant among the utility costs, which represent an important part of the housing-related costs (Drehobl & Ross, 2016; Samarripas & York, 2019). As previously explained, lower-income renters are

[1] RAI – A value of 100 means that a renter household with median income has exactly enough income to qualify for a lease on a median-priced rental home.

[2] HAI – A value of 100 means that a family with the median income has exactly enough income to qualify for a mortgage on a median-priced home

[3] Data for Q2-Q4 2020 and Q1 2021 were based surveys conducted under COVID-19 restrictions (U.S. Department of Housing and Urban Development, 2021a)

among the most severely housing-cost burdened households and could highly benefit from incentives and programs to reduce utility costs.

A significant number of energy efficiency programs in the US has been promoted by utility companies, local governments, state agencies, and the federal government. Unfortunately, the multifamily housing market has been underserved by energy efficiency programs due to barriers such as split incentives, types of ownership and utility metering split incentives (Samarripas & York, 2019). As for the affordable multifamily housing market, and more specifically the rental buildings, the access to energy efficiency programs is even more complicated because it involves homeowners, which are not very prone to invest in more energy efficient buildings that will mostly benefit their renters (Pivo, 2014; Samarripas & York, 2019). A research developed by Drehobl and Ross (2016) revealed that the energy burden of low-income households (7.2% of income) is more than two times that of median households (3.5% of income), or more specifically:

- Energy burden of low-income households living in multifamily buildings is 5% of their income, compared to 1.5% for non-low-income households living in multifamily buildings.
- Energy burden of 4% of renters' income contrasted to 3.3% of owner's income.

The U.S. Department of Housing and Urban Development (HUD) acknowledges that resource-efficient, environmentally friendly, and water- and energy-efficient technologies are now mainstream practice for market-rate projects. HUD has established energy efficiency in affordable housing as a strategic priority and has been encouraging the integration of energy efficiency and green features in affordable housing projects. (U.S. Department of Housing and Urban Development - Office of Community Planning and Development, 2008).

Since 2005, HUD has been partnering with the Environmental Protection Agency (EPA) and the Department of Energy (DOE) to improve the energy efficiency of the nation's affordable housing stock, aligned with the requirements of Section 154 of the Energy Policy Act of 2005. More recent legislation also promotes and prioritizes the development of energy-efficient and sustainable affordable housing, including training, technical assistance, incentives, funding and financing opportunities for sustainable and affordable multifamily housing (U.S. Department of Housing and Urban Development, 2012; U.S. Environmental Protection Agency, 2018).

2.1.4 Housing sustainability and OSC

Green or sustainable building involves much more than energy efficient buildings, comprehending structures and processes that are responsible and resource-efficient throughout a building's life-cycle (Olubunmi et al., 2016). Therefore, innovative constructions technologies are needed to not only increase the sustainability of buildings throughout their lifecycle, but also to push the AEC industry to a much higher level in terms of environmental, social and economic sustainability, which has not been possible to achieve through conventional methods of construction (Dave et al., 2017).

Research and practice suggested that an appropriate strategy for using OSC significantly increases the affordability and sustainability of construction processes, reducing costs, waste of resources and the time of construction (Dave et al., 2017), especially in multifamily housing which are usually large scale developments, where the repeatability of elements can guarantee economies of scale (Wang et al., 2018). In fact, almost all contemporary buildings integrate some degree of prefabrication, from single prefabricated components to panelized, modular and hybrid structures (Boafo et al., 2016). Literature often associates the use of OSC with environmental benefits, due to its potential to affect the product's life cycle and sustainable characteristics, which are defined through sustainable design strategies (Sonego et al., 2018). Sustainable design seeks to balance "balances the private interests of the firm and engineering functionality against broader environmental, economic, and societal considerations" (Skerlos, 2015, p. 13). OSC, in turn, facilitates upgrades, adaptations, modifications and product assembly and disassembly; increases product variety; enables economies of scale and reduces production time (Sonego et al., 2018), and can be one innovative approach to achieve sustainability and construction quality, and at the same time, fulfill the occupants' need for affordability, comfort and flexibility (Ahn & Kim, 2014).

In terms of environmental sustainability, studies focusing on the use of OSC technologies compared to conventional construction revealed that the use of OSC in construction provides improved environmental performance, including lower ecosystem damage, lower health damage and lower resource depletion (X. Cao et al., 2015; Quale et al., 2012). This is because the use of OSC in construction results in lower consumption of energy, materials and water; lower emissions of GHG and pollutants and lower waste generation (Aye et al., 2012; X. Cao et al., 2015; Jaillon & Poon, 2008; Quale et al., 2012). OSC techniques also promote the reuse and recycling of materials due to manufacturing processes involved in the construction (Jaillon et al., 2009) and because they allow the disassembly and deconstruction of structures (Aye et al., 2012; Jaillon & Poon, 2014).

As for social sustainability, when compared to conventional construction, the use of OSC is much safer and healthier for the construction workers, since most of the work is performed in the controlled environment of a factory (Jaillon & Poon, 2008). The economic benefits of using OSC are mostly related to the life cycle costs of the buildings (design, construction, operation and maintenance phases), considering that the higher quality of the OSC components results in reduced maintenance costs (Jaillon & Poon, 2008). The reduction in the time of construction is another important economic benefit which also relates to (1) cost because the shorter the construction time, the faster the building can be occupied and operated and (2) workers' safety because the shorter the construction time, the lower the risk of accidents offsite and on-site.

2.2 Offsite Construction

This study use the acronym OSC, which is widely used in the literature to refer to prefabrication, modularization and offsite fabrication (Chen et al., 2010; Gosling et al., 2016; Nadim & Goulding, 2011; O'Connor et al., 2014; Pan et al., 2012; Pan & Goodier, 2012; Yunus & Yang, 2012). Prefabrication, modularization and offsite fabrication are closely related concepts, often used interchangeably, but with different meanings.

Modularization is a broad concept but, in this study, it refers to the use of modules manufactured offsite to build more complex structures or systems, through standardized interfaces, rules, and specifications (Gosling et al., 2016; Miller & Elgård, 1998). Modularization is also connected to standardization reduce not only the product variability but also the complexity of systems and processes. (Lennartsson et al., 2009; Miller & Elgård, 1998). At first, the use of modular components in building projects may seem complex but due to standardization, once the product is defined the design and manufacturing of the modules become rather repetitive, favoring higher productivity and economies of scale (Bertram et al., 2019; Gibb & Isack, 2003; McGraw-Hill Construction, 2011; Peltokorpi et al., 2018).

Modular buildings are not necessarily monotonous and aesthetically poor, since modular construction can combine the advantages of both standardization and customization (Jensen et al., 2012; Miller & Elgård, 1998), allowing for mass customization, i.e. a variety of products can be achieved by combinatorial assemblies of a limited number of modular components with standardized connections, which are manufactured in large quantities but with additional value to the product (Linner & Bock, 2012; Miller & Elgård, 1998; Ulrich, 1995)

The connections between modularization in construction and prefabrication relies on the fact that usually the modules are prefabricated. Prefabrication is the process of manufacturing and pre-assembling offsite the components of a structure or a building, which will be then transported and assembled on the construction-site (Goodier & Gibb, 2007). Since prefabrication involves offsite fabrication technologies, it promotes the industrialization and the automation of some processes in construction (Bertram et al., 2019). The industrialization of the AEC industry, involving OSC strategies has the potential to dramatically increase productivity and quality in the construction industry (Bertram et al., 2019; Jensen et al., 2012; World Economic Forum & The Boston Consulting Group, 2016).

2.2.1 Categorization of OSC

OSC categorization is related to the level of modularization and/or prefabrication of a building, thus the importance of this analysis. OSC comprehends components and systems. The components are the specific elements which can be combined within a construction system. The building system defines the elements and the relationships between them, i.e. how they will be combined and organized (Staib et al., 2008).

Researchers categorize construction systems in different ways. Staib, Dörrhöfer, and Rosenthal (2008) categorize the construction systems according to their flexibility:

- Closed systems – all elements are manufactured by only one manufacturer and organized in a way that does not allows for changes, i.e., a fixed combination of elements.
- Modular construction systems – are closed systems based on a pre-defined number of elements which can be combined in different ways according to specific rules, allowing for some flexibility.
- Open systems – allow the use of elements manufactured by different manufacturers, which can be combined as required, i.e., variable combination of elements.

Luther (2009) presents two forms of categorization. The first categorization is based on the buildings categories as follows (Figure 2.3):

- Panel systems – system based on a single prefabricated element (panel), which can provide an integrated solution for walls, floors, or roof surfaces of a building envelope. A panel wall, for example, may include cladding, structure, insulation, internal lining, air/vapor barriers, fenestration, and design for ventilation, minimizing the building elements.
- Skeletal systems – are composed by individual prefabricated components assembled to provide a structural frame, which will support the floors, roof and walls of a building, all attached to the frame, e.g., modular prefabricated columns and beams.
- Cellular systems – are composed by prefabricated components that form a volumetric unit which can stand alone or be combined with other volumetric units to assemble a building. The volumetric unit can integrate all the buildings elements, including envelope, structure, mechanical, electrical, and plumbing (MEP) systems, and even finishes, e.g., bathroom units.

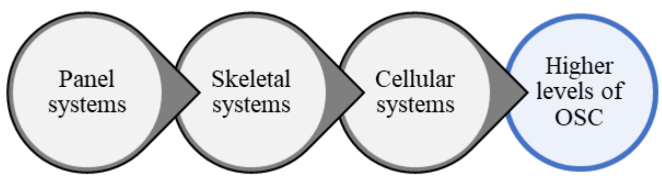


Figure 2.3. OSC categorization 1 according to Luther (2009).

Luther (2009) also presents a categorization based on design systems, which can be combined with each other and involve the following systems (Figure 2.4):

- Element or component systems – consist of single prefabricated components which can be combined to create a panel or skeletal system.
- Kit-of-parts – consist of a variety of components packed together to build a volumetric unit or a building according to a unique assembly solution. A kit-of-parts can be prefabricated or assembled on-site and allows for mass customization, e.g., Toyota Housing.

- Fill-in systems – consist of components integrating two complete units or any combination of modular prefabricated systems: panel, skeletal or cellular units.
- Complete units – consist of volumetric units, which can be broken down into completely complete independent units (e.g., prefabricated student rooms), dependent modules enclosing space without structural functions (bathroom pods), and modules with structural and envelope functions (e.g., stackable concrete pods).

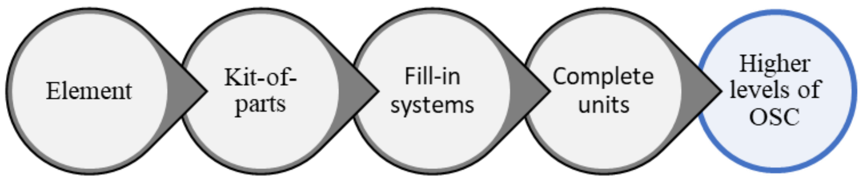


Figure 2.4. OSC categorization 2 according to Luther (2009).

The OSC categorization proposed by Gibb (2001) is one of the most accepted and referenced in the literature (Goodier & Gibb, 2007; Hu et al., 2019; Soto Ortiz, 2014) and is based on the level of offsite work undertaken on the product (Figure 2.5):

- Component manufacture & sub-assembly – small scale sub-assemblies never considered to be produced/assembled on-site, e.g., doors, windows.
- Non-volumetric pre-assembly – pre-assembled components which do not enclose usable space, e.g., wall panels, flat-packed modular components, kits-of-parts.
- Volumetric pre-assembly – pre-assembled volumetric components which enclose usable space without forming building's structure, e.g., bathroom pods.
- Modular buildings – pre-assembled volumetric units which enclose usable space and form building's structure, e.g., hotel rooms, students' room.

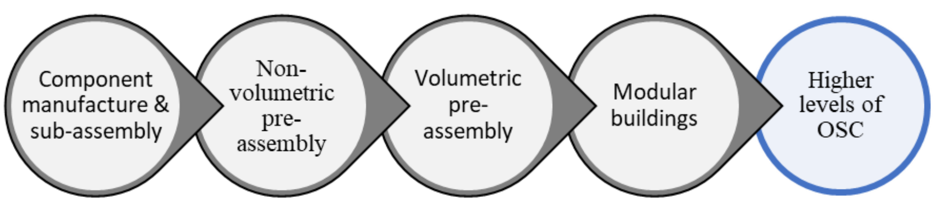


Figure 2.5. OSC categorization 3 according to Gibb (2001).

2.2.2 Types and use of OSC in the United States

In the United States OSC has been widely used in manufactured standardized single-family homes, going back to the times of catalog houses, such as the kit houses provided by Sears Modern Homes in the beginning of the 20th century, or to the times of the first prefabricated and modular houses produced by National Homes, founded in the 1940's. However, the use of OSC has also been associated with prefabricated mobile homes, which has negatively impacted the market's perception of OSC, associated with low quality products and poor aesthetics. Thus, the production of modular houses is not significant in the United States, having reached a peak in 2005, when a total of 40,000 modular houses were built, which represented 2.5% of the housing market at the time (M. Lawson et al., 2014).

The housing modules can be quite large, due to fewer transportation restrictions in the less urbanized areas of the United States. Hence, few modules result in large houses with standardized designs and few customizations. The housing systems in general use timber framed modules, but light steel framing is used in some areas (M. Lawson et al., 2014). More recently, a shift in perceptions regarding the quality and performance of OSC has led to its use in other construction markets, such as in healthcare, college and dormitory buildings and in buildings for manufacturing industries (McGraw-Hill Construction, 2011).

A comprehensive study developed by Dodge Data & Analytics (2020b) presents an up-to-date overview of the use of prefabrication and modular construction in the United States according to the perspectives of the AEC industry practitioners, more specifically, architects/engineers (A/E) and general contractors/construction managers (GC/CM). The Dodge Data & Analytics (2020b) study also presents different categories of prefabrication and modular construction (identified as types) and the percentage of use, according to these categories. Focusing on the modular construction data, the study reported that according to A/E and GC/CM the types of modular construction most often used in the United States over the past three years were:

1. Panelized modular construction – used by 84% of A/E and 80% of GC/CM:
    - Wall modules
    - Structural Insulated Panels

- Roof Panels
- Floor Panels

2. Full volumetric modular construction – used by 72% of A/E and 79% of GC/CM:
    - 3D modules built to be joined together on-site
    - Flat-packed construction system for site assembly – similar to the definition of kits-of-parts (Luther, 2009); e.g. AVAVA Dwellings, Katerra
    - 3D modules slotted into a structure that can be transported – similar to the definition of modular building (Gibb, 2001), e.g. Factory OS, Skystone, Skender prefabrication.

3. Factory-made turnkey modular building units – used by 68% of A/E and 72% of GC/CM.

As for the use of modular construction by building type, the report identified that according to 51% of A/Es participating in the study, multifamily buildings had the highest potential for using modular construction in the next three years (Dodge Data & Analytics, 2020b). In addition, in the last three years, GC/CM had been using modular construction more intensely in multifamily buildings (34% of the responses).

2.3 OSC Transforming the AEC industry

A recent report (Hoover & Snyder, 2018) developed for Fails Management Institute (FMI) pointed out that the traditional resistance of the AEC industry to change its processes was receding in face of the need to deal with pressing issues. The availability of advanced technologies is enabling the emergence of new business models that seriously threaten the lethargy of the AEC industry, which is now at an inflection point. However, changes within the AEC industry must be managed with prudence by all the stakeholders (Hu et al., 2019), for too many change-related issues are among the most important root causes of contractor failure (Rice & Howsam, 2016).

Among the advanced technologies that are causing the most dramatic changes in the AEC industry is the use of OSC, which has a strong impact on the way construction projects are produced and delivered. OSC is making the AEC industry move from artisanal to industrialized and automated processes applicable to both design and construction phases. In fact, with OSC the construction phase is divided into two parts, one comprises the offsite production of modular components and the other involves the assembly of the modules in the construction-site. Logistics-related activities (delivery and storage) integrate these two parts and differ from a conventional construction scenario. Therefore, design and construction companies are susceptible to changes resulting from the use of OSC and need to better understand the challenges and opportunities within OSC technologies in the context of an evolving and wider strategy of delivering a project (Hoover & Snyder, 2018).

Most academic studies that assessed the transformative potential of OSC in the AEC industry addressed isolated aspects, such as business model and organizational culture (Linner & Bock, 2012), sustainability aspects (Kamali et al., 2018; Quale et al., 2012; Tam et al., 2007), new technologies (Zhong et al., 2017), planning (Shewchuk & Guo, 2012), workers' skills (Arashpour et al., 2015; Goodier & Gibb, 2007), safety at work (Kamali et al., 2018), etc. Thus, broader studies are needed to address the numerous issues and their connections (i.e., socio-technical, organizational, change management, etc.) involving the use of OSC in design and construction companies, focusing more specifically on the company level.

Whereas there is a lack of research providing this general overview, industry reports, developed by reliable institutions, provided valuable data (KPMG, 2016; McKinsey Global Institute, 2017; World Economic Forum & The Boston Consulting Group, 2016). The Dodge Data & Analytics (2020b) study, for example, which was based on the responses of 608 professionals from the AEC industry with experience in prefabrication or modular construction, reported important benefits resulting from the use of both prefabrication and modular construction (Table 2.3).

Table 2.3. Benefits from the use of prefabrication and modular construction based on percentage of users/respondents (n=608)

Benefit	Modular Construction	Prefabrication
Improved productivity	93%	89%
Improved quality	90%	90%
Increased schedule certainty	90%	87%
Improved cost predictability	88%	81%
Reduced waste generated by construction	86%	81%
Increased client satisfaction	86%	80%
Improved safety performance	83%	79%

Source: Tabulations made by the author based on data from Dodge Data & Analytics (2020b).

Another report developed by the World Economic Forum – WEF (2016) presented a framework with 30 practices to transform the AEC industry (Figure 2.6). The report was supported by case studies of innovation and best practices and encompassed the company level, the sector level and the government level. The framework focused on the company level was used in this study as an outline to assess the changes caused by the use of OSC in AEC companies, adopting an approach that includes: (1) technology, materials, and tools; (2) processes and operations; (3) strategy and business model; and (4) people, organization and culture.

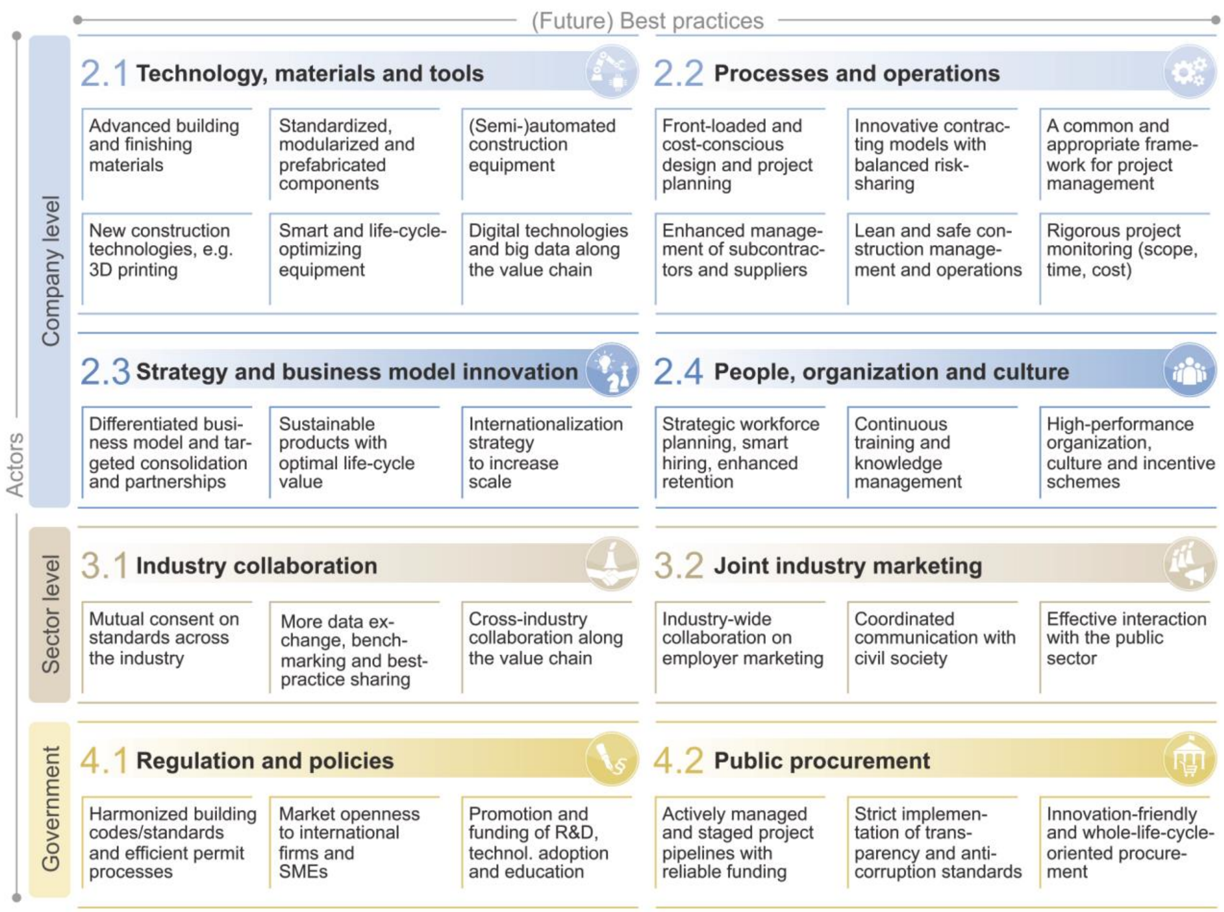


Figure 2.6. Industry Transformation Framework.

Note. Reprinted from "Shaping the Future of Construction - A Breakthrough in Mindset and Technology", by World Economic Forum and The Boston Consulting Group, 2016, *World Economic Forum*, p.9. Copyright 2016 by World Economic Forum. Reprinted with permission.

2.3.1 Technology, materials and tools

Technologies, materials, and tools used in OSC are facilitating a more widespread adoption of OSC; in this sense, it is important to highlight the importance of building information modeling (BIM). Even though it is not implemented in many design and construction firms across the US, the importance of BIM tools is acknowledged among AEC professionals, but when it comes to OSC, BIM is even more important as it helps to streamline the flow of information required to integrate the design, manufacturing and construction processes (Dodge Data & Analytics, 2020; Smith, 2011). BIM allows the project team members to share information back and forth and to continuously update the BIM model based on fabrication information, which helps the whole team to anticipate and predict the fabrication and installation challenges (Smith, 2011). When engaging in higher levels of OSC, designers are also required to understand design for manufacturing and assembly (DfMA) strategies, while focusing on constructability and sustainability issues (Luo et al., 2017; Yuan et al., 2018). Design automation is another component of this equation that is facilitating customization of modular components, particularly with BIM adoption (Benros & Duarte, 2008; Goulding et al., 2015; Jensen et al., 2012).

Because the BIM model developed by the designers represents accurately the objects' properties for fabrication, digital tools like computer numerical control (CNC) can be integrated with the BIM model to facilitate tooling to precise dimensions. This process allows multiple manufacturers to simultaneously produce components offsite, and then deliver and assemble them on-site (Smith, 2011). BIM models can also be integrated with 3D laser scanning to ensure exact measurements for offsite preparations and manufacturing, reducing problems with allowance and joining components during installation (World Economic Forum & The Boston Consulting Group, 2016; Zhong et al., 2017).

Regarding monitoring and control, technologies such radio-frequency identification (RFID), internet of things (IoT) and smart construction objects (SCOs) allow real-time monitoring and are being used to monitor delivery, storage and assembly of building components (C. Z. Li et al., 2018; W. Lu et al., 2011; Niu et al., 2017; Zhong et al., 2017). In fact, starting in the pre-construction phase and continuing throughout the construction, advanced project planning tools, especially when associated with lean construction practices, allow contractors to optimize the procurement, logistics and assembly in OSC while ensuring the transparency of the entire process (Hamzeh et al., 2015; McKinsey Global Institute, 2017; Smith, 2011).

New materials and technologies also play an important role in OSC, for they can be used to make components lighter and more resistant, which facilitates the transport and optimizes the on-site installation (de Laubier et al., 2019; Liew et al., 2019). In addition, some materials and technologies improve connections between components and modules (Liew et al., 2019). In fact, offsite friendly materials are key pieces in AEC's transformation from a project-based model to a product-based model (de Laubier et al., 2019; Liew et al., 2019)..

2.3.2 Processes and operations

When it comes to the impact of OSC on the design processes, it is necessary to emphasize that important design decisions must be made early in the design process to avoid rework since the use of OSC significantly reduces the project's flexibility and makes it more difficult to deal with design issues during the construction phase (Jaillon & Poon, 2010). Therefore, the whole design process is supposed to change, for OSC buildings are designed as a series of assemblies and systems (Smith, 2011). Focusing on architects, their roles are becoming broader, involving the coordination of the design process and changing from conventional "architectural work" to building product, as noted by Luo, Zhang and Sher (2017). A detailed coordination of design disciplines and constructability analysis is paramount in OSC due to its reduced design flexibility, hence the importance of adopting lean construction principles during the design phase, especially to determine customer needs and define project values (Smith, 2011).

In terms of production, the use of OSC in construction involves manufacturing the components and assembling them on-site, which favors concurrent scheduling over the critical path method (CPM), which is the most used scheduling method in construction (Smith, 2016). In addition, delivery may need to become front-loaded, which requires a radically different approach to benefit the overall project schedule, through an integrated process including cost, labor and supply chain management (Smith, 2011; World Economic Forum & The Boston Consulting Group, 2016).

Collaborating with this approach are the technologies discussed previously, such as the use of BIM tools, especially in the pre-construction phase, when strategic activities such as cost estimating, value engineering, construction planning and scheduling are performed (Smith, 2011). Whereas OSC involves complex logistics, the support of BIM tools integrated to other technologies and the collaboration of all stakeholders to enable better sequencing in the construction process is vital (Niu et al., 2017). The procurement process is also different, involving risks related to committing to a specific OSC supplier (World Economic Forum & The Boston Consulting Group, 2016). In this sense, if contractors work jointly with suppliers it is possible to improve applicability and generate systems to meet the demand for affordable projects (World Economic Forum & The Boston Consulting Group, 2016).

Focusing on the site construction processes, on-site activities must be adjusted to eventually handle large prefabricated components, especially in space-constrained construction-sites (World Economic Forum & The Boston Consulting Group, 2016). Construction processes monitoring is enhanced both offsite, where work is carried out in the controlled environment of a factory, and on-site, where improved technologies allow the monitoring of materials, labor, and equipment productivity. Better performance monitoring systems generate better data that must be feedback into the design-manufacturing-assembly processes. Considering this scenario, it is paramount to collaboratively establish key performance indicators (KPIs) for each project (World Economic Forum & The Boston Consulting Group, 2016). In addition, the more controlled environment of OSC benefits from the adoption of lean construction practices, which focus on reducing waste and adding value throughout the entire value chain. (Smith, 2011; World Economic Forum & The Boston Consulting Group, 2016).

To realize the full potential of OSC it is crucial to get all relevant parties engaged and well-coordinated early on the project. Interesting options may arise when AEC companies take on new roles by applying innovative contracting models to allow them to provide full design and construction services, ensuring streamlined integration of design and construction, which is possible in collaborative delivery methods, such as design-build (DB) and integrated project delivery model (IPD), which is the most collaborative delivery method, based on shared risks and benefits between the main stakeholders, allowing for greater collaboration among the partners and collaborative decision-making to reduce conflicts between partners (Kent & Becerik-Gerber, 2010; McKinsey Global Institute, 2017). However, the study developed by Dodge Data & Analytics (2020b) revealed that the IPD method is still very little used among AEC industry professionals who use modular construction and prefabrication.

2.3.3 Strategy and business model

Differentiated business models can be an excellent strategy for a company to stand out among its peers and build resilience. AEC companies need to define their market, that is, to define the balance between specialization in a given market, focusing on customization, or serving different markets, betting on gains of scale (Dodge Data & Analytics, 2020b). As for the scope of services, companies need to define the scope from design and engineering to construction and operation and maintenance (Dodge Data & Analytics, 2020b). The application of standardized offsite design and construction solutions in a company's portfolio can produce more value and generate financial savings (KPMG, 2016).

Focusing on the UK house building industry, Pan and Goodier (2012) addressed the factors that capture and create value in projects by linking different types of OSC (different levels of offsite work and different materials) employed in house projects to different business models. Further studies focused on the relationship between business models and the use of OSC were scarce (Peltokorpi et al., 2018), especially in countries such as the United States, where offsite construction is not yet an established industry (Dodge Data & Analytics, 2020b).

Among the strategies of a company is the option to incorporate principles of sustainability and life cycle analyzes into its projects, which is especially important in the operation and maintenance phase, when costs are usually high, reaching values similar to the initial costs of the project. Therefore, efficient buildings, with reduced consumption of resources (energy, water, and materials) and minimized environmental impact are mandatory, especially in housing projects focusing on higher affordability.

Another important strategy refers to the company's geographic area of activity, that is, whether it will focus on the local, regional, national or international market, considering that certain locations may offer restricted options for OSC suppliers. At the same time, the expansion of the operating area may stand for increased scale (Dodge Data & Analytics, 2020b). This decision impacts on another strategy: whether the company will opt for vertical integration or outsourcing. The traditional design firm Giattina Aycock Architecture Studios from Alabama created a vertically integrated company – BLOX – to reduce construction costs, by placing design, manufacturing, and construction on the same floor. BLOX's is investing heavily in a product-based business model, but its currently mostly focused on the healthcare market. Blokable, a Seattle-based company, was born as a vertically integrated modular company with a focus on sustainable housing development. Blokable has proven that its product-platform business model is capable of delivering housing units at a lower cost.

2.3.4 People, organization and culture

The increasing use of OSC results in processes that are closer to the manufacturing industry, alleviating workers shortage (Boyd et al., 2013; Dodge Data & Analytics, 2020b) because labor demand is reduced (Jaillon & Poon, 2008). Focusing on the production/construction phase, OSC contributes to the strategic planning of the workforce as it is related to higher quality and more secure jobs, with the workforce less subject to the seasonality of projects (Dodge Data & Analytics, 2020b). This fact, associated to a safer work environment is attractive to employees, enhancing retention of good employees, which is a serious problem in the AEC industry. In the United States, according to the US Bureau of Labor Statistics, the E&C sector has some of the highest employee turnover rates across all industries (World Economic Forum & The Boston Consulting Group, 2016).

The efforts and investments of construction companies in training must be continuous, because regardless of the adoption of OSC, it is necessary to invest in the reformulation of a workforce that is aging and also to train the workers to use new equipment and digital tools. (McKinsey Global Institute, 2017). The adoption of OSC requires specific skills that are not currently adequate or transferable (Blismas & Wakefield, 2009). Therefore, training and preparing a skilled workforce is essential in adopting OSC (Nadim & Goulding, 2011), but in many cases the companies involved with OSC train their workers to acquire the skills necessary (Jaillon & Poon, 2008). The issue of availability of trained workforce to install prefabricated or modular components is identified by design firms as the greatest obstacle to implementing prefabrication, but curiously this perception is quite different in the case of the use of modular components (Dodge Data & Analytics, 2020b).

Training professionals and managing knowledge in design firms include measures such as providing feedback to the design team with information from the construction phase; capturing lessons learned on projects and accessing key project data; and encouraging knowledge sharing among the firm’s employees through workshops and by connecting employees that work in different projects (World Economic Forum & The Boston Consulting Group, 2016).

As for culture, it is important to highlight that the conservative culture of the AEC industry needs to be reformulated to accept innovations (Blismas & Wakefield, 2009; Wu et al., 2019). In this sense, the role of design firms is fundamental, as such firms, which usually are the first ones to engage in a project, contribute to innovative thinking and creative solutions that end up influencing construction firms. The adoption of OSC represents a disruptive innovation for the AEC industry, impacting on design, manufacturing and construction through the introduction of new products and processes that completely replace existing ones (Dodge Data & Analytics, 2020b; Steinhardt & Manley, 2016).

2.4 Resilience within the AEC Industry

Resilience is "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks" (Walker et al., 2004, p. 2). Walker (2004) complements the definition by explaining four concepts essential to define resilience:

1. Latitude: refers to the maximum limit of changes supported by a system from which its recovery capacity becomes difficult or impossible.
2. Resistance: refers to how resistant a system is to changes.
3. Precariousness: refers to the proximity of the current state of a system to its threshold.
4. Panarchy: refers to how cross-scale interactions (scales above and below) affect the resilience of a system at a particular focal scale.

Walker (2004) also emphasized that strategies related to resilience should be context dependent and had to change over time, due to the changes in the social-ecological systems. Given the complexity of the interactions between systems, all policies aimed at improving resilience need to clearly define what is desired to be resilient and to what (Biggs et al., 2012).

Considering the definitions provided, we could apply the concept of resilience to multifamily affordable housing projects from two different perspectives: one focusing on the people and communities benefited by the project, and the other, which was the focus of this study, focusing on companies that design and build multifamily housing projects, while striving to adapt to a changing market highly impacted by the COVID19 pandemic.

2.4.1 Resilience in small and medium construction enterprises in the US

Resilience is paramount in the AEC industry to ensure the ability of the built environment to absorb strikes without suffering complete failure, especially in view of the growing concerns about risk mitigation in face of natural disasters such as hurricanes, and earthquakes. However, it is just as important to create resilient organizations capable of surviving turbulences in the unstable environment of business (Ates & Bititci, 2011). Resilience is even more critical for companies in the fragmented AEC industry, characterized by a hostile and challenging business environment.

In order to increase resilience in the AEC industry, it is necessary to give special attention to small and medium-sized enterprises (SMEs), for their role within the American AEC industry is paramount. According to the United States Census Bureau, in 2015, 92% of all construction enterprises in the USA were classified as small enterprises (U.S. Census Bureau, 2018a). Furthermore, in smaller developments, the importance of SMEs is even greater, as in these cases SMEs very often represent all stakeholders: developers, designers, contractors, and suppliers (Tezel et al., 2020).

Focusing on the residential construction market, a recent study by the National Association of Home Builders (Siniavskaia, 2021) identified that in the United States most companies were small, with less than 500 employees and below $36.5 million of average annual receipts (U.S. Small Business Administration, 2017). Although companies in the multifamily segment were somewhat larger than companies focused on single-family construction, in 2017 43% of multifamily construction companies generated less than $1 million in total business and only 23% surpassed the $10 million mark (Siniavskaia, 2021).

Research has revealed that in the United States small construction firms were less productive than large firms (McKinsey Global Institute, 2017). This is due to a number of factors, but the important point here is that this revealed that SMEs were more vulnerable to the turbulences of the AEC industry, so the importance of building resilience in them. The lack of organizational slack for SMEs impairs their ability to test strategies and commit to medium and long-term return investments, which significantly limits their ability to change efficiently and effectively, and ultimately compromise their resilience (Sexton & Barrett, 2003). To increase resilience, SMEs must understand the interdependencies brought about by changes in the AEC industry and plan restructurings as a result of these changes. In this sense, the principles for increasing resilience defined in the seminal work by Biggs et al. (2012) and revisited by (Yu et al., 2020) provided a good foundation for those SMEs to build on resilience:

- Maintain diversity and redundancy: it is related to the variety and redundancy of systems used by design and construction firms, which are important for resilience as they offer alternatives when disturbances occur in a system. Strategies include equipment, software, personnel, operating in different markets, and diversity in terms of services that the design and construction firms offer to clients (World Economic Forum & The Boston Consulting Group, 2016). Diversity and redundancy also increase the potential for innovation, which is a challenge for companies in the traditional AEC sector (Ozorhon et al., 2014).
- Manage connectivity: connectivity refers to all connections between the company associates, partners, construction-related organizations and institutions, and industry collaboration, especially with other SMEs within the AEC industry. Such connections will enhance resilience by improving collaboration along the value-chain, best practices sharing, data exchanging (McKinsey Global Institute, 2017; World Economic Forum & The Boston Consulting Group, 2016).
- Foster social capital: social capital is related to interactions between various individuals and organizations, which can positively affect organizations and communities, making them more resilient to disturbances. In this way, social network-based capital can contribute to the improvement of design and contruction firms' resilience since the relationships between individuals and organizations allow them to have access to resources that would otherwise not be available by other means (Yu et al., 2020). Leadership and trust are essential to facilitate those interactions and relationships (Yu et al., 2020). Social capital also relates to people capability, which is a driver for innovation (Ates & Bititci, 2011; Biggs et al., 2012; Sexton & Barrett, 2003).
- Encourage learning and experimentation: learning has been considered pivotal in building resilience and dealing with uncertainty (Biggs et al., 2012). Monitoring and experimentation is also a crucial aspect of resilience, involving adaptive management (Biggs et al., 2012), especially within the AEC industry, where capturing lessons learned has become an important part of its process (World Economic Forum & The

Boston Consulting Group, 2016). In this way, knowledge and learning sharing that involves different professionals from different levels of the AEC industry are capable of fostering resilience in the sector. This is even more important in the universe of small and medium-sized design and construction companies, for which social capital and tacit knowledge are the greatest assets, but which still face many difficulties that hamper their capacity for experimentation.

2.5 Delphi Technique

The Delphi technique has been used since the late 1950s when the Rand Corporation conducted a series of studies with the purpose of reaching reliable consensus in anonymous judgments from a group of experts (Okoli & Pawlowski, 2004; Schmidt, 1997). Delphi is defined as

> … a method for the systematic solicitation and collation of judgements on a particular topic through a set of carefully designed sequential questionnaires interspersed with summarized information and feedback of opinions derived from earlier responses. (Delbecq et al., 1975, p. 10)

Three features clearly defines the Delphi technique, namely: (1) anonymity, (2) iteration and controlled feedback, and (4) the statistical aggregation of group responses (Dalkey, 1969; Rowe & Wright, 1999). These features will be further discussed in next sections.

This technique is especially beneficial under certain circumstances (Hsu & Sandford, 2007; Murry & Hammons, 1995; Yousuf, 2007), such as:

- Issues involving high uncertainty, ill-defined problems, not requiring precise analytical techniques, but depending more on subjective judgmental information (Okoli & Pawlowski, 2004; Yousuf, 2007) or when objective data is unavailable (Hallowell & Gambatese, 2010).
- There is a need to combine the knowledge and experience of different experts and reach consensus on their judgments or opinions (Powell, 2003).
- A minimum number of individuals, sometimes, from different geographic regions, is required, which makes effective interactions in a face-to-face exchange difficult and costly (Murry & Hammons, 1995; Yousuf, 2007).

- Studies or research that involves the dual purpose of soliciting experts' opinions and asking them to rate or rank their opinions in order of importance (Okoli & Pawlowski, 2004; Schmidt, 1997).

The rank form of Delphi, which aims to get consensus on experts' opinions about the relative importance of a subject has been widely used. Since this technique relies on successive iterations, interspersed with analysis of responses and feedback to the participants, it allows Delphi expert panelists to re-evaluate their previous judgments with each new round. Seminal studies addressing the use of Delphi technique have been developed through the years, providing principles to select the experts, collect and analyze data and validate the methodology (Hsu & Sandford, 2007; Murry & Hammons, 1995; Okoli & Pawlowski, 2004; Rowe & Wright, 1999; Schmidt, 1997). This study mostly focused on the studies developed by Okoli and Pawlowski (2004) and Schmidt (1997), which addressed the ranking-type Delphi and used more than one expert panel in their studies.

2.5.1 Expert panel

In research, the only participants in a Delphi technique are the experts integrating the expert panel and the researcher conducting the study. According to Sekaran & Bougie (2016)

> An expert panel is a group of people specifically convened by the researcher to elicit expert knowledge and opinion about a certain issue. The criteria for qualification as an expert are many and varied, but the expert panel usually comprises independent specialists, recognized in at least one of the fields addressed during the panel sessions. Expert panels may thus bring together a wide variety of experts, including scientists, policy makers, and community stakeholders. (p. 122)

The definition of an expert varies within academic studies, but there is a certain consensus that experts must possess knowledge, credibility and experience in their field (Baker et al., 2006; Chi et al., 2009; Powell, 2003), which need to be evidenced by specific requirements such as "working appointments, professional qualifications, working experience, and relevant publications" (Ameyaw et al., 2016, p. 993). However, it is important to clearly characterize knowledge, credibility and experience if experts will be used in a project depending on experts' judgements. Knowledge is related to professional qualification, but it can go beyond that, involving, for example, academic achievements and scientific production in a specific area, which also guarantees credibility to an expert (Baker et al., 2006; Powell, 2003). As for the experience, it is often related to the number of years that an individual works in an area, but this criterion can be fallacious, as some individuals work many years in an area and still have little relevant knowledge about it (Baker et al., 2006). Perhaps a way to resolve this issue is to associate years of experience with the individual's hierarchical position in a company or organization, but without a doubt, real experience in an specific domain allows an expert to use the knowledge obtained academically or over the years in a practical, assertive and efficient way, as explained previously (Chi et al., 2009).

It is noteworthy that the Delphi technique highly depends on experts' performance, therefore, it requires a rigorous process of selection of experts, which have to be truly qualified to judge and provide significant opinions on the subject under analysis (Hsu & Sandford, 2007; Okoli & Pawlowski, 2004).

2.5.2 Selection of participants

The Delphi technique does not rely on samples that are representative of a population, rather on a purposive sample that requires qualified experts with strong experience and knowledge in their domains (Powell, 2003). The danger of bias in the selection of participants was acknowledged in research, which recommended avoiding selecting participants based on the researchers' personal network and instead focusing on recognized specialists within a domain (Okoli & Pawlowski, 2004; Powell, 2003). Ways to select participants include identifying and contacting respected experts, stakeholders, top management decision makers or organizations related to the desired field; solicitation of nomination of experts by the individuals or organizations contacted. Powell (2003) remarked that "potential users of the findings may be willing and useful members" (p. 379).

As for the sample size of a Delphi study, there was no consensus on the literature. It depends on the complexity of the study and the type of sample, which can be homogeneous or heterogeneous (Ameyaw et al., 2016). Homogeneous samples include experts from the same domain and expertise, e.g., a construction related study can have experts representing only contractors, or only designers. Therefore, homogeneous groups can facilitate achieving a consensus, but will provide not so rich perspectives on the issue under analysis (Baker et al., 2006). According to Delbecq et al. (Delbecq et al., 1975) a homogeneous sample with ten to fifteen subject is sufficient to provide a representative pooling of judgments regarding the target issue.

Heterogenous samples, on the other hand, include experts from the same domain, but with different expertise, e.g., the same construction domain study can integrate experts representing designers, contractors, developer, etc. Research suggested that heterogeneous samples provided more diverse and richer opinions and judgements, leading to higher quality results (Baker et al., 2006; Powell, 2003). However, reaching consensus among diversity and with a wider range of alternatives could be difficult (Baker et al., 2006). Although there was not a precise definition about the minimum and maximum number of subjects integrating an heterogeneous expert panel, research suggested that heterogeneous groups required larger sample sizes, and many studies have used between 15 and 20 participants (Hsu & Sandford, 2007).

Okoli and Pawlowski (2004) provided an interesting appproach to reduce the drawbacks related to the adoption of ordinary homogeneous or heterogeneous groups, while ensuring the high quality of the study. Based on an extensive review of the literature, Okoli and Pawlowski (2004) adopted four distinct experts' panels with a homogenous sample of ten to eighteen participants in each of them.

2.5.3 Data collection and data analysis

The Delphi technique involves the systematic solicitation of opinions from the panelists, usually experts in their fields, in the form of survey rounds (iterations). At each new round, controlled feedback is provided to participants, including statistical aggregation of group response, questions are asked, answers are collected and data is analyzed and compiled (Okoli & Pawlowski, 2004; Rowe & Wright, 1999; Schmidt, 1997).

The properly managed Delphi technique requires that data collection and analysis take place simultaneously, i.e., at each round of data collection, the researcher must analyze the data (experts' judgements), including statistical analysis and aggregation of group response, and provide controlled feedback to all participants, so that they can also verify the results and eventually review their opinions and judgments, if they wish (Rowe & Wright, 1999; Schmidt, 1997).

Statistical analysis is performed for each panel responses, and comprehend the whole ranks, mean ranks, along with Kendall's *W*, as recommended by Schmidt (1997). "Kendall's method measures current agreement (the ordered list by mean ranks) with a least squares solution. It is the most popular method for this purpose, mainly due to its simplicity of application" (Schmidt, 1997, p. 765). A low value for Kendall's W (0.1 – 0.3) indicates weak agreement among the responses e low level of confidence in the ranks, while higher values (≥ 0.7) indicate strong agreement and high level of confidence in the ranks.

2.5.4 Limitations

Delphi technique is a good methodology to collect experts' opinions, but it presents limitations and weaknesses, which have been pointed out in research (Chan et al., 2001). The main problems and limitations associated to the use of Delphi technique are presented as follows:

- Difficulty of identifying and selecting experts to comprise the panel (Chan et al., 2001; Murry & Hammons, 1995, p. 433; Okoli & Pawlowski, 2004).
- The length of time needed to complete a study (Chan et al., 2001; Murry & Hammons, 1995, p. 433).
- Difficulty of maintaining the participants commitment to the study (Chan et al., 2001; Hasson et al., 2000; Murry & Hammons, 1995, p. 433).
- Potential biases that may affect the results (Hallowell & Gambatese, 2010).
- Difficulty of reaching consensus on the issues under analysis (Schmidt, 1997; Yousuf, 2007).
- Conformity of the panel, for "the consensus reached in a Delphi may not be a true consensus; it may be a product of specious or manipulated consensus" (Yousuf, 2007, p. 4), or a result of pressure to conform with group opinions (Hsu & Sandford, 2007).

Some of the limitations mentioned above can be tackled through the efficient performance of the panel facilitator (usually the researcher), by providing controlled feedback and rigorous analysis of the group response. More recent research has shown that the use of Delphi associated with statistical analysis assures a good level of reliability to research from different domains (Al-araibi et al., 2019; Chalmers & Armour, 2019; Von Der Gracht, 2012).

2.6 Summary

By reviewing updated literature, this chapter provided an overview of five topics of great relevance to this study: (1) multifamily housing in the United States, which provided the background for the research, (2) offsite construction (OSC), (3) how OSC is transforming the AEC industry, (4) resilience in AEC companies, and (5) the use of the Delphi technique in research. Taking the analysis of these topics as a starting point, the researcher created principles for design and construction companies to implement changes to successfully and efficiently use OSC, a technology with extremely beneficial impacts for the AEC sector. This way, such companies, especially SMEs, would become more resilient to the turbulences of the multifamily housing market, while producing more affordable and sustainable housing.

CHAPTER 3. METHODOLOGY

This study addressed the problem of adjusting design and construction firms to successfully using OSC in multifamily housing projects, considering the need for more affordable and sustainable housing in the United States. Evidence from research and practice suggested that OSC is a feasible alternative to produce higher-quality housing in a faster way and at lower costs (Dodge Data & Analytics, 2020b; Galante et al., 2017).

The purpose of this research was to identify and provide principles on how to implement strategic changes in design and construction companies aiming at the successful use of OSC in multifamily projects in the United States. To achieve this purpose, the study investigated the following questions:

1. What are the most relevant factors affecting the adoption of OSC in multifamily projects in the United States?
2. What are the most relevant changes to be implemented in design and construction firms focused on successfully using OSC in multifamily projects in the United States?
3. How to implement strategic changes in design and construction companies aiming at the successful use of OSC for delivering more affordable and sustainable multifamily buildings in the United States?

3.1 Research Design

Mixed-method research, which is a combination of qualitative and quantitative methods, was utilized in this study to answer the research questions. Figure 3.1 visually describes the conceptual framework for the present study. First, to identify the most relevant factors affecting the adoption of OSC in multifamily projects in the U.S. (research question 1), the researcher conducted the following tasks:

1. Reviewed the literature (Phase 1).
2. Used a panel of experts from the AEC industry and the Delphi technique to validate and rank the 10 most significant factors based on group consensus, while analyzing and consolidating the data, which required several rounds of questionnaires-responses-analysis, including statistical analysis (Phase 2).

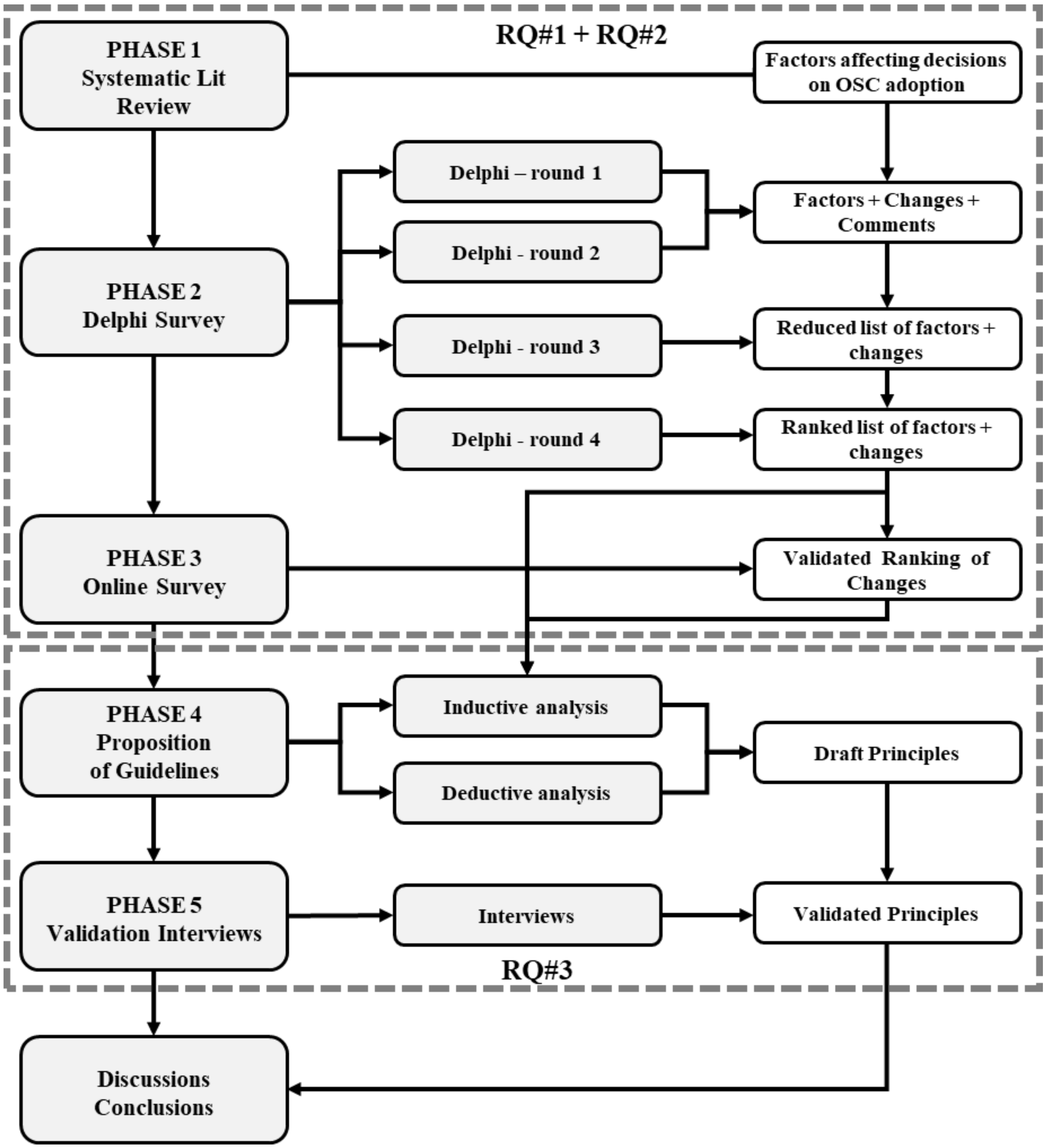


Figure 3.1. Research design – conceptual framework

Then, to identify the most relevant changes required to adjust design and construction firms to use OSC in multifamily projects in the United States (research question 2), the researcher performed the following tasks:

3. Used a panel of experts from the AEC industry and the Delphi technique to identify, validate and rank the changes based on group consensus; while analyzing and

consolidating the data, which required several rounds of questionnaires-responses-analysis, including statistical analysis (Phase 2).

4. Conducted an online survey to improve the reliability of the rankings of changes previously obtained on the Phase 2 (Phase 3).

Finally, to identify how to implement strategic changes in design and construction companies aiming at the successful use of OSC for delivering more affordable and sustainable multifamily buildings in the United States (research question 3), the researcher performed the following tasks:

5. Performed inductive and deductive qualitative analyses to make sense on the data collected on the previous phases and proposed a set of draft principles to implement changes in design and construction firms to successfully use OSC in multifamily projects in the United States (Phase 4).
6. Conducted interviews with designers (A/E) and construction professions to validate the draft principles (Phase 5).
7. Analyzed the results, revised the draft principles, and presented a set of revised principles to implement changes in design and construction firms to successfully use OSC in multifamily projects in the United States (Phase 5).

Considering that phases 2, 3 and 5 involved data collected from human participants, the researcher submitted the project to be reviewed by the Purdue Institutional Review Board (IRB). An exemption from the IRB was received on May 20, 2020, under the approval number #IRB-2020-481. The most recent amendment to the original exemption was obtained on April 9, 2021 and is included in APPENDIX A.

3.2 Phase 1 – Systematic literature review

The methodology used in his phase consisted of a systematic literature review to identify the factors that influence the adoption of OSC in multifamily projects in the US. This phase contributed to the publication of Research Article 1 (Gusmao Brissi, Debs, et al., 2021), which detailed the methodology used to collect and analyze the data related to the identification of the factors affecting the adoption of OSC in multifamily projects in the US.

3.3 Phase 2 – Delphi survey

The methodology for this phase consisted of using the Delphi technique to obtain expert's opinions and achieve the following goals:

1. Validate and rank the most significant factors affecting the adoption of OSC in multifamily housing, which were previously identified in Research Article 1 (Gusmao Brissi, Debs, et al., 2021).
2. Identify, validate and rank the most significant changes required to adjust design and construction firms to successfully adopt OSC for delivering more affordable and sustainable multifamily buildings in the United States.

3.3.1 Variables

The variables analyzed in Phase 2 were:

- The factors – validated and ranked by the Delphi panelists.
- The changes – validated and ranked by the Delphi panelists.

3.3.2 Population and sample

The population under analysis was made up of professionals of American design (architecture and engineering) and construction firms also including OSC manufacturing companies that provide full-service solutions, i.e., design, manufacturing, and construction of multifamily housing projects. To ensure a comprehensive view of the subjects under analysis, it was necessary to obtain the perspectives from different players of the AEC industry, namely, designers, contractors, OSC manufacturers, developers, market researchers and analysts. Therefore, the researcher invited representants from the main stakeholders to integrate the panel of experts.

This study followed a methodology similar to the one used by Okoli and Pawlowski (2004) and Schmidt (1997), which addressed the ranking-type Delphi and used more than one expert panel in their studies. Therefore, the study design purposefully grouped the experts into three distinct panels, according to their experience, with a homogenous sample of participants in panels 1 and 2, and a heterogeneous sample of participants in panel 3 (Table 3.1).

Table 3.1. Delphi survey – participants' characteristics

Group/ Panel	Participants field	Years of experience in the field	Number of participants
1	Designers – Architects and Engineers	⩾ 8	⩾ 4
2	Construction professionals	⩾ 8	⩾ 4
3	Other AEC related professionals	⩾ 8	⩾ 4

The panel of experts' participants comprised a purposive sample, i.e., the participants were selected based on their knowledge, credibility, and experience in the AEC field. The professionals were required to have a minimum of 8 years of experience and previous experience with both multifamily projects and offsite construction. A minimum of 10 participants was targeted to participate in the survey, as recommended in previous literature (Okoli & Pawlowski, 2004; Schmidt, 1997). In order to reach the largest number of professionals, the researcher used the following strategies to contact and eventually invite them to participate in the Delphi Survey expert panel:

- Sending direct emails to potential participants among the researcher's acquainted professionals.
- Sending messages to potential participants through LinkedIn.
- Posting invitations on LinkedIn with information about the research, both on the researcher's professional page and on the pages of groups of offsite construction, multifamily projects, design and construction in general.
- Sending emails to professionals who are members of the construction advisory council of the Purdue University School of Construction Management Technology through the school industry outreach specialist.

Once the panel of experts was formatted, the researcher started the first round of the survey to collect opinions. The first questionnaire also included demographic questions about the participants and the companies they worked for. many emails were exchanged between the researcher and the participants, in order to keep the participants engaged in the research. At the end of the survey, the researcher sent emails to all participants, informing them that the Delphi survey had been completed and that some of the results had not been conclusive. At the end of the survey, the researcher sent emails to all participants, informing them that the Delphi survey had been completed and that some of the results had not been conclusive.

3.3.3 Instrumentation

In order to obtain the experts' opinions on the subjects under analysis, the researcher developed questionnaires that were sent to the experts as the Delphi panel evolved. The questionnaires were developed to answer the research questions #1 and #2. Different questionnaires were required throughout Phase 2 (see APPENDIX B). The questions and the questionnaires formatting followed recommendations from the literature (Okoli & Pawlowski, 2004; Schmidt, 1997).

The experts were approached through email and through LinkedIn. The anonymity of each participant was ensured during the whole surveying process. The questionnaires were sent, collected, and managed electronically, since the researcher used e-mails to communicate with the participants. Following, the administration of the survey is described.

3.3.4 First round: gathering the issues

In this round the experts were treated as individuals, not grouped by panels, which reduced some of the problems associated with using homogeneous panels, such as inhibiting creativity, as the creative part of the Delphi technique occurs in the discovery of issues phase. The first round was equivalent to an anonymous brainstorming session. Once the minimum number of expert's agreed to serve on the Delphi panel, the researcher send the first questionnaire using the experts' e-mail. The Questionnaire 1 consisted of a solicitation of ideas (APPENDIX B).

To address the research question #1, the questionnaire asked the experts to select factors from a list with all the previously identified factors affecting the adoption of OSC in affordable and sustainable multifamily housing in the United States. The experts were instructed to include in their selection any factor they considered relevant and that was not included in the list provided. The responses allowed to validate a list of the most relevant factors affecting the adoption of OSC in multifamily housing in the United States, which from now on will be referred as “the factors' list”.

To address the research question #2, the questionnaire asked the experts to list at least six relevant changes required to adjust design and construction firms to successfully adopt OSC for delivering affordable and sustainable multifamily buildings in the United States. This question resulted in a list of the most relevant changes to be implemented in design and construction firms interested in successfully using OSC in multifamily housing in the United States, which from now on will be referred as “the changes’ list”.

The participants were asked to provide a brief explanation (two or three sentences for each factor and change) of the importance of each factor and change listed in the first two questions. The purpose of this request was twofold: (1) to facilitate the reconciliation, consolidation and classification of the factors and changes identified by the various specialists, and (2) to provide a qualitative empirical basis to understand the relationships between the aforementioned factors and the changes, which would help the researcher to answer research question #3.

A qualitative analysis was performed to aggregate the information obtained from the different responses, which allowed the identification of the factors and changes under investigation. The analysis included identification of patterns, coding, thematic analysis and categorization.

- The experts’ responses were content analyzed, according to the thematic analysis method (Patton, 2014) and the concepts discussed on the literature review, to capture important patterns and themes related to the research questions. Factors and changes were analyzed separately. The analysis of the changes was more complex because the researcher did not provide an initial list of changes, then each participant suggested the changes that they regarded as more relevant.
- After identifying and reviewing the factors selected by the participants, the researcher compiled a list of the factors – consolidated factors’ list – categorized according to the categories originally proposed in the literature review, based on the triple bottom line of sustainability, which comprehends economic, environmental and social factors.
- The themes of the changes were compiled in a list – consolidated changes’ list – and grouped according to the different players to implement each change: designers, general contractors, manufacturers, owners/developers. Because they were chosen by some participants, changes that were applicable to manufacturers and owners/developers were also included in the consolidated list, but the participants were informed that they should focus on changes to be implemented in design and construction firms.

Since this round considered all the experts as individuals, two lists were obtained, namely, the factors list and the changes list, representing the creativity of all panelists. The output of this round consisted of:

a. A consolidated list with all the factors selected by the participants, including frequencies and comments.
b. A consolidated list of changes based on the researcher's interpretation of the participants responses and comments.

3.3.5 Second-round: determining the most important issues

The goal of this round was to validate and reduce the number of issues by understanding the importance of the factors and changes based on the different perceptions of the various experts' groups. This round considered the experts as three distinct panels. Some panels of experts could evaluate the challenges and opportunities for OSC in multifamily housing differently, and these differences would likely have important implications for design and construction firms interested in successfully using OSC in their multifamily housing projects.

Participants were asked to answer Questionnaire 2 (APPENDIX B). Aiming at validating the previous answers and reducing the list of factors and changes, the participants of each panel selected the 10 most relevant factors and changes from a consolidated list with all the relevant issues identified in the previous round, while being able to reflect on and review their previous answers. The researcher shared with the panelists a copy of each participant's responses to Questionnaire 1.

The responses from each panel were separately analyzed upon return of all questionnaires. The researcher kept in the lists only the issues selected by at least 50% of the experts from each panel. The goal was to reduce the two lists to a maximum of 20 factors and 20 changes, which was manageable size for ranking, as recommended by Schmidt (1997).

The output of this round consisted of:

a. Three pared lists with the most important factors selected by each panel.
b. Three pared lists with the most important changes selected by each panel.

3.3.6 Third round: ranking the most important issues

The goal of this round was to rank and reach a consensus in the ranking of the relevant factors and changes within each panel by combining individual rankings. Thus, instead of trying to reconcile very different perspectives that could make it impossible to reach consensus, the strategy was to work with groups that thought likewise and could decide among themselves which factors and changes were the most important.

In this round the researcher sent Questionnaire 3 (APPENDIX B) to the experts within each panel. Questionnaire 3 included a pared list with the most important issues (factors and changes) previously selected by each expert's panel. The pared list was organized in alphabetical order to avoid bias in the order of listing the issues. The participants were asked to rank the factors and changes and ties were not allowed. Upon return of all questionnaires the responses were analyzed.

The results were aggregated into three lists with the rankings of factors and three lists with the rankings of changes, reflecting the rankings for each specific panel. Statistical analysis were performed, including frequencies, mean ranks, standard deviations, variances of rank, and Kendall's coefficient of concordance (W), as recommended by Schmidt (1997). The researcher also analyzed the comments related to each factor or change in each list, explaining the experts' perceptions of their rankings.

The output of this round consisted of:

a. Three lists with the rankings of factors reflecting the rankings for each specific panel.
b. Three lists with the rankings of changes reflecting the rankings for each specific panel.
c. Statistical analysis for each list with the rankings of factors and changes.

3.3.7 Fourth round: ranking refinement the most important issues

The goal of this round was to reach a consensus in the ranking of the relevant factors and changes within each panel by combining individual rankings. Thus, the researcher provided feedback on the previous round results to the participants within each specific panel. The information shared with each group included the ranked list of factors and changes, the statistical results (issues ranks, mean ranks, standard deviation, variance of rank, number of respondents and Kendall's *W*), and the participant's previous ranked lists. Questionnaire 4 (APPENDIX B1.1.1.1.1APPENDIX B) asked the panelists to analyze the results, review their previous ranking of factors and changes as wished, and provide comments on eventual modifications. The purpose of the fourth round was to gain consensus on the responses of the panel members.

Once again, the results were aggregated into three lists with the rankings of factors and changes reflecting the rankings for each specific panel. The statistical analysis performed for each panel responses was the same performed in the previous round, but now including comparisons of final mean ranks, standard deviations, variances of rank, number of participants, and Kendall's coefficient of concordance (W) for both round 3 and round 4, as recommended by Schmidt (1997).

3.3.8 Validity and reliability

In the case of this study, it was necessary to verify if the Delphi technique's results truly correspond to the real world (1) factors affecting the adoption of OSC in multifamily housing projects in the United States; and (2) changes required to adjust design and construction firms to successfully use OSC in multifamily housing projects in the United States.

According to Sekaran and Bougie (2016) "content validity is a function of how well the dimensions and elements of a concept have been delineated" ((Sekaran & Bougie, 2016, p. 221). Therefore, since the research was designed to ensure that the experts participating in the study are representative of the area of knowledge under study the content validity can be assumed (Goodman, 1987).

Face validity indicates that the items that are intended to measure a concept, do, on the face of it, look like they measure the concept (Sekaran & Bougie, 2016). So, considering that the Delphi technique is based on group judgments, the process itself collaborates to ensure construct and face validity. In addition, the questionnaires' face validity was assessed by faculty integrating the researcher's dissertation committee.

Construct validity is difficult to achieve through a single study. However, the whole process used in the Delphi technique, involving multiple iterations and enabling participants to review their responses based on a detailed understanding of their meaning, contributes to ensuring the methodology's construct validity (Okoli & Pawlowski, 2004).

The Delphi technique allows to check the consistency of the participants' responses by comparing the responses obtained for each round. As participants can review their judgments, variations in responses may occur, until stability is reached, which ensures consistency and reliability for the study. In addition, the reliability of the method can also be evaluated by comparing the statistical results measured by group.

3.3.9 Mitigation strategies to reduce impact of participant mortality

The researcher selected a number of participants greater than the minimum necessary (10 participants in total), in order to obtain a buffer in case of attrition, withdrawal or death of participants. Although research suggested that “participant drop-out tends to be very low when respondents have verbally assured their participation” (Okoli & Pawlowski, 2004, p. 23).

In face of issues with participant mortality, the researcher used an additional phase (Phase 3) consisting of online survey to validate the findings of the Delphi panel.

3.4 Phase 3 – Online survey

As the results of the Delphi survey regarding the ranking of changes were not conclusive, due to mortality of some of the Delphi panels at the later rounds, the researcher developed an online survey whose objective was to obtain a reliable classification of the most important changes previously identified and pre-classified by the specialists participating in the Delphi Survey. The Delphi survey resulted in three lists of changes, one for each panel of experts, the researcher then merged these three lists and compiled a single list with all the most important changes identified in the Delphi survey.

3.4.1 Population and sample

The population under analysis was made up of professionals working for American design (architecture and engineering) and construction firms also including OSC manufacturing companies that provide full-service solutions, i.e., design, manufacturing, and construction of multifamily housing projects. The online survey participants comprised a purposive sample made up of professionals from the AEC industry with experience in multifamily and offsite construction projects in the US.

3.4.2 Data analysis and data interpretation

The researcher organized and analyzed all the data gathered in the previous phases, focusing on the most significant changes to be implemented in design and construction firms aiming at successfully using OSC for delivering affordable and sustainable multifamily buildings in the United States. Data analyzed included:

- Three lists with the most relevant changes ranked in order of importance by the participants of the Delphi survey – refers to the changes to be implemented by design and construction firms to successfully use OSC in multifamily projects in the United States. The three lists reflected the perceptions of different players in the AEC industry, namely, designers, contractors, researchers, and consultants.
- All the comments provided by the experts of the Delphi survey – Phase 2 of the study.
- One list with the most relevant changes ranked in order of importance by the participants of the online survey.
- Data from the literature.

Following, the researcher performed inductive and deductive qualitative analysis.

3.4.3 Instrumentation

In order to answer the research question #2, the researcher developed a questionnaire that was sent to potential participants. The list with the most important changes identified in the Delphi survey was included in the questionnaire of the online survey (see APPENDIX C) and sent to a purposive sample.

3.4.4 Data collection and data analysis

The participants were approached through email or LinkedIn messages and the responses were anonymous. Descriptive statistical analyses were performed, including minimum and maximum ranks, mean ranks, standard deviations, and variances of rank. The results were present in a list with the rankings of changes based on the means ranks, with lower means indicating top positions in the rank.

3.5 Phase 4 – Proposition of Principles

To answer research question #3 the researcher used the following methods: qualitative analysis and interpretation of data obtained in Phases 1, 2 and 3; and deductive qualitative analysis to generate propositions. The result of this phase is a set of draft principles to support design and construction firms in implementing strategic changes required to successfully use OSC in multifamily projects in the United States.

3.5.1 Inductive qualitative analysis

The inductive qualitative analysis consists of identifying patterns, themes and categories in the data, but this phase basically consolidated the analyses performed on the previous phases and related them with patterns and themes from the literature (see CHAPTER 2). By following the steps suggested by Succar et al. (2012) in a study related to measuring BIM performance, the researcher derived dimensions and concepts, and identified their properties (Patton, 2014) through a process of inductive inference, conceptual clustering and reflective learning (Succar et al., 2012).

3.5.2 Deductive qualitative analysis

Deductive analysis was performed according to an existing framework (Patton, 2014). However, differently from the method used by Succar et al. (2012), the researcher used the framework developed by the World Economic Forum – WEF (2016) to generate the theoretical propositions (see Figure 2.6).

Due to the findings from the previous phases, some adjustments were made to the WEF framework. The purpose was to organize the most important changes to be implemented in design and construction firms according to this framework, and then connect them to an implementation plan. So, based on the concepts and premises previously identified through inductive inferences, the researcher used the WEF framework to hypothesize about the relationships between concepts and generate the propositions (draft principles) on how to implement significant changes in design and construction firms aiming at the successful and increasing use of OSC in multifamily projects in the United States.

3.6 Phase 5 – Validation Interviews

Still, to answer research question #3, the researcher performed interviews with professionals from the AEC industry to validate the propositions previously generated in Phase 4 of this study. The interviews provided the participants' perspectives on the draft principles to support design and construction firms in implementing the most strategic changes to the successful use of OSC for delivering more affordable and sustainable multifamily buildings in the United States.

3.6.1 Population and sample

The population under analysis consisted of design (architecture and engineering) and construction firms that work with multifamily housing projects in the United States. As this is a qualitative investigation focused on in-depth interviews with a clear purpose, the interviews participants comprised a relatively small purposive sample, as recommended in qualitative inquiry (Patton, 2002).

The participants were selected based on their experiences working in companies that have successfully implemented and/or unsuccessfully tried to implement changes to use OSC in multifamily projects, and should comply with the following requirements:

- Position: mid-level professionals, including architects and engineers, coordinators, supervisors and managers.
- Years of experience: minimum of 5 years.
- Number of participants: 12 professionals, with 6 participants from design (A/E) firms, and 6 participants from construction firms.

3.6.2 Instrumentation

In order to get the interviewees' expertise on the subjects under analysis, the researcher conducted semi-structured interviews based on an interview guide designed to verify the appropriateness of the propositions. The interview guide comprehended structured demographically oriented questions; open-ended main questions; follow-up questions and sub questions. The guide was divided into the following domains of inquiry (see APPENDIX D):

- Status of the interviewees' firm regarding the adoption of OSC, especially on multifamily projects.
- Interviewees' perceptions of the principles to implement significant changes in design and construction firms aiming at the successful and increasing use of OSC for delivering multifamily buildings in the United States, which were sent to them through email (see APPENDIX E).
- Discussion of the changes implemented or not in the interviewees' firms to adjust them to successfully use OSC in their projects and more specifically in multifamily housing projects.
- Interviewees' perceptions about the differences and similarities of the strategies and changes to be implemented by companies for multifamily projects and for other projects (healthcare, commercial, educational).
- Discussion of the changes that should have been implemented or that will be implemented in the next 5 years to allow the interviewees' company to start adopting or increase the adoption of OSC in their projects.

3.6.3 Data collection

The participants were firstly approached through email or LinkedIn messages. Following, all the participants that agreed to participate in the study were contacted by email and/or telephone. A few days before a before each interview, the researcher sent through email to the interviewees a document with a summary of the draft principles (see APPENDIX E). The interviews were conducted by videoconference and, with the consent of the participants the audio was recorded. Since the researcher used an interview guide, the interviewees were asked similar semi-structured open-ended questions, but follow-up and sub questions varied according to the participants' responses and behavior.

3.6.4 Data analysis

Upon conclusion of the interviews, the researcher transcribed the data and performed a qualitative analysis similar to the one performed in the previous phase (see Phase 4 –), which included inductive analysis to identify patterns and make sense of the data (content analysis); and deductive analysis, to verify if the participants responses corroborated and validated the propositions.

The content analysis allowed the researcher to convert qualitative data into quantitative data. The data was systematically analyzed and coded. The coding categories were defined before the content analysis was performed and were based on the results of the previous phases of the research, i.e., factors affecting the use of OSC, the changes to be implemented on design and construction firms and the draft principles previously generated. The outcome of this phase were the potential adjustments to the draft principles.

3.6.5 Validity and Reliability

The interviews provided an opportunity to triangulate the analyzes performed by the researcher to create the principles. In this way, it was possible to check for the consistency of both the data collected through the Delphi survey, the online survey and literature, as well as the researcher's analysis and interpretations (Patton, 2002).

3.7 Chapter Summary

This chapter presented the methodology used in the five phases of this study:

- Phase 1 – literature review: the goal was to identify the factors affecting the use of OSC in multifamily projects in the United States.
- Phase 2 – Delphi survey with experts from the AEC industry: the goal was (1) to validate and rank the most significant factors affecting the adoption of OSC in multifamily projects, which were previously identified in the literature; and (2) to identify, validate and rank the most significant changes required to adjust design and construction firms to successfully adopt OSC for delivering more affordable and sustainable multifamily housing in the United States. Part of the Delphi survey data (rankings of factors and changes) was not conclusive and required validation.
- Phase 3 – online survey with professionals of the AEC industry provided data to improve the reliability of the Delphi survey results regarding the ranking of changes, which were not conclusive.

- Phase 4 – generation of propositions: the goal was to obtain a set of preliminary principles on how to implement strategic changes in design and construction companies aiming at the successful use of OSC in their multifamily projects in the United States. The proposed principles required validation from design and construction professionals.
- Phase 5 – validation of principles and data from previous phases: the goal was to obtain a set of validated principles on how to implement strategic changes in design and construction companies aiming at the successful use of OSC in their multifamily projects in the United States.

In the following chapter, the researcher will present the results of all the five phases of this study.

CHAPTER 4. RESULTS AND DISCUSSION

In this chapter, the researcher presents the results for the three first phases of the study. Results and brief discussions are presented by phase.

4.1 Phase 1 – Systematic Literature Review

In Research Article 1 (Gusmao Brissi, Debs, et al., 2021), the researcher performed a review of the literature published between 2000 and 2019 focused on factors that influence the use of OSC in diverse construction sectors from different countries. This investigation provided a total of 45 papers, which were analyzed and resulted in a total of 28 factors identified as significant in the adoption of OSC in construction.

It is important to highlight that this article focused on a holistic approach to the factors in question to ensure that the three dimensions of sustainability – social, economic, and environmental – are considered in decisions involving the use of the OSC. Therefore, the literature review was based on articles that focused on the triple bottom line of sustainability, which is aligned with recent research on the adoption of OSC in construction (Hammad et al., 2019; Kamali & Hewage, 2016, 2017; Yunus & Yang, 2012).

Of the reviewed literature, only eight studies (including academic and industry studies) focused on multifamily projects in the US. And from those eight studies, a total of 27 factors were cited in the scarce literature– see Research Article 1 (Gusmao Brissi, Debs, et al., 2021). Table 4.1 presents the identified factors and the frequency with which they were cited in the investigated literature.

The factors were grouped into the three categories of sustainability: social (9 factors), environmental (7 factors), and economic (11 factors). Aesthetics, included in the original list of 28 factors, was not a significant factor identified in the literature focused on the use of OSC in multifamily projects in the US, therefore it was removed from the list of factors. Individually, the most frequent factors, which were present in over 75% of papers, were (1) costs, (2) risks and financing, (3) time, (4) design, (5) labor, (6) market and demand, (7) productivity, (8) regulations and incentives, (9) transportation and logistics, an (10) technology and innovation.

Table 4.1. Factors affecting the use of OSC in multifamily housing in the US most frequently cited in the literature

ID	Factors	Category	Percentage of studies citing
1	Costs	ECO	100%
2	Risks and financing	ECO	100%
3	Time	ECO	100%
4	Design	ECO	88%
5	Labor	SOC	88%
6	Market and demand	ECO	88%
7	Productivity	ECO	88%
8	Regulations and incentives	SOC	88%
9	Transportation and logistics	ECO	88%
10	Technology and innovation	ECO	75%
11	Materials and practices	ENV	63%
12	Planning and processes	ECO	63%
13	Safety and health in construction	SOC	63%
14	Waste and pollution	ENV	63%
15	Building performance	ENV	50%
16	Experience of professionals and suppliers	SOC	50%
17	Quality and product value	SOC	50%
18	Site disruption	ENV	50%
19	Social attitude and market culture	SOC	50%
20	Stakeholders' alignment	SOC	50%
21	Supply chain and procurement	ECO	50%
22	Climate, weather and resilience	ENV	38%
23	Environmental sustainability	ENV	38%
24	Building comfort and IEQ	ENV	25%
25	Customer's attitude	SOC	25%
26	Influence on society and local communities	SOC	25%
27	Management	ECO	13%

Due to the scarce literature focused on the use of OSC in multifamily projects in the US, these results may be skewed, as they differ greatly from the results obtained in the literature review on the use of OSC in different types of markets and countries, which revealed the following factors as the most important (1) costs, (2) time, (3) quality and product value, (4) transportation and logistics, and (5) labor. Hence the importance of validating these results.

4.2 Phase 2 – Delphi Survey

Phase 2 was designed to answer research questions #1 and #2. Therefore, the goal of Phase 2 was twofold:

- Validate and rank the most significant factors affecting the adoption of OSC in sustainable multifamily housing, which were previously identified in the literature.
- Identify, validate, and rank the most significant changes required to adjust design and construction firms to successfully adopt OSC for delivering more affordable and sustainable multifamily buildings in the United States.

4.2.1 Demographics

A total of 14 participants agreed to participate as an expert in the Delphi survey and were grouped as presented in Table 4.2. The group of designers was the most experienced, since all the six participants had more than 21 years of experience in the AEC industry.

Table 4.2. Delphi survey participants (*n*=14)

Group/ Panel	Participants field	Years of experience in the field	Number of participants
1	Designers – Architects and Engineers	≥ 21	6
2	Construction professionals	⩾ 8	5
3	Consultants, academics, and offsite construction manufacturers **[1]**	⩾ 16	3

Note. the representant of manufacturers only participated in the first round. Therefore, from round 2, this panel started to be identified as "Panel 3 – Consultants and academics".

In fact, the responses provided by the participants revealed that very experienced professionals integrated the three panels of experts, since almost 80% (11 of the 14 participant) had more than 20 years of experience in the AEC industry (Figure 4.1).

As for the professionals' experience with OSC, 50% of them have worked in more than 10 projects with adoption of OSC and although one of the participants has never used OSC in any project, the use of OSC has been analyzed and considered in several of their projects (Figure 4.2).

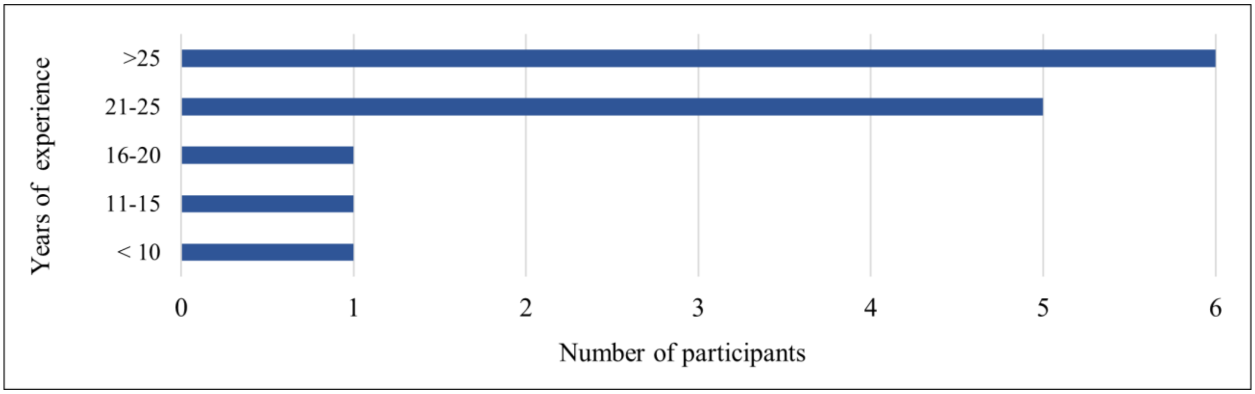


Figure 4.1 Number of participants by years of experience in the AEC industry

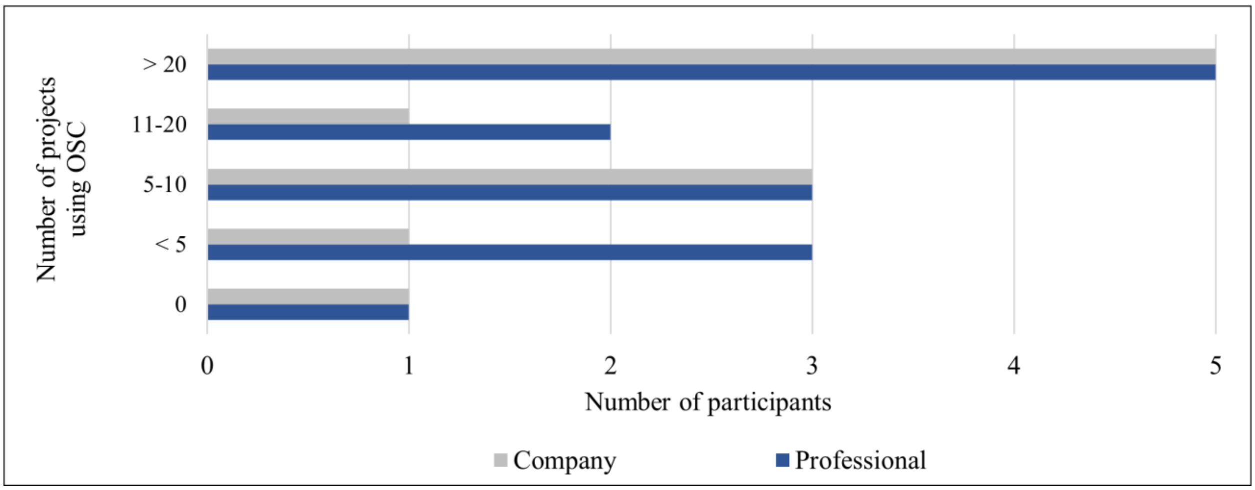


Figure 4.2 Number of participants by number of projects using OSC

Figure 4.3 provides the breakdown of participants by type of organization at the time of the survey. It is important to highlight that some participants had experience in more than one type of AEC organization and their expertise could be relevant to more than one panel. In such cases, the researcher consulted with them to decide which panel they could contribute most significantly to (see and Table 4.2). These particular cases are explained below.

- Three participants were working for educational institutions (which are not considered AEC companies), although they have already worked in AEC companies and have had experience with offsite construction in multifamily projects. One of those participants, current working as a professor, asked to be included in panel 2 (construction professionals). Another participant, a professor who also works as consultant, asked to be categorized as a consultant and be included in panel 3 (consultants, academics and manufacturers). The third participant, with many years of experience in construction companies, asked to be categorized as a professor and be included in panel 3.

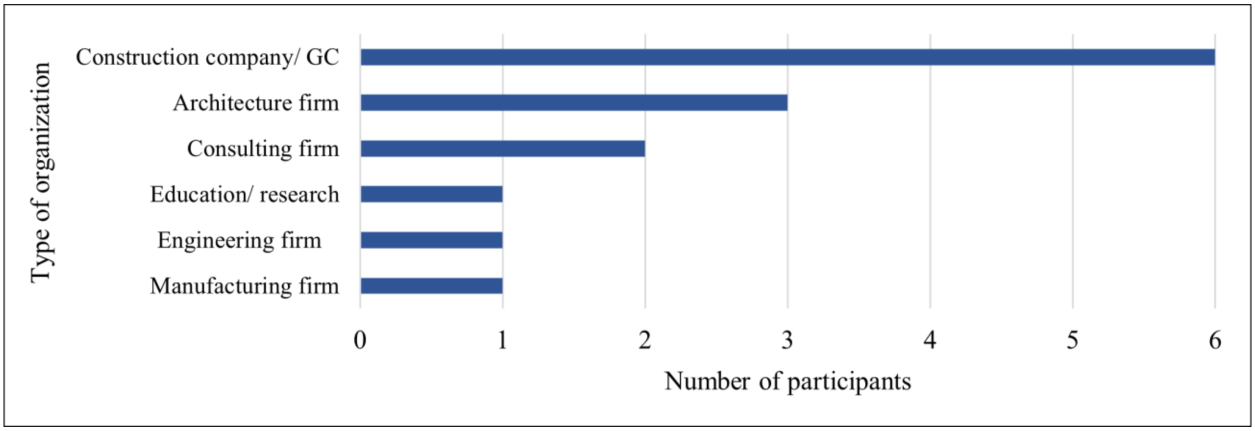


Figure 4.3 Number of participants by type of organization (current position of the participants)

- A participant who was currently working for a construction company had just relocated from a position in an offsite construction company but categorized themselves as a manufacturer representant and was included in panel 3 (consultants, academics and manufacturers). This expert only participated in the first round of the Delphi Survey.

The first questionnaires of the Delphi survey started to be sent on 09/21/2020 and the last answers were received on 01/18/2021. During this period of approximately four months, some participants gave up participating in the Delphi survey (Table 4.3).

Table 4.3. Number of participants per round

Group/ Panel	Participants field	Number of participants			
		Round 1	Round 2	Round 3	Round 4
1	Designers	5	4	5	3
2	Construction professionals	6	4	5	3
3	Offsite construction manufacturers, Developers, Consultants and academics	3	1	2	2
	Total	14	9	12	8

4.2.2 Delphi survey – consolidated results

The initial rounds of the Delphi survey were essential to achieving the research purpose, but they only provided partial results. Therefore, such results were included in APPENDIX G.

The Questionnaires sent to the participants at each round of the Delphi survey are presented in APPENDIX B. Following, a brief summary of each round of the Delphi survey is presented.

1. First round: the objectives of the first round were to (1) validate the list with all the factors affecting the adoption of OSC in multifamily housing in the United States, which were identified in the literature and provided to the participants by the researcher, and (2) identify the most significant changes required to adjust design and construction firms to successfully adopt OSC for delivering more affordable and sustainable multifamily buildings in the United States. A total of 14 responses were obtained and all the experts were considered as individuals. The output of this round consisted of (1) a consolidated list with all the factors selected by the participants, including frequencies and comments, and (2) a consolidated list of changes based on the researcher's interpretation of the participants responses and comments.
2. Second round: the goal of this round was to reduce the number and validate the most important factors and changes according to the perceptions of the various experts' groups. Therefore, in this round the experts were grouped into three distinct panels. Only nine participants responded. The output of this round consisted of (1) three pared lists with the most important factors selected by each panel, and (2) three pared lists with the most important changes selected by each panel.
3. Third round: the goal of this round was to rank the most important factors and changes according to the perceptions of the various experts' groups. Once again, the experts were grouped into three distinct panels. A total of 12 participants responded. The output of this round consisted of (1) three lists with the rankings of factors reflecting the rankings for each specific panel, (2) three lists with the rankings of changes reflecting the rankings for each specific panel, (3) statistical analysis for each list with the rankings of factors and changes.
4. Fourth and final round of the Delphi survey was performed to increase the level of agreement among the participants' responses obtained by the end of the third round. However, only 8 participants responded (Table 4.3). Due to the low participation rate in the fourth round and because of some of the participants' expressed desire to maintain the rankings that they had suggested in the previous round, few changes have occurred regarding the level of consensus. Given the increasing participant mortality, the

researcher decided to close the Delphi survey at the end of this round. The results of fourth round are presented as follows.

4.2.2.1 Factors

In the fourth round of the Delphi survey, the researcher provided the participants of each group with the ranked list of the most relevant factors affecting the adoption of OSC in multifamily housing in the United States, which was obtained in the previous round. Based on the participants responses, the researcher performed the same statistical analysis used in the third round using the software SPSS.

Panel 1 - Designers

The three experts who participated in this round reported they would like to keep their previous rankings of the factors. The statistics considering the responses of the three participants were analyzed and the resulting statistics showed a slight increase in Kendall's *W* (0.412), which still indicated weak agreement and a low level of confidence in the ranking of factors of panel 1 (Table 4.4).

Table 4.4. Descriptive Statistics – Factors Panel 1 (*n*=3)

Factors	Rank position	Minimum	Maximum	Mean	Std. Dev.	Variance
Time	1	1.00	4.00	2.333	1.528	2.333
Risks	2	1.00	6.00	3.000	2.646	7.000
Quality	3	1.00	7.00	4.667	3.215	10.333
Costs	4	3.00	8.00	5.667	2.517	6.333
Technology and innovation	5	3.00	7.00	5.667	2.309	5.333
Productivity	6	4.00	10.00	6.000	3.464	12.000
Labor	7	5.00	9.00	6.333	2.309	5.333
Design	8	3.00	10.00	7.000	3.606	13.000
Planning, strategy and processes	9	2.00	11.00	7.333	4.726	22.333
Logistics	10	8.00	10.00	9.000	1.000	1.000
Waste and pollution	11	5.00	11.00	9.000	3.464	12.000
Kendall's coefficient of concordance (W)						0.412

Note. Lower ranks represent more significant factors.

Panel 2 - Construction professionals

Two out of the three participants in this round revised some of their rankings of factors and one did not want to change his previous rankings. The modifications made by the participants were analyzed and here again the statistics showed a slight increase in Kendall's *W* (0.442), which still indicated a weak agreement and a low level of confidence in the ranking of factors of panel 2 (Table 4.5).

Table 4.5. Descriptive Statistics –Factors Panel 2 (*n*=3)

Factors	Rank position	Minimum	Maximum	Mean	Std. Dev.	Variance
Time	1	1.00	3.00	2.000	1.000	1.000
Planning, strategy and processes	2	1.00	11.00	4.667	5.508	30.333
Costs	3	3.00	6.00	4.667	1.528	2.333
Logistics	4	5.00	6.00	5.333	0.577	0.333
Quality	5	3.00	12.00	6.333	4.933	24.333
Site disruption	6	4.00	10.00	7.000	3.000	9.000
Safety and health	7	1.00	15.00	7.667	7.024	49.333
Materials	8	4.00	13.00	7.667	4.726	22.333
Technology and innovation	9	9.00	10.00	9.333	0.577	0.333
Waste and pollution	10	8.00	16.00	10.667	4.619	21.333
Client's attitude and market culture	11	2.00	16.00	11.000	7.810	61.000
Management	12	10.00	12.00	11.000	1.000	1.000
Experience	13	7.00	14.00	11.333	3.786	14.333
Labor	14	11.00	13.00	12.000	1.000	1.000
Aesthetics	15	8.00	15.00	12.333	3.786	14.333
Climate and weather conditions	16	9.00	16.00	13.000	3.606	13.000
Kendall’s coefficient of concordance (W)						0.480

Note. Lower ranks represent more significant factors.

Panel 3 – AEC Consultants and academics

In the previous round, the results of panel 3 indicated a high level of agreement (Kendall’s W = 0.688). In the fourth round the participants indicated they did not like to modify their previous inputs. Therefore, the ranking of the factors and the statistics remained unaltered as presented in Table 4.6.

Table 4.6. Descriptive Statistics –Factors Panel 3 (*n*=2)

Factors	Rank position	Minimum	Maximum	Mean	Std. Dev.	Variance
Design	1	1.00	3.00	2.000	1.414	2.000
Costs	2	2.00	2.50	2.250	0.354	0.125
Business model	3	1.00	6.00	3.500	3.536	12.500
Management	4	4.00	5.00	4.500	0.707	0.500
Time	5	2.50	9.00	5.750	4.596	21.125
Quality	6	4.00	8.00	6.000	2.828	8.000
Experience	7	6.00	7.00	6.500	0.707	0.500
Supply chain, manufacturing, and procurement	8	5.00	8.00	6.500	2.121	4.500
Labor	9	7.00	9.00	8.000	1.414	2.000
Climate and weather conditions	10	10.00	10.00	10.000	0.000	0.000
Kendall's coefficient of concordance (W)						0.688

Note. Lower ranks represent more significant factors.

4.2.2.2 Changes

In the fourth round of the Delphi survey, the researcher provided the participants of each group with the ranked list of the most relevant changes required to adjust design and construction firms to successfully adopt OSC in multifamily buildings in the United States, which was obtained in the previous round. Based on the participants responses, the researcher performed the same statistical analysis used in the third round using the software SPSS.

Panel 1 - Designers

The three participants who participated in this round reported they would like to keep their previous rankings of the changes. In addition, some of the participants in this round and in the previous one commented that the meanings of two *changes* in the list of *changes* were basically the same, so the researcher unified those two *changes* into one, with the wording slightly altered, as shown in Table 4.7.

Table 4.7. Changes consolidation

Original Change	Consolidated Change
Transition to digital delivery methods (3D models) with a more intense use of building information modeling (BIM) and higher level of details (LOD 400) in 3D models to facilitate the manufacturing and construction/ assembly process.	Implement BIM technologies and adopt a higher level of detail for all projects to promote digital fabrication strategies and to improve delivery methods, procurement process, logistics, and even installation monitoring.”
Implement technology (BIM) to promote digital fabrication strategies (including tools like computer numerical control (CNC) and 3D printing) and to improve the procurement process, logistics and installation monitoring.	

The results and the rank of the *changes* required to adjust design and construction firms to successfully adopt OSC in multifamily buildings in the United States according to the participants from panel 1 are presented in Table 4.8.

The statistics resulting from this round showed a slight increase in Kendall's *W* (0.336), which was not enough to reach a strong agreement that would represent a high level of confidence in the ranking of changes of panel 2.

Table 4.8. Descriptive Statistics – Changes Panel 1 (*n*=3)

Changes	Rank position	Min.	Max.	Mean	Std. Dev.	Var.
Design for OSC since the project conceptualization.	1	2.00	5.00	3.000	1.732	3.000
Understand OSC limitations and characteristics, how they affect the flexibility and creativity of design and work to improve the aesthetics and technical aspects of projects and align them with owners' and customers' expectations.	2	2.50	7.00	4.167	2.466	6.083
Allocate more time for improved design coordination, submittals analysis, planning and scheduling. Coordination focusing on: MEP and structural coordination; alignment of AOR/EOR documentation with the required factory production documentation, assembly requirements and code requirements.	3	1.00	8.00	4.333	3.512	12.333
Implement BIM technologies and adopt a higher level of detail for all projects to promote digital fabrication strategies and to improve delivery methods, procurement process, logistics, and even installation monitoring.	4	1.00	9.00	4.667	4.041	16.333
Align lenders requirements with owner's schedule to ensure financing of early off-site fabrication expenses.[1]	5	1.00	8.00	5.000	3.606	13.000
Develop partnerships and collaboration with large material suppliers and experienced trades/subs in OSC that work to create value reaching up into the supply chain and owning more manufacturing for OSC. Cooperate with partners training and involve suppliers and subcontractors in planning work.	6	3.00	7.00	5.333	2.082	4.333
Promote wider acceptance and understanding of OSC among AEC professionals and stakeholders by providing information on the characteristics, limitations, and potential benefits of OSC. Align expectations and promote collaboration between the stakeholders.[2]	7	2.50	10.00	5.833	3.819	14.583
Promote the standardization and simplification of processes and products by engaging in product platform and DFMA strategies.	8	4.00	9.00	6.000	2.646	7.000
Adopt enhanced management techniques, including lean construction practices.	9	6.00	10.00	7.667	2.082	4.333
Work with government, institutions and the AEC industry to incentivize the market by reviewing tax codes and creating incentives.[3]	10	8.00	10.00	9.000	1.000	1.000
Kendall's coefficient of concordance (W)						0.336

Notes. Lower ranks represent more significant factors.
(1) Although it was identified by the participants, this proposed change does not apply to design and construction firms, but to owners and developers. Therefore, it was removed from the final ranking of changes.
(2) (3) These changes were connected and after further analysis they were consolidated as one sole change (see Table 4.14).

Panel 2 - Construction professionals

Two out of the three participants in this round revised some of their rankings of factors and one did not want to change his previous rankings. As a result of the modifications, the statistics showed a slight increase in Kendall's *W* (0.521) achieving moderate agreement, which represented a fair level of confidence in the ranking of factors of panel 2 (Table 4.9).

Table 4.9. Descriptive Statistics – Changes Panel 2 (n=3)

Changes	Rank position	Min.	Max.	Mean	Std. Dev.	Var.
Allocate more time for improved design coordination, submittals analysis, planning and scheduling. Coordination focusing on: MEP and structural coordination; alignment of AOR/EOR documentation with the required factory production documentation, assembly requirements and code requirements.	1	1.00	3.00	1.667	1.155	1.333
Develop partnerships and collaboration with large material suppliers and experienced trades/subs in OSC that work to create value reaching up into the supply chain and owning more manufacturing for OSC. Cooperate with partners training and involve suppliers and subcontractors in planning work.	2	2.00	6.00	3.333	2.309	5.333
Plan logistics carefully considering size restrictions for transportation and travel distances from manufacturing facilities to the jobsite.	3	3.00	6.00	4.000	1.732	3.000
Adopt quality control standards similar to the manufacturing industry.	4	4.00	7.00	5.000	1.732	3.000
Understand OSC limitations and characteristics, how they affect the flexibility and creativity of design and work to improve the aesthetics and technical aspects of projects and align them with owners' and customers' expectations.	5	1.00	9.00	5.000	4.000	16.000
Plan for reduced schedule with OSC. Commit to delivery deadlines for project's drawings and documentation.	6	2.00	9.00	5.333	3.512	12.333
Promote wider acceptance and understanding of OSC among AEC professionals and stakeholders by providing information on the characteristics, limitations and potential benefits of OSC. Align expectations and promote collaboration between the stakeholders.[1]	7	5.00	8.00	7.000	1.732	3.000
Plan to deal with labor unavailability and develop a strategy to deal with labor issues such as crew reduction, union trades, workers training.	7	6.00	8.00	7.000	1.000	1.000
Work with municipalities to educated them on the characteristics and benefits of OSC.[2]	8	4.00	10.00	8.000	3.464	12.000
Adopt more innovative contracting models sharing responsibilities, risks, profits and expenses.	9	7.00	10.00	8.667	1.528	2.333
Kendall's coefficient of concordance (W)						0.521

Notes. Lower ranks represent more significant factors.
(1) (2) These changes were connected and after further analysis they were consolidated as one sole change (see Table 4.14)

Panel 3 – AEC Consultants and Academics

In the previous round, the results of panel 3 indicated a high level of agreement (Kendall's W = 0.810). In the fourth round the participants indicated they did not like to modify their previous inputs. Therefore, the ranking of the changes and the statistics remained unaltered as presented in Table 4.10.

Table 4.10. Descriptive Statistics – Changes Panel 3 (*n*=2)

Changes	Rank position	Min.	Max.	Mean	Std. Dev.	Var.
Allocate more time for improved design coordination, submittals analysis, planning and scheduling. Coordination focusing on: MEP and structural coordination; alignment of AOR/EOR documentation with the required factory production documentation, assembly requirements and code requirements.	1	1.00	2.00	1.500	0.707	0.500
Establish continuous training and knowledge management strategies.	2	3.00	3.00	3.000	0.000	0.000
Promote the standardization and simplification of processes and products by engaging in product platform and DfMA strategies.	3	1.00	5.00	3.000	2.828	8.000
Adopt enhanced management techniques, including lean construction practices.	4	2.00	5.00	3.500	2.121	4.500
Plan for reduced schedule with OSC. Commit to delivery deadlines for project's drawings and documentation.	5	4.00	4.00	4.000	0.000	0.000
Design and build sustainable and efficient buildings: sustainable building materials specs, energy and water efficiency, higher IEQ.	6	6.00	7.00	6.500	0.707	0.500
Focus on the three dimensions of sustainability to improve the business performance	7	6.00	8.00	7.000	1.414	2.000
Plan for maximum waste reduction.	8	7.00	8.00	7.500	0.707	0.500
Kendall's coefficient of concordance (W)						0. 810

Note. Lower ranks represent more significant factors.

4.2.3 Discussion

Due to the high mortality in the sample participating in the Delphi survey, which had only 8 participants in the last round, it was not possible to complete the survey aiming at strengthening the agreement and consequently increasing the level of confidence in the results obtained. Only the panel of participants representing AEC consultants and academics reached a strong consensus, but this one also had only two participants since the second round of the Delphi survey.

The part of the research focused on the ranking of factors was secondary in this research, but it was necessary to provide a better understanding of the changes that need to be implemented in the design and construction companies to successfully adopt OSC in multifamily buildings in the United States. Therefore, due to this secondary role, the researcher paused the analysis of the factors with the conclusion of the Delphi research and resumed it during the interviews with professionals from design and construction firms – Phase 5.

However, the issue of ranking the most important changes to be implemented in the design and construction firms was important to the development of the principles to implement changes in design and construction firms aiming at the successful use of OSC in multifamily projects. Therefore, the ranking of changes was further investigated in the next phase of the research.

4.2.3.1 Factors affecting the use of OSC in multifamily projects in the US

As anticipated by the researcher in the beginning of the study, the lists of factors ranked by the experts of each panel were different (Table 4.11), with few factors in common across the results of the tree panels, which indicated that different professionals with different experiences (design, construction, academic, etc.) have different perceptions regarding the use of OSC and therefore should be grouped according to their experiences.

Table 4.11. Comparison of factors rankings[1] between panels – alphabetical order

ID	Factors Selected [2]	Category	Panel 1[3]	Panel 2[3]	Panel 3[3]
F01	Aesthetics	SOC	-	11	-
F02	Business model	ECO	-	-	3
F03	Client's attitude and market culture	SOC	-	7	-
F04	Climate and weather conditions	ENV	-	16	10
F05	Costs	ECO	4	3	2
F06	Design	ECO	8	-	1
F07	Experience	SOC	-	14	7
F08	Labor	SOC	7	12	9
F09	Logistics	ECO	10	6	-
F10	Management	ECO	-	15	4
F11	Materials	ENV	-	10	-
F12	Planning, strategy, and processes	ECO	9	2	
F13	Productivity	ECO	6	-	-
F14	Quality[4]	SOC	3	4	6
F15	Risks	ECO	2	-	-
F16	Safety and health	SOC	-	5	-
F17	Site disruption	ENV	-	8	-
F18	Supply chain, manufacturing, and procurement	ECO	-	-	8
F19	Technology and innovation	ECO	5	9	-
F20	Time	ECO	1	1	5
F21	Waste and pollution	ENV	11	13	-

Notes. Gray cells indicate factors common to two or three panels.
(1) Lower ranks represent more significant factors.
(2) This list of factors was later adjusted - see Table 4.12.
(3) Panel 1 = designers ranked 11 factors/ Panel 2 = construction professionals ranked 16 factors/ Panel 3 = consultants and academics ranked 11 factors.
(4) Quality was initially categorized as an Economic factor, but based on participants responses and the researcher analysis, it was revised and categorized as a Social factor.

The list of factors obtained by the end of Phase 1 had a total of 27 factors, therefore, six factors from that list were not included in the list of factors defined by the Delphi survey participants in Phase 2:

- Building comfort and IEQ
- Building performance
- Environmental sustainability
- Influence on society and local communities
- Regulations and incentives
- Stakeholders' alignment

The group of designers (panel 1) had a total of 11 factors ranked (resulting from the pared list) and 8 of them were categorized as economic factors. The five most important factors selected by panel 1 were (1) time, (2) risks, (3) quality, (4) costs, and (5) technology and innovation.

The group of construction professionals (panel 2) had a total of 16 factors ranked (resulting from the pared list), with 6 economic, 6 social and 4 environmental factors, so this group was the most balanced in terms of considering the three aspects of sustainability of in multifamily projects. The five most important factors selected by panel 2 were (1) time, (2) planning, strategy, and processes, (3) costs, (4) logistics, and (5) quality.

The group of AEC consultants (panel 3) had a total of 10 factors ranked (resulting from the pared list) and 6 of them were categorized as economic factors. The five most important factors selected by the group of AEC consultants and academics were (1) design, (2) costs, (3) time, (4) quality, and (5) management.

It is interesting to note that, based on the comments provided by the participants throughout the Delphi survey, but mostly during the first round, the researcher identified that some factors were associated with benefits and challenges resulting from the adoption of OSC in multifamily projects in the US (Figure 4.4). For example, the factor *labor* was associate to challenges such as lack of professionals experienced in OSC, but also to benefits such as a way to address the construction workers shortage.

The analysis of literature performed in Research Article 1 (Gusmao Brissi, Debs, et al., 2021) focused on the use of OSC in multifamily projects in the US and revealed that the 10 most frequently cited factors (frequency ≥ 75%) were: (1) time, (2) costs, (3) risks and financing, (4) market and demand, (5) transportation and logistics, (6) design, (7) productivity, (8) labor, (9) regulations and incentives, and (10) technology and innovation. Eight of those factors were categorized as economic factors and two were social factors.

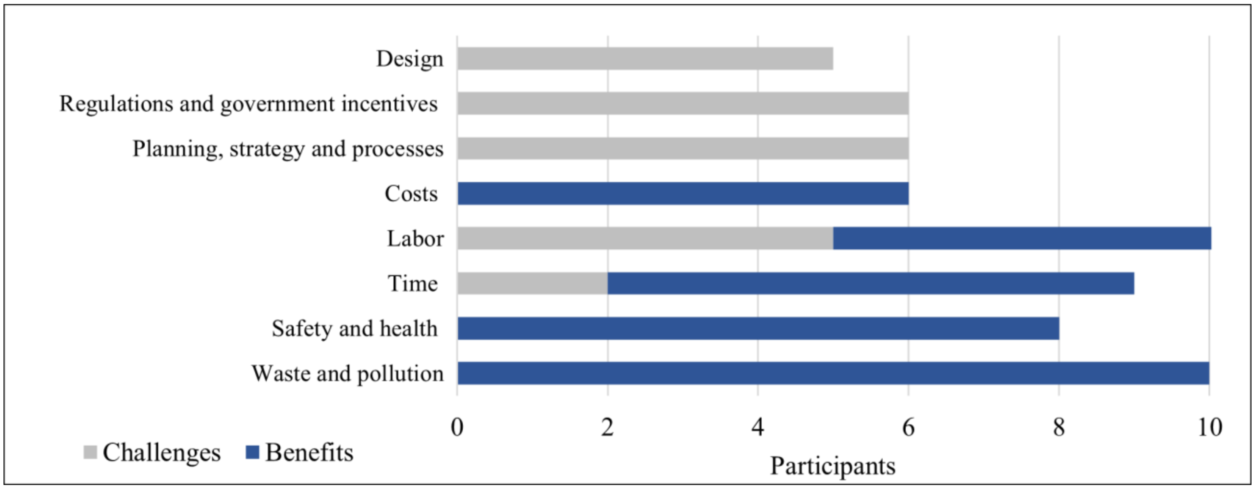


Figure 4.4. Factors associated with challenges and benefits by the Delphi survey participants (*n*=14)

Figure 4.5 shows that across the three groups, the majority of the factors identified as the most important (lower rank position) were economic factors, confirming the prevalence of economic aspects in decisions related to the choice of the constructive method to be adopted in multifamily projects in the US that had already been identified in the literature reviewed in Phase 1 (Gusmao Brissi, Debs, et al., 2021).

The only non-economic factor that appeared in the top five ranking across the three panels was *quality* (F14), categorized as a social factor, which was not among the top ranked factors identified in the literature focused exclusively on the use of OSC in multifamily projects in the US (Gusmao Brissi, Debs, et al., 2021). The experts from the three groups agreed on the importance of *costs* (F05), *time* (F20), which along with *quality* (F14) are related to the triple constraint model (Pollack et al., 2018). *Labor* (F08) was included in the list of factors ranked by the three groups, but it was not ranked in top positions, differing from what was identified in the literature (Gusmao Brissi, Debs, et al., 2021).

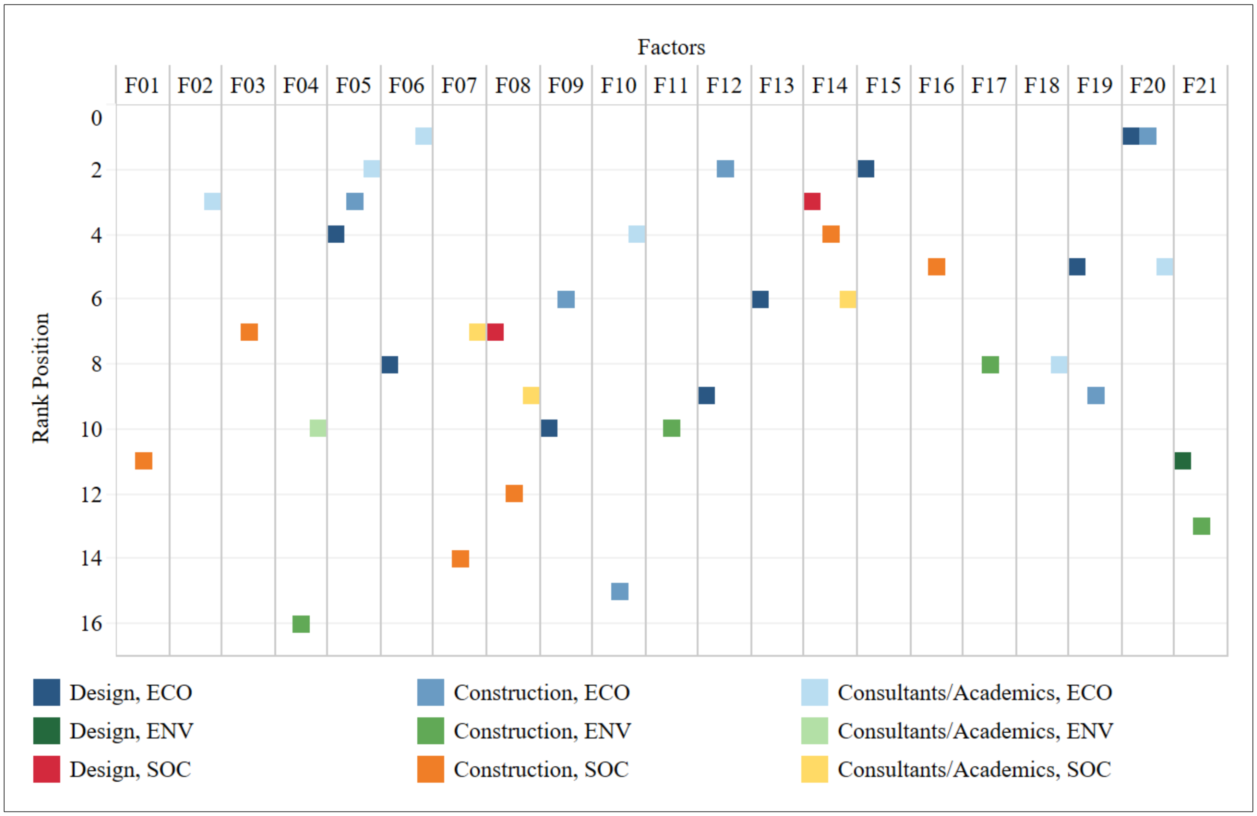


Figure 4.5. Comparison of the rankings of factors by categories between panels – lower ranks represent more important factors

Disregarding the differences between panels and comparing the factors validated and ranked by at least one group of experts with the factors identified in the Research Article 1 – Phase 1, the researcher consolidated a revised list with the 18 most important factors affecting the use of OSC in multifamily projects in the US – Table 4.12. The grey cells indicate factors that were combined in the revised list of factors.

The list of factors and what was encompassed in each factor suggested that some factors were more relevant at the local level, while others were important regardless of the project's location or geographic region (Table 4.13). This helped to understand the great discrepancy between the experts' opinions, who were from different regions of the country.

Table 4.12. Consolidated list based on all ranked factors by categories

Factors from RA 1[1]	ID	Factors ranked by the experts	ID	Revised factors	Cat
-	F01	Aesthetics	RF01	Aesthetics	SOC
Market and demand	F02	Business model	-	Combined with RF10	ECO
Customer's attitude Social attitude and market culture	F03	Client's attitude and market culture	RF02	Customer's/social attitude and market culture	SOC
Climate, weather and resilience	F04	Climate and weather conditions	RF03	Climate, weather and resilience	ENV
Costs	F05	Costs	RF04	Costs	ECO
Design	F06	Design	RF05	Design and coordination	ECO
Experience of professionals and suppliers	F07	Experience	RF06	Labor and experience	SOC
Labor	F08	Labor			
Transportation and logistics	F09	Logistics	RF07	Transportation and logistics	ECO
Management	F10	Management	RF08	Management and Productivity	ECO
Materials and practices	F11	Materials	RF09	Materials and practices	ENV
Planning and processes	F12	Planning, strategy and processes	RF10	Planning, processes and business	ECO
Productivity	F13	Productivity			
Quality and product value	F14	Quality	RF11	Quality and product value	SOC
Risks and financing	F15	Risks	RF12	Risks and financing	ECO
Safety and health in construction	F16	Safety and health	RF13	Safety and health in construction	SOC
Site disruption	F17	Site disruption	RF14	Site disruption	ENV
Supply chain and procurement	F18	Supply chain, manufacturing, and procurement	RF15	Supply chain and procurement	ECO
Technology and innovation	F19	Technology and innovation	RF16	Technology and innovation	ECO
Time	F20	Time	RF17	Time	ECO
Waste and pollution	F21	Waste and pollution	RF18	Waste and pollution	ENV

Note. (1) Six factors from the list of factors of Research Article 1 were not included in the list of factors defined by the Delphi survey participants: Building comfort and IEQ, Building performance, Environmental sustainability, Influence on society and local communities, Regulations and incentives, and Stakeholders' alignment.

Table 4.13. Level of importance of Factors

Factors with more universal relevance	Cat.	Factors with more local relevance	Cat.
Costs	ECO	Design and coordination	ECO
Management	ECO	Transportation and logistics	ECO
Planning, processes and business	ECO	Risks and financing	ECO
Technology and innovation	ECO	Supply chain and procurement	ECO
Time	ECO	Climate, weather and resilience	ENV
Materials and practices	ENV	Site disruption	ENV
Waste and pollution	ENV	Aesthetics	SOC
Quality and product value	SOC	Customer's/social attitude and market culture	SOC
Safety and health in construction	SOC	Labor and experience	SOC

4.2.3.2 Changes to be implemented in design and construction firms to successfully adopt OSC in multifamily projects in the US

Like the lists of factors, the lists of changes ranked by the experts of each panel were different. Table 4.14 (gray cells indicate the changes common to two or three panels) shows the final set of changes ranked by all the experts, remembering that one *change* was removed from the list because it did not apply to design and construction firms, and three similar *changes* were consolidated as a sole *change* (C16). In addition, the wording of some *changes* was adjusted.

Figure 4.6 shows how the changes were ranked across the three groups of experts. The group of designers (panel 1) had a total of eight changes ranked (after the final revision of all changes ranked). Panel 1 found that *Design for OSC since the project conceptualization* (C06) was the most important change/strategy to be implemented in design firms and curiously they were the only group to have this change in their list of changes, indicating that the other two groups did not find this change even worth to be in the list to be ranked. In fact, to ensure the full benefits of OSC, it is important to involve all the stakeholders since the project onset, for the project team needs to make important decision at very early stages, which will affect the design, cost, completion time, and project quality (Hu et al., 2019; Hwang et al., 2018a). *Understand OSC limitations and characteristics* (C17) was ranked by designers as the second most important change, indicating the strong impact that the adoption of OSC has on the aesthetic and technical concepts of the projects, which requires that designers and construction professional enhance their skills on OSC (Goulding et al., 2015; Hwang et al., 2018b). The third change in the designers' rank was *Allocate more time for improved design coordination, submittals analysis, planning, and scheduling* (C04), which was the only change ranked by the three panels, being in first position in the ranks of both construction professionals and consultants/academics Detailed planning and coordination is acknowledged as paramount because OSC projects have more compressed schedules than traditional construction projects and design changes have major impacts on OSC schedule (Smith, 2011).

Table 4.14. Comparison of changes rankings between panels – alphabetical order

Change	Description	Panel 1	Panel 2	Panel 3
C01	Adopt enhanced management techniques, including lean construction practices.	X	-	X
C02	Adopt more innovative contracting models sharing responsibilities, risks, profits and expenses.	-	X	-
C03	Adopt more strict quality control standards for all the phases of the project, similar to the ones used in the manufacturing industry.	-	X	-
C04	Allocate more time for improved design coordination, submittals analysis, planning and scheduling.	X	X	X
C05	Design and build sustainable and efficient buildings, comprehending sustainable building materials specs, energy and water efficiency, higher indoor environmental quality.	-	-	X
C06	Design for OSC since the project conceptualization.	X	-	
C07	Develop partnerships and collaboration with experienced manufacturers and suppliers in OSC that work to create value to the product.	X	X	-
C08	Establish continuous training and knowledge management strategies for the different hierarchical levels of the company.	-	-	X
C09	Focus on the three dimensions of sustainability (social, economic, environmental) to improve the overall business performance.	-	-	X
C10	Implement BIM technologies and adopt a higher level of detail for all projects to promote digital fabrication strategies and to improve delivery methods, procurement process, logistics, and even installation monitoring.	X	-	X
C11	Plan for maximum waste reduction.			
C12	Plan for a reduced schedule with OSC and commit to the deadlines for the delivery of the various phases of the project (design, planning, preconstruction, construction, and close-out).	-	X	X
C13	Plan logistics carefully considering size restrictions for transportation and travel distances from manufacturing facilities to the jobsite.	-	X	-
C14	Plan to deal with labor unavailability and develop a strategy to deal with labor issues such as crew reduction, union trades, workers training.	-	X	-
C15	Promote the standardization and simplification of processes and products by engaging in product platform and DFMA strategies.	X	-	X
C16 [1]	Promote wider acceptance and understanding of OSC among AEC professionals, stakeholders, and even the government to incentivize the market, review building codes and create incentives.	X	X	-
C17	Understand OSC limitations and characteristics, how they affect the flexibility and creativity of design and work to improve the aesthetics and technical aspects of projects and align them with owners' and customers' expectations.	X	X	-

Note. (1) C16 is the result of three changes that were consolidated as one sole change during the analysis that followed the fourth round. The changes connected were: (a) Promote wider acceptance and understanding of OSC among AEC professionals and stakeholders by providing information on the characteristics, limitations, and potential benefits of OSC. Align expectations and promote collaboration between the stakeholders, (b) Work with government, institutions, and the AEC industry to incentivize the market by reviewing tax codes and creating incentives, and (c) Work with municipalities to educate them on the characteristics and benefits of OSC.

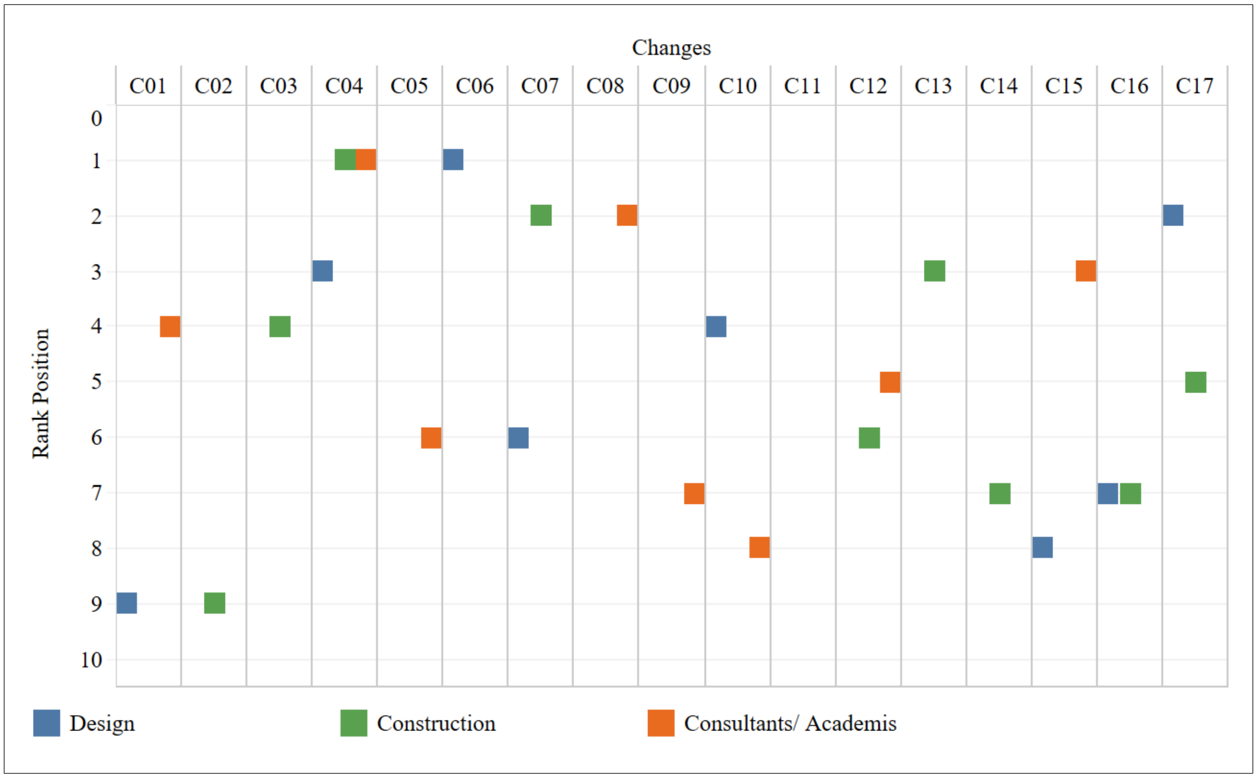


Figure 4.6. Comparison of the rankings of changes between panels – lower ranks represent more important changes

The group of construction professionals (panel 2) had a total of nine changes ranked (after the final revision of all changes ranked). The most important change selected by panel 2 was *Allocate more time for improved design coordination, submittals analysis, planning and scheduling* (C04), which has already discussed. The second change selected as the most important was *Develop partnerships and collaboration with experienced manufacturers and suppliers in OSC that work to create value to the product* (C07). These partnerships can be beneficial for both design and construction companies, as they improve relationships, facilitating the flow of information, and reducing problems throughout the project phases (Hu et al., 2019; Lessing et al., 2005). The third change in the rank was *Plan logistics carefully considering size restrictions for transportation and travel distances from manufacturing facilities to the jobsite* (C13), which mostly impacts construction firms, but considering that OSC involves an integrated system that needs to be defined in the early phases of the project, logistics affect the design phase as well (Bertram et al., 2019; Niu et al., 2017).

Panel 3 (consultants/academics) had a total of eight changes ranked. Alike the results of panel 2, the first change in the ranking was *Allocate more time for improved design coordination, submittals analysis, planning, and scheduling* (C04). The second change in the ranking was *Establish continuous training and knowledge management strategies* (C08), which is a very important strategy in OSC, but was not included in the list of changes ranked by the experts from panels 1 and 2. In fact, this change is similar to change C17 (ranked #2 in panel 1) as it highlights that designers and construction professional need to improve their skills on OSC (Goulding et al., 2015; Hwang et al., 2018b), but it is more comprehensive because knowledge management involves the dissemination of lesson learned to promote the continuous improvement of processes and products (Smith, 2011). The fact that the two participants of this panel are academics (one is also a consultant) has likely contributed to emphasize the importance of this change in OSC. The third most important change was *Promote the standardization and simplification of processes and products by engaging in product platform and DFMA strategies* (C15). Here again, we have an important strategy applicable to design and construction companies involved with OSC, which was not considered very important by the experts of panel 1 and was not even ranked by the experts of panel 2. This change helps to reduce the variability of processes and products, enables economies of scale and can lead to a new business model, product-oriented and no longer project-oriented (Andersson & Lessing, 2019; Lessing & Brege, 2018; Peltokorpi et al., 2018).

Since the main purpose of this study was to develop principles to support design and construction firms to implement changes to successfully use OSC in multifamily projects, which depended on the identification of the topmost important changes, it was paramount to increase the reliability in the ranking of changes to reduce the list with the most important changes. Therefore, the researcher included in the study another phase (Phase 3 – online survey) to collect the opinions of professionals from the AEC industry on the ranking of the changes identified and validated as significant by the Delphi survey. The list with the changes to be ranked in Phase 3 was based on a consolidated list with all the changes ranked by the experts from the three groups of the Delphi survey (see results of Table 4.14). The unification of the three lists of changes into a single list was required because the online survey was submitted to anonymous participants, so it was not possible to separate participants by area of expertise (e.g., designers or construction professionals).

4.2.3.3 Relationship between the changes to be implemented in design and construction firms to successfully use OSC and the factors affecting the adoption of OSC in multifamily projects in the US

In order to better understand the strategic changes to be implemented in design and construction firms, the researcher analyzed the relationships between the changes suggested and ranked by the experts and the factors that they validated and ranked. Table 4.15 shows the proposed relationship between the changes considered most significant, which were therefore ranked by at least one of the three groups of experts, and the most significant factors, which also include only the factors which were ranked by at least one of the groups. In total there were 17 significant changes.

The change placed in the 9th row (red cells) was associated to a factor that was not ranked by at least one of the expert groups: *Building performance*. The change *Promote wider acceptance and understanding of OSC among AEC professionals, stakeholders, and even the government to incentivize the market, review building codes and create incentives* was associated to three different factors, but two of them were not ranked by at least one group of experts, namely *Regulations and incentives* and *Stakeholders' alignment* (red cells).

It is important to note that no change was directly associated with the following factors:

- Costs – factor considered very significant by the three groups of experts (panel 1 rank 4/11 , panel 2 rank 3/16, panel 3 rank 2/10).
- Safety and health – factor considered somewhat important for the experts of panel 2 (rank 5/16).
- Climate, weather, and resilience – factor considered slightly significant, but still included in the list of factors ranked by the experts of panels 2 (rank 16/16) and 3 (rank 10/10).
- Productivity – factor considered somewhat important by the experts of panel 1 (rank 6/11).
- Site disruption – factor considered somewhat important but ranked by the experts of panel 2 (rank 8/16).

Table 4.15. Relation between the most significant changes and factors

ID	Changes	Applicable to	Related Factors	Category
1	Adopt enhanced management techniques, including lean construction practices.	Designer/ GC	Management	ECO
2	Adopt more innovative contracting models sharing responsibilities, risks, profits, and expenses.	Designer/ GC	Risks and financing Planning, processes and business	ECO
3	Adopt more strict quality control standards for all the phases of the project, similar to the ones used in the manufacturing industry.	Designer/GC	Quality and product value	SOC
4	Allocate more time for improved design coordination, submittals analysis, planning, and scheduling.	Designer/ GC	Time	ECO
5	Design and build sustainable and efficient buildings, comprehending sustainable building materials specs, energy and water efficiency, higher indoor environmental quality.	Designer/ GC	Materials and practices	ENV
6	Design for OSC since the project conceptualization.	Designer	Design	ECO
7	Develop partnerships and collaboration with experienced manufacturers and suppliers in OSC that work to create value to the product.	Designer/ GC	Supply chain and procurement	ECO
8	Establish continuous training and knowledge management strategies for the different hierarchical levels of the company.	Designer/ GC	Planning, processes and business	ECO
9	Focus on the three dimensions of sustainability (social, economic, environmental) to improve the overall business performance.	Designer/ GC	Building performance	ENV
10	Implement BIM technologies and adopt a higher level of detail for all projects to promote digital fabrication strategies and to improve delivery methods, procurement process, logistics, and even installation monitoring.	Designer/ GC	Technology and innovation	ECO
11	Plan for a reduced schedule with OSC and commit to the deadlines for the delivery of the various phases of the project (design, planning, preconstruction, construction, and close-out).	Designer/ GC	Time	
12	Plan for maximum waste reduction.	Designer/ GC	Waste and pollution	ENV
13	Plan logistics carefully considering size restrictions for transportation and travel distances from manufacturing facilities to the jobsite.	GC	Transportation and logistics	ECO
14	Plan to deal with labor unavailability and develop a strategy to deal with labor issues such as crew reduction, union trades, workers training.	Designer/ GC	Labor and experience	SOC
15	Promote the standardization and simplification of processes and products by engaging in product platform and DfMA strategies.	Designer/ GC	Planning, processes, and business Design and coordination	ECO
16	Promote wider acceptance and understanding of OSC among AEC professionals, stakeholders, and even the government to incentivize the market, review building codes and create incentives.	Designer/ GC	Customer's/social attitude and market culture	SOC
			Regulations and incentives	SOC
			Stakeholders' alignment	SOC

Table 4.15 continued

ID	Changes	Applicable to	Related Factors	Category
17	Understand OSC limitations and characteristics, how they affect the flexibility and creativity of design and work to improve the aesthetics and technical aspects of projects and align them with owners' and customers' expectations.	Designer/ GC	Design and coordination	ECO
		Designer/ GC	Customer's/social attitude and market culture	SOC
		Designer	Aesthetics	SOC

Note. The red cells indicate factors that were not ranked by any of the three groups of experts participating in the Delphi survey.

4.3 Phase 3 – Online Survey

The Online survey was performed to improve the reliability of the Delphi survey results regarding the ranking of changes, which were not conclusive due to mortality of some of the Delphi panels at the later rounds of the Survey.

The Delphi survey resulted in three lists of changes, one for each panel of experts, the researcher then merged these three lists and compiled a single list with a total of 17 most important changes (see Table 4.14). Because of this merge on one single list, from now on, the researcher decided to focus on higher-level changes that would be applicable to design and construction companies, rather than focusing on different perspectives.

This list was included in the questionnaire of the online survey (see APPENDIX C) and sent to a targeted sample made up of professionals from the AEC industry with experience in multifamily and offsite construction projects in the US. The responses were anonymous, and the survey was conducted between 02/11/2021 and 04/06/2021. A total of 59 responses were recorded, but only 25 of them ranked the most important changes.

4.3.1 Demographics

Among the 25 participants only three responded that they had not worked with OSC in their multifamily projects, but they had considered using OSC in some of them. The participants were design firms (*n*=9), construction firms (*n*=8) and mixed firms – including consultancy, development, manufacturing, vertically integrated and federal agency (*n*=7). Focusing on the regional distribution[1], 13 of the 24 participants were from regions Region 1: Northeast – Division 2: Mid-Atlantic (*n*=7) and Region 4: West – Division 9: Pacific (*n*=6) Participants from these regions were also more familiar with OSC – see Figure 4.7.

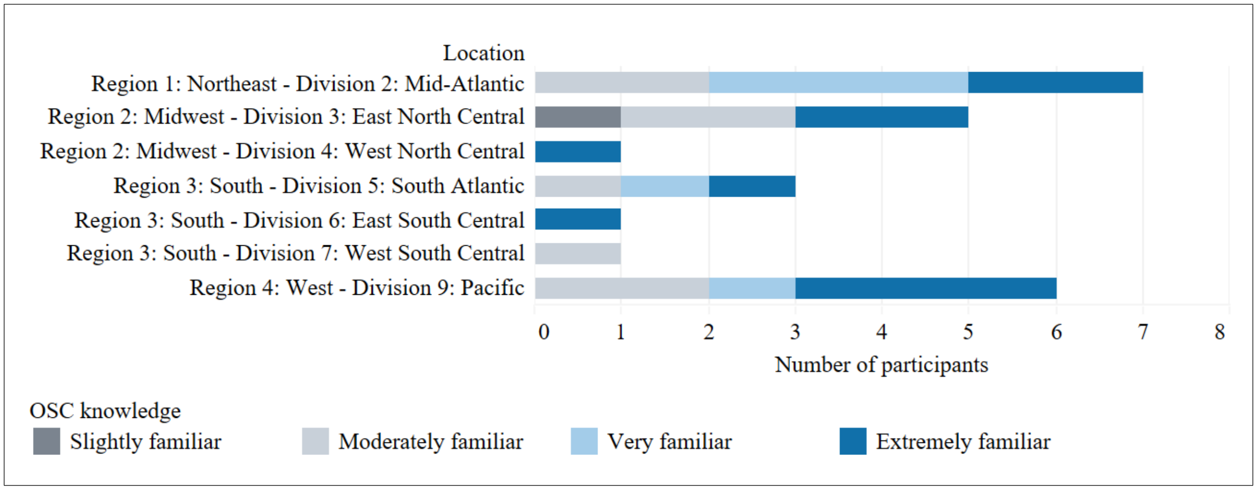


Figure 4.7. Participants' knowledge of OSC by location (*n*=24).

A total of 15 out of the 24 respondents (62.5%) considered themselves very and extremely familiar with OSC, and the six participants from the group of mixed professionals were all very or extremely familiar with OSC (see Figure 4.8). As for the participants experience, 15 out of 24 (62.5%) have more than 20 years of experience (see Figure 4.9).

[1] Regional distribution considered in the study:
Region 1: Northeast - Division 1: New England (CT, MA, ME, NH, RI, VT) / Region 1: Northeast - Division 2: Mid-Atlantic (NJ, NA, PA) / Region 2: Midwest - Division 3: East North Central (IL, IN, MI, OH, WI) / Region 2: Midwest - Division 4: West North Central (IA, KS, MN, MO, ND, NE, SD) / Region 3: South - Division 5: South Atlantic (DC, DE, FL, GA, MD, NC, SC, WV) / Region 3: South - Division 6: East South Central (AL, KY, MS, TN) / Region 3: South - Division 7: West South Central (AR, LA, OK, TX) / Region 4: West - Division 8: Mountain (AZ, CO, ID, MT, NM, NV, UT, WY) / Region 4: West - Division 9: Pacific (AK, CA, HI, OR, WA)

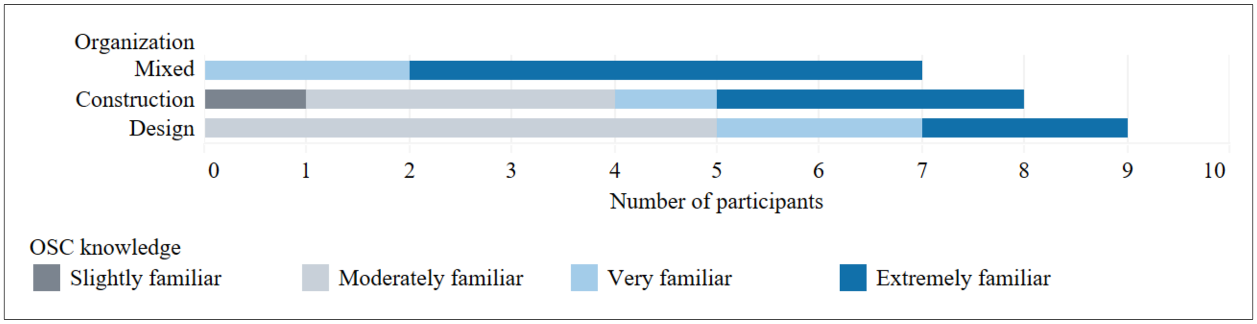


Figure 4.8. Participants' knowledge of OSC by organization type (*n*=24).

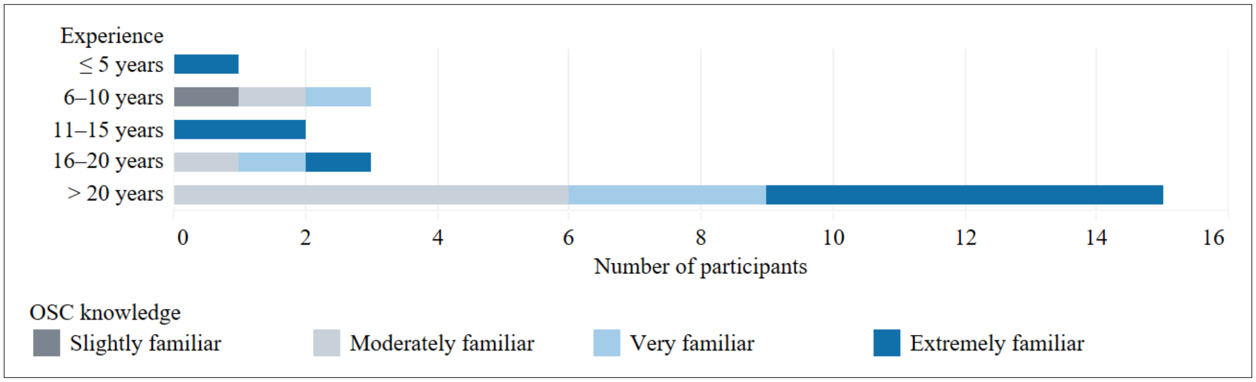


Figure 4.9. Participants' knowledge of OSC by years of experience (*n*=24).

Figure 4.10 shows that across the three groups, 15 of the 24 participants (~63%) were involved in decisions and/or were main decision makers, being the group of participants from mixed firms the one with the higher number of decision makers (*n*=6).

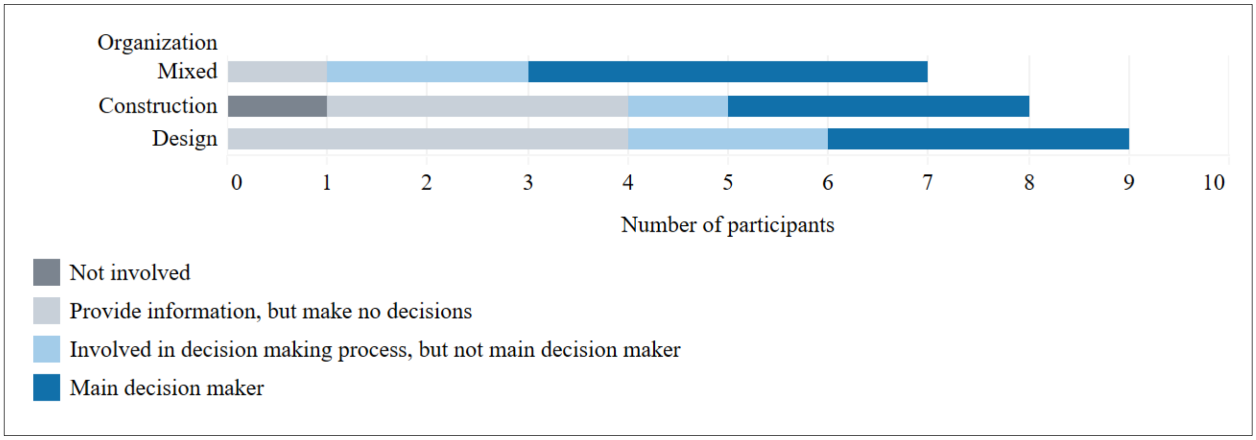


Figure 4.10. Participants' involvement in decisions by organization type (n=24).

Focusing on the effective adoption of OSC by the participants' firms, they reported approximately how many construction projects with significant use of offsite construction their companies had worked on in the last five years. The researcher defined "significant use" as a percentage of offsite construction greater than 30% of the total contracted work for the construction project. The group of designers was the one with the lower adoption of OSC, with a total of 7 of 9 (~ 78%) designers reporting a maximum of 10 projects. The group of professionals from construction firms was the one with the higher adoption of OSC, with a total of 3 participants reporting the use of OSC in more than 20 projects (Figure 4.11).

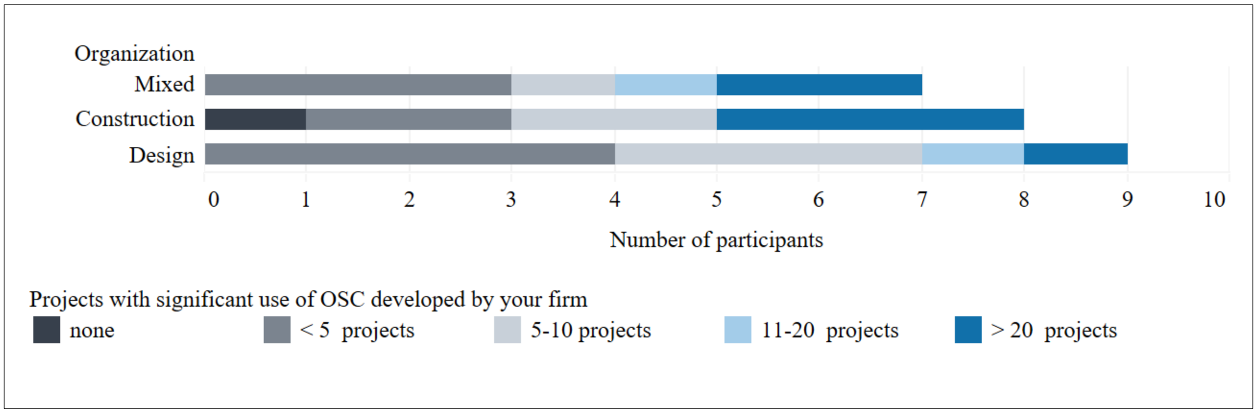


Figure 4.11. Participants' responses on projects with significant use of OSC developed by their firms (*n*=24).

4.3.2 Rankings of changes

Table 4.16 presents the results of the online survey with the ten top ranked changes indicated in grey. The lower means indicates top positions in the rank. The higher variance values reveal greater heterogeneity of the responses, what means a lower level of agreement among the participants. Changes C06 and C12, respectively in the first and last positions in the ranking, were the changes with the least variance and therefore with the highest level of agreement between the responses. Although these results demonstrate that ranking the changes is a controversial issue among AEC professionals, they allowed the researcher to assess which changes would bring more significant results when implemented in design and construction companies, in order to ensure greater and more efficient use of OSC in multifamily projects.

Table 4.16. Ranking of Changes – Descriptive Statistics (n=25)

ID	Change	Rank position	Min.	Max.	Mean	Std. Dev.	Var.
C06	Design for OSC since the project conceptualization.	1	1.00	12.00	3.920	3.054	9.327
C02	Adopt more innovative contracting models sharing responsibilities, risks, profits, and expenses.	2	1.00	17.00	6.040	3.857	14.873
C04	Allocate more time for improved design coordination, submittals analysis, planning and scheduling.	3	1.00	17.00	6.040	4.411	19.457
C07	Develop partnerships and collaboration with experienced manufacturers and suppliers in OSC that work to create value to the product.	4	1.00	17.00	7.120	4.065	16.527
C01	Adopt enhanced management techniques, including lean construction practices.	5	1.00	16.00	7.360	4.261	18.157
C10	Implement BIM technologies and adopt a higher level of detail for all projects to promote digital fabrication strategies and to improve delivery methods, procurement process, logistics, and even installation monitoring.	6	2.00	15.00	8.000	4.453	19.833
C03	Adopt more strict quality control standards for all the phases of the project, similar to the ones used in the manufacturing industry.	7	2.00	17.00	8.320	4.625	21.393
C11	Plan for a reduced schedule with OSC and commit to the deadlines for the delivery of the various phases of the project (design, planning, preconstruction, construction, and close-out).	8	1.00	17.00	8.320	4.776	22.81
C05	Design and build sustainable and efficient buildings, comprehending sustainable building materials specs, energy and water efficiency, higher indoor environmental quality.	9	1.00	17.00	9.320	3.976	15.810
C08	Establish continuous training and knowledge management strategies for the different hierarchical levels of the company.	10	3.00	17.00	9.680	3.881	15.060
C13	Plan logistics carefully considering size restrictions for transportation and travel distances from manufacturing facilities to the jobsite.	11	3.00	14.00	9.760	3.5388	12.523
C17	Understand OSC limitations and characteristics, how they affect the flexibility and creativity of design and work to improve the aesthetics and technical aspects of projects and align them with owners' and customers' expectations.	12	1.00	17.00	10.360	5.9574	35.49
C09	Focus on the three dimensions of sustainability (social, economic, environmental) to improve the overall business performance.	13	1.00	16.00	11.120	4.076	16.610
C15	Promote the standardization and simplification of processes and products by engaging in product platform and DfMA strategies.	14	2.00	17.00	11.160	5.5203	30.473
C16	Promote wider acceptance and understanding of OSC among AEC professionals, stakeholders, and even the government to incentivize the market, review building codes and create incentives.	15	1.00	17.00	11.280	4.9541	24.543
C14	Plan to deal with labor unavailability and develop a strategy to deal with labor issues such as crew reduction, union trades, workers training.	16	1.00	17.00	12.040	4.6501	21.623
C12	Plan for maximum waste reduction.	17	3.00	17.00	13.160	3.338	11.140

Figure 4.12 shows graphicly the results of the changes rankings, based on the mean values of the responses of all participants from the online survey, which were normalized to allow for more precise comparisons.

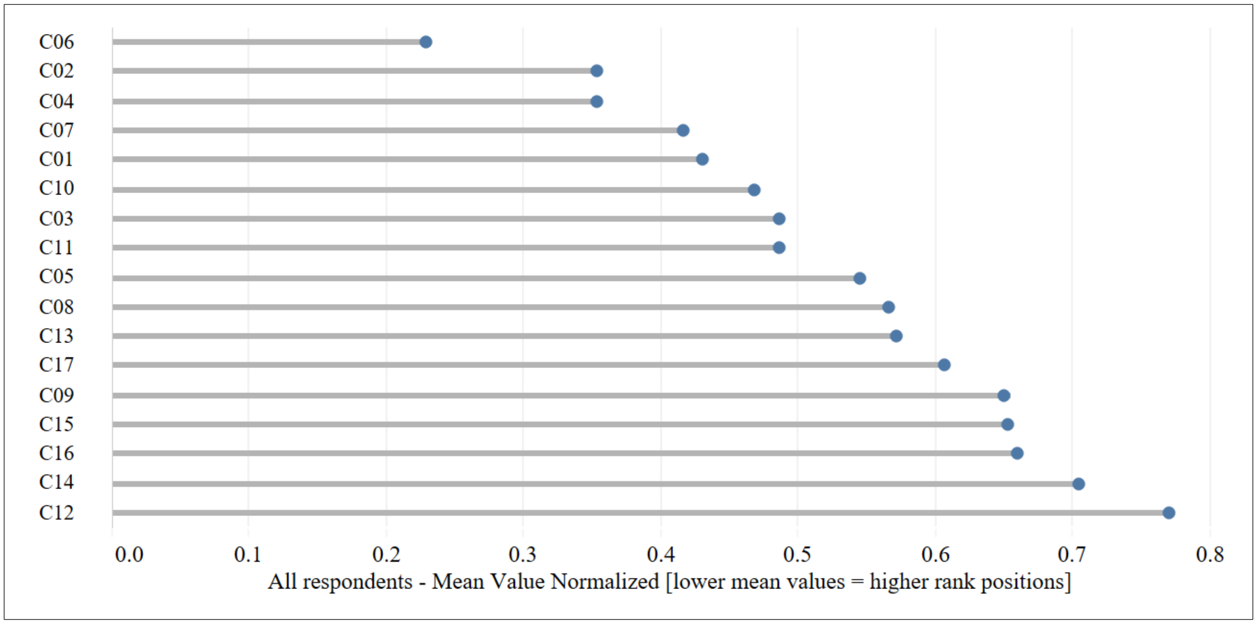


Figure 4.12. Rankings of changes – online survey (all professionals participating)

The Delphi survey was important to identify and pre-select the most important changes, but with regard to ranking the changes, the results were inconclusive. Thus, through the online survey, the researcher achieved the objective of obtaining a consolidated ranking with the most significant changes to be implemented in design and construction companies interested in the more efficient use of OSC in multifamily projects. Having a list of the priority changes was important for the researcher to develop the principles to implement the changes.

4.4 Chapter Summary

This chapter presented major results for the three phases of this study. In Phase 1, the researcher identified 27 factors that affect the use of OSC in multifamily projects in the US based on a systematic review of literature.

In Phase 2 the researcher conducted a Delphi survey with experts from the AEC industry which allowed to (1) obtain a validated list with the 18 most significant factors affecting the adoption of OSC in multifamily housing projects in the US; and (2) obtain a validated list with the 17 most significant changes required to adjust design and construction firms to successfully adopt OSC for delivering more affordable and sustainable multifamily buildings in the US. Due to participants' mortality, the Delphi survey results were not conclusive to rank the factors and the changes identified and validated. Because of this limitation, the researcher decided to further explore the validation of a consolidated list of changes affecting design and construction companies, rather than focus on different changes for design and for construction companies.

In Phase 3, the researcher carried out an online survey with professionals of the AEC industry to improve the reliability of the Delphi survey results regarding the ranking of changes. The results of Phase 3 consisted of a list with the rankings of the most important changes required to adjust design and construction firms to successfully adopt OSC for delivering more affordable and sustainable multifamily buildings in the US.

In the following chapter the researcher will present the results of Phases 4 and 5, which refers to the development of the principles to implement strategic changes in design and construction companies aiming at the successful use of OSC in their multifamily projects in the United States.

CHAPTER 5. DEVELOPMENT OF PRINCIPLES

In this chapter, the researcher presents the results of Phase 4 and 5, which involved (1) analyzing and interpreting all the data gathered in previous phases, particularly the ranking of changes from Phase 3 (see

Table 4.16), to propose a set of draft principles, and (2) interviewing professionals from design and construction firms to validate the proposed principles and adjust them as needed.

5.1 Phase 4 – Proposition of Principles

Design and construction firms aiming at using or increasing the use of OSC in their multifamily projects, are required to acknowledge the differences between the processes encompassed in OSC and conventional construction to understand (Figure 5.1).

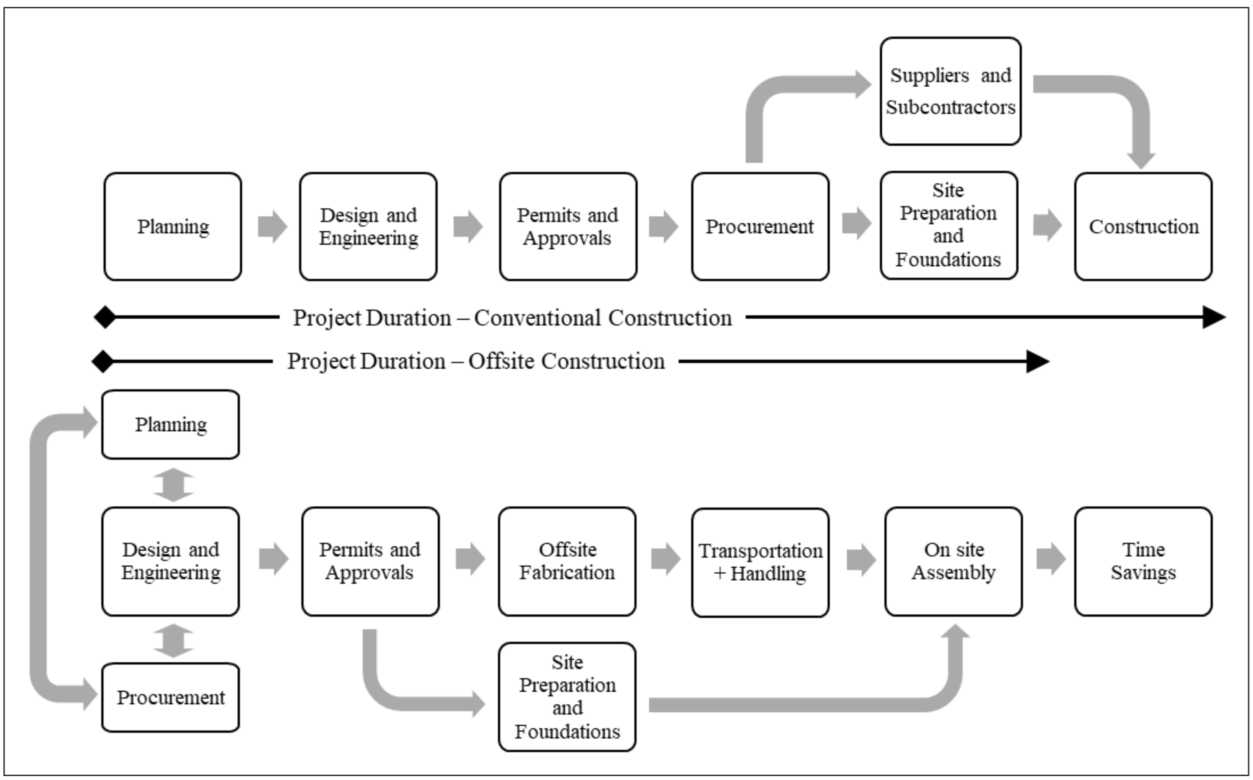


Figure 5.1. Construction processes in conventional and offsite construction

Understanding the impact of the use of OSC in the design and construction processes and analyzing all the data gathered in the previous phases of this research, allowed the researcher to develop a set of principles to support design and construction companies in the US to embrace a more intensive use of OSC in their projects, particularly in multifamily projects. Through this process, the researcher not only identified the principles and the most important changes (what), but also concisely provided some ways to implement such changes in design and construction companies (how).

The result was a set of ten draft principles (DP) (Figure 5.2) categorized according to the framework developed by the World Economic Forum – WEF (2016), comprehending: (1) technology, materials and tools; (2) processes and operations; (3) strategy and business model; and (4) people, organization, and culture (see Figure 2.6).

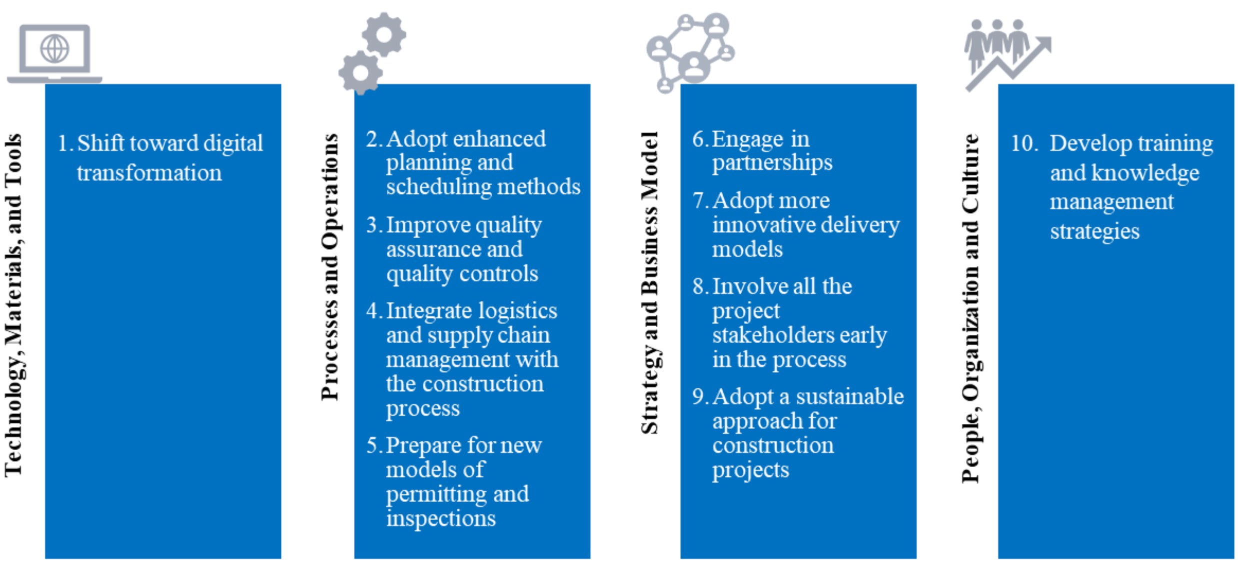


Figure 5.2. Draft principles categorized according to the WEF framework

5.1.1 Technology, materials, and tools

DP01: Shift toward digital transformation

Related to change C10: Implement BIM technologies and adopt a higher level of detail for all projects to promote digital fabrication strategies and to improve delivery methods, procurement process, logistics, and even installation monitoring – Rank position: 6th

BIM is paramount to achieve the benefits of adopting OSC in construction projects, including multifamily projects. However, BIM implementation in design and construction firms must be part of a more comprehensive strategy to achieve the full benefits of engaging in OSC adoption, as explored in the Research Article 2 (Gusmao Brissi, Wong Chong, et al., 2021).

The strategy should involve digital transformation, which encompasses transforming the company's business model to digital business, going through (1) digitization, that is, the conversion of information and data to digital format, and (2) digitalization, which involves improving processes by taking advantage of digital technologies and digitized data (Andersson & Lessing, 2017). In this context, information flow is paramount, and so is the need to establish information standards (Andersson & Lessing, 2020), which ultimately affects the implementation of BIM.

Digitalization results in the integration of information based on the use of software, algorithms, digital platforms and automated equipment, which ultimately enables the automation of processes, e.g., CNC machines and robots that can pull the project information from digital models (BIM) and automatically produce different types of components without compromising the efficiency of the production system (Bertram et al., 2019).

Depending on the strategy adopted by the design team in the onset of the project, in addition to the drawings created by the design team, the OSC manufacturer will need to generate the production drawings, with information to be transferred to the automated equipment, to the production team and to the installation team in the field. Thus, if the design team uses design for manufacture and assembly (DfMA) strategies, the integration between design, manufacture and on-site assembly is streamlined (Yuan et al., 2018).

The implementation of BIM in design and construction firms, associated with the use of sensors and automated equipment creates new layers of information to be generated, such as data from IoT and sensors, which facilitates the integration of the supply chain to the construction process and the overall logistics of the project (Razkenari et al., 2020).

5.1.2 Processes and operations

DP02: Adopt enhanced planning and scheduling methods

Related to the following changes:

C04: Allocate more time for improved design coordination, submittals analysis, planning, and scheduling – Rank position: 3rd

C11: Plan for a reduced schedule with OSC and commit to the deadlines for the delivery of the various phases of the project (design, planning, preconstruction, construction, and close-out) – Rank position: 8th

C01: Adopt enhanced management techniques, including lean construction practices – Rank position: 5th

OSC requires the development of a detailed scope early in the planning stage (McGraw-Hill Construction, 2011). In addition, the schedule, front-loaded and more compressed when compared to traditional construction, must be as reliable as possible throughout the phases of the project (Bertram et al., 2019; Smith et al., 2015). In this sense, the engagement of design and construction firms with lean construction principles is highly beneficial, especially when associated with digital tools such as BIM, as it will result in more assertive schedules based on pull planning (Gusmao Brissi, Wong Chong, et al., 2021).

Design changes have major impacts on OSC schedules, so the need for improved coordination is critical (Smith, 2011). Focusing on construction companies, it is necessary to improve procurement and collaboration with designers, consultants, and suppliers of prefabricated and modular components, to ensure a reliable schedule, progressing as planned and with costs and time certainty (Smith, 2011).

DP03: Improve quality assurance and quality controls

Related to the following changes:

C03: Adopt more strict quality control standards for all the phases of the project, similar to the ones used in the manufacturing industry – Rank position: 7th

C04: Allocate more time for improved design coordination, submittals analysis, planning, and scheduling – Rank position: 3rd

Quality assurance and quality control need to be rigorous throughout OSC processes. The design team needs to develop controls to ensure the project is fully prepared to be manufactured. In a way, as the project to be manufactured will be thoroughly verified before starting the production, eventual design flaws can be captured in the manufacturing phase. In addition, the offsite production process usually involves prototyping (virtually or physically) to simulate the actual situation of a component installed on the construction site, so that it is possible to carry out various tests and future problems (H. Li et al., 2008). Therefore, it is important to record any problems and provide feedback to the design team. As for field controls, these need to be more accurate to avoid serious problems of incompatibility/ tolerances between the elements built on-site and the prefabricated components. Issues identified during on-site assembly, such as geometry variability of modular and prefabricated components, also must be monitored, identified and fed back to design and manufacturing teams (Arashpour et al., 2020).

As quality control in OSC heavily relies on monitoring, identifying issues, and feedbacking information as fast as possible, it is necessary to develop a monitoring and quality control system to facilitate this process. The identification of incompatibilities between what was built (as-built status) and what was designed (as-designed status) is fundamental to correct flaws and avoid future problems from the design stage (Arashpour et al., 2020). This process of data collection and recording of experiences extracted from activities carried out throughout the project must be actively taken into account in future projects, constituting lessons learned that must be disseminated among all the project stakeholders (Lessing et al., 2005). This cyclic process is essentially a process of continuous improvement, aligned with lean principles.

DP04: Integrate logistics and supply chain management with AEC processes

> Related to change C13: Plan logistics carefully considering size restrictions for transportation and travel distances from manufacturing facilities to the jobsite – Rank position: 11th

One important point to consider in OSC projects is the need to integrate construction activities carried out in a factory with the on-site activities (Bertram et al., 2019; Niu et al., 2017). The activities performed at the construction site involve a configuration of final assembly, so the logistics of delivering and storing components must be carefully planned, in close collaboration with the suppliers of OSC components (Lessing et al., 2015, 2005). However, from the project onset, logistical issues must be considered by the design and construction teams to define the dimensions of modules and components, temporary reinforcements, lifting points, etc., for these issues impact the transport and handling of the components (Hwang et al., 2018b). During the planning phase, the pre-construction team can have a logistics specialist working with the suppliers the on-site team and the design team to define the site layout, paying special attention to the placement of cranes and/or other heavy lift equipment, delivering/receiving and storing areas.

When suppliers and subcontractors are deemed as partners, it is easy to integrate them to the process since the beginning. This allows for opportunities for differentiated delivering and storing strategies, involving, for example, the implementation of just-in-time (JIT) deliveries or the optimization of storage and installation of OSC components based on scanning/tracking systems. Ultimately, it is important to highlight the opportunities for on-site automation that arise with the use of OSC, such as tracking components, use of smart construction objects and the Internet of things (IOT), which enables an smart construction site, as briefly explored in the Research Article 2 (Gusmao Brissi, Wong Chong, et al., 2021).

DP05: Prepare for new models of permitting and inspections

> The researcher has identified this topic as very relevant based on her own experience and further review of the literature, but none of the changes ranked in Phase 3 could be associated to this principle.

Depending on the type and level of OSC adopted and the jurisdiction of the project, different strategies to deal with licenses and inspections are necessary, but it is very important to define a strategy in the project onset because more documentation, coordination, and longer time frames are required to enable permits and approvals (Smith et al., 2015). Volumetric OSC very often requires the inspection of the modules in the factory, which usually is performed by state-licensed third-party agencies (The American Institute of Architects, 2019).

The traceability of the entire manufacturing process facilitates the inspections, but if different types of components will be used in a project (e.g., wall panels, floor panels, bathroom pods) each of those components will require inspections according to the applicable codes. In OSC projects using only non-volumetric components, the permitting process usually works very similarly to traditional construction projects. Volumetric modules with a high degree of completion in the factory require complete in-plant inspections, involving all aspects of conventional on-site inspections, which include technical aspects, compliance with codes, standards, regulations, specifications, and quality requirements. In addition, special permits might be required to transport large components to the jobsite (Smith et al., 2015).

5.1.3 Strategy and business model

DP06: Engage in partnerships

Related to changes:
C07: Develop partnerships and collaboration with experienced manufacturers and suppliers in OSC that work to create value to the product – Rank position: 4th

This is one of the best strategies to deal with the fragmentation within the AEC industry, as it improves relationships and collaboration, allows to share the risks and benefits of projects, contributing to the success of OSC in multifamily projects (Hu et al., 2019; Pan et al., 2007). Partnerships are beneficial for design and construction companies, as they improve the relationship among consultants and suppliers, which facilitates the coordination of projects, improves the flow of information, and reduces problems of offsite production and on-site installation of components (Lessing et al., 2005; McKinsey Global Institute, 2017). Ultimately, this impacts the duration and the cost of the project, as well as the quality of the final product.

Focusing more specifically on the construction phase, partnerships and collaboration with experienced manufacturers and suppliers, involving long-term contracts, ensure an optimized supply process especially for GCs, resulting in the creation of value for the product and benefiting all stakeholders (Pan et al., 2007).

DP07: Adopt more innovative contracting and delivery models

Related to change C02: Adopt more innovative contracting models sharing responsibilities, risks, profits and expenses – Rank position: 2nd

The contractual structures used in construction projects in the USA favors adversarial relationships rather than transparent collaboration (McKinsey Global Institute, 2017). This environment of hostility compromises the advancement of OSC use because its adoption requires a much more collaborative process involving the project's stakeholders since the project onset (KPMG, 2016).

Relational contracts across the whole AEC supply chain will help the industry to move towards collaboration and higher productivity. Focusing on delivery methods, Dodge & Analytics (2020b) has identified project delivery method as one of the most important barriers preventing greater adoption of OSC; since the most common project delivery method adopted in multifamily projects is design-bid-build, it is clear that changes need to be made in this regard. This way, Integrated Project Delivery arises as the most appropriate type of contract model for projects adopting high levels of OSC, where greater standardization and predictability of project scope facilitate relationships (McKinsey Global Institute, 2017; Razkenari et al., 2020).

IPD is a collaborative delivery method that requires stakeholders to collaborate throughout the project, including an agreement on shared risks and rewards. This early engagement between the parties reduces adverse relationships in the process and encourages true inter-and-multidisciplinary collaboration and transparency throughout the process. IPD is extremely aligned with lean construction principles and highly facilitates the use of building information modeling (BIM) for construction projects (Kent & Becerik-Gerber, 2010; McKinsey Global Institute, 2017). Despite being the most suitable type of contract for projects adopting OSC, IPD has not been widely adopted by AEC industry professionals using modular construction and prefabrication (Dodge Data & Analytics, 2020b).

DP08: Involve all the project stakeholders early in the process

Related to change C06: Design for OSC since the project conceptualization – Rank position: 1st

To ensure the full benefits of adopting OSC and the quality of the final product (building), it is important to involve all the stakeholders from early stages of the project (Hwang et al., 2018a). This is necessary because the project team needs to make important decision at very early stages, which will affect the owners and developers' expectations regarding design, cost, completion time, and project quality (Hu et al., 2019; Hwang et al., 2018a).

Once all parties are involved, it is easier to align the design with the technical requirements and constraints of a building system. In addition, the project may evolve with a design that balances standardization and customization, that is, even though the design is based on the use of standardized components, mass customization strategies allow for some level of customization agreed from the start, aiming at satisfying the needs of owners, developers, and customers and with little impact on cost and production efficiency (Jensen et al., 2014).

DP09: Adopt a sustainable approach for construction projects

> Related to change C05: Design and build sustainable and efficient buildings, comprehending sustainable building materials specs, energy and water efficiency, higher indoor environmental quality – Rank position: 9th

This is a strategic measure that involves the top management of companies. Focusing on the triple bottom line of sustainability, a sustainable approach for construction projects may seem costly but considering how much this is worth as a competitive advantage, in addition to impacting waste reduction and product quality, it is a fundamental decision.

The adoption of OSC is aligned with sustainable initiatives for several reasons. The precision of prefabricated components production optimizes the use of materials, which reduces natural resources consumption, waste generation and GHG emissions (Aye et al., 2012; X. Cao et al., 2015; Jaillon & Poon, 2008; Quale et al., 2012). The superior quality of prefabricated modules and components ensures superior performance, greater durability and comfort (Ahn & Kim, 2014), and better energy performance, since the components that make up the building envelope present better insulation and tightness (Razkenari et al., 2020). In addition, the use of OSC is safer for the construction workers, which resonates with social sustainability (Jaillon & Poon, 2008).

5.1.4 People, organization, and culture

DP10: Develop training and knowledge management strategies

> Related to change C08: Establish continuous training and knowledge management strategies for the different hierarchical levels of the company – Rank position: 10th

The adoption of OSC requires training many of the professionals involved in the different phases of the project, including developers, designers, consultants, manufacturing teams, construction professionals, contractors, and on-site laborers (Nadim & Goulding, 2011). However, this study only focuses on design and construction firms.

Designers need to understand how to design to reduce design variability by focusing on component standardization, which involves design for manufacturing and assembly (DfMA) strategies (Goulding et al., 2015). DfMA strategies, which are vital to enable the development of more complex OSC projects, require knowledge on modular systems and the use of digital tools such as BIM. In addition, designers need more knowledge on the manufacturing of modules and components early in the design phase to avoid rework and the identification of design issues in later phases of the project (J. Cao et al., 2021; Luo et al., 2017)

As for construction professionals, they need to learn new models of planning, procurement, and job site management. It is advisable to create the role of the prefabrication leader to promote OSC internally and externally and assist multiple teams in working with OSC. The on-site work will require reduced staff, as much of the work will be performed offsite. Part of the on-site work will be differentiated from conventional projects, for workers will be more assemblers than craftworkers and will also need to be prepared for these new assignments (Goulding et al., 2015).

As already mentioned, the knowledge acquired during an OSC project needs to be shared with the different parties involved in the project, both to solve design, manufacturing, and construction/installation problems and to disseminate good practices, which will promote the continuous improvement of processes and products (Smith, 2011). In addition, it is important to define a knowledge management strategy encompassing all company levels (Lessing, 2015). Taking successful practices in the AEC industry as examples, it is possible to highlight: (1) creating platforms to share lessons learned and other important project data, such as key performance indicators (KPIs); promoting workshops and internal training, (3) creating and sharing BIM libraries, (4) promoting a culture of learning from experienced colleagues (World Economic Forum, 2016).

5.2 Phase 5 – Validation Interviews

Based on the interviews with professionals from the AEC industry with experience in multifamily projects in the United States and familiar with the use of OSC, the researcher assessed the consistency of the draft principles to make the necessary adjustments and secure a final set of validated principles to implement significant changes in design and construction firms aiming at the successful use of OSC in multifamily projects in the US. The set of draft principles associated to correspondent changes is presented in Table 5.1.

Table 5.1. Relationships between the draft principles and the changes ranked in Phase 3

Draft Principle	Change (with ranking position from Phase 3)
Technology, materials, and tools	
DP01. Shift toward digital transformation	C10. Implement BIM technologies and adopt a higher level of detail for all projects to promote digital fabrication strategies and to improve delivery methods, procurement process, logistics, and even installation monitoring – Rank position: 6th
Processes and operations	
DP02. Adopt enhanced planning and scheduling methods	C01. Adopt enhanced management techniques, including lean construction practices – Rank position: 5th C04. Allocate more time for improved design coordination, submittals analysis, planning and scheduling – Rank position: 3rd C11. Plan for a reduced schedule with OSC and commit to the deadlines for the delivery of the various phases of the project (design, planning, preconstruction, construction, and close-out) – Rank position: 8th
DP03. Improve quality assurance and quality controls	C03. Adopt more strict quality control standards for all the phases of the project, similar to the ones used in the manufacturing industry – Rank position: 7th
DP04. Integrate logistics and supply chain management with AEC processes	C13. Plan logistics carefully considering size restrictions for transportation and travel distances from manufacturing facilities to the jobsite – Rank position: 11th
DP05. Prepare for new models of permitting and inspections	None of the changes ranked in Phase 3 were associated to this draft principle.
Strategy and business model	
DP06. Engage in partnerships	C07. Develop partnerships and collaboration with experienced manufacturers and suppliers in OSC that work to create value to the product – Rank position: 4th
DP07. Adopt more innovative delivery models	C02. Adopt more innovative contracting models sharing responsibilities, risks, profits and expenses – Rank position: 2nd
DP08. Involve all the project stakeholders early in the process	C06. Design for OSC since the project conceptualization – Rank position: 1st
DP09. Adopt a sustainable approach for construction projects	C05. Design and build sustainable and efficient buildings, comprehending sustainable building materials specs, energy and water efficiency, higher indoor environmental quality – Rank position: 9th
People, organization, and culture	
DP10. Develop training and knowledge management strategies	C08. Establish continuous training and knowledge management strategies for the different hierarchical levels of the company – Rank position: 10th

Interview responses were systematically examined and coded by the researcher to assess the significance of each principle in the context of the research. Through this method of content analysis, qualitative data was extensively analyzed, and part of the data was converted into quantitative data, allowing for differentiated analysis.

5.2.1 Demographics

The goal of the interviews was to validate the draft principles. The researcher conducted a total of 12 interviews with professionals from design (A/E) and construction firms (Table 5.2). Six of the 12 participants had more than 20 years of experience in the AEC industry and only two participants (both from construction firms) had less than 10 years of experience. As for the geographic location, four of the participants work in firms from California, two from Illinois, and the others from different states – Florida, Massachusetts, Alabama, District of Columbia, Indiana and Minnesota – which allowed a certain level of regional representation.

Table 5.2. Interviewees – Demographics

ID	Field	Experience (years)	State
1	Design	16-20	CA
2	Design	>20	CA
3	Construction	5-10	FL
4	Construction	16-20	IL
5	Construction	< 5	MA
6	Design	>20	CA
7	Construction	>20	CA
8	Construction	11-15	IL
9	Design	>20	AL
10	Design	16-20	DC
11	Construction	>20	MN
12	Design	16-20	IN

All the 12 interviewees revealed that their companies use or have used OSC in their multifamily projects (Table 5.3). Six of the interviewees work in companies where the level of OSC adoption is restricted to non-volumetric components (interviewees from white cells), basically wall panels and prefabricated structural elements, but two of those companies no longer use prefabricated components in multifamily projects; the other six interviewees (interviewees from gray cells) work in companies that use modular volumetric modules, but one firm (Interviewee #9) no longer works with multifamily projects.

Table 5.3. Interviewees' firms' characteristics

ID	Firm Field	Type of Firm	OSC current use	Type of OSC used [1]
1	Design	Engineering	Y	modular volumetric
2	Design	Architecture	N	panelized walls
3	Construction	Full Service General Contractor	N	precast panelized systems
4	Construction	General Contractor	Y	panelized walls, precast components
5	Construction	General Contractor	Y	prefab trusses and structures
6	Design	Engineering	Y	modular volumetric
7	Construction	General Contractor	Y	modular volumetric
8	Construction	Construction	Y	modular volumetric
9	Design	Architecture	N	modular volumetric
10	Design	Architecture	Y	modular volumetric
11	Construction	Development, Design, Construction and Management	Y	panelized walls, precast walls
12	Design	Architecture	Y	panelized walls

Note. (1) Type or category of OSC currently used or previously used (for those not currently using OSC) by the interviewee's firms.

5.2.2 Interviewees' perceptions on the draft principles

The interviewees provided their perceptions on the draft principles previously sent to them through email. In addition to comments, they indicated the propositions they considered more important to implement significant changes in design and construction firms aiming at the successful use of OSC in multifamily projects. Some of the draft principles did not attract the attention of respondents and were therefore, not commented upon, suggesting that such principles have a lower degree of importance. In some situations, respondents were not sure of the importance of a principle for various reasons, such as lack of familiarity with the proposed strategy. Other times the interviewees perceived a principle clearly as important or not important.

The perceptions of the interviewees working with volumetric modules suggested that they think it is necessary to implement deeper changes in design and construction firms interested in adopting OSC in multifamily projects, for they perceive OSC as a means of industrializing the AEC industry, transforming constructive processes into processes similar to those of the manufacturing industry.

Figure 5.3 provides an overview of the revised principles according to the interviewees' perceptions on the draft principles, which were discussed during the interviews.

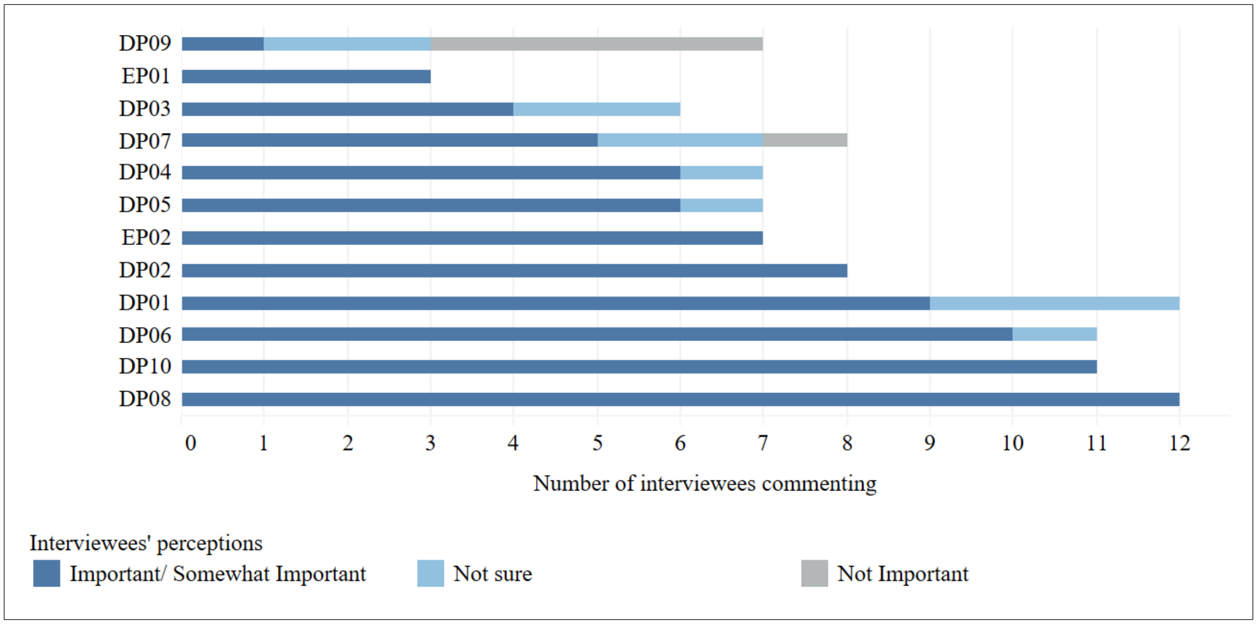


Figure 5.3. Interviewees' perceptions on the importance of the draft principles and the two extra principles discussed during the interviews (n=12).

In addition to the 10 principles that the researcher sent to the interviewees, two additional principles emerged (EP) during the interviews: EP01. Develop product-oriented business models, and EP02. Promote leadership and mindset engagement with OSC principles. The following principles were considered important by at least half of the interviewees:

- DP04. Integrate logistics and supply chain management with AEC processes – 50% of the interviewees
- DP05. Plan for new models of permitting and inspections – 50% of the interviewees
- EP02. Promote leadership and mindset engagement with OSC principles – 58% of the interviewees
- DP02. Adopt enhanced planning and scheduling methods – 67% of the interviewees
- DP01. Shift towards digital transformation – 75% of the interviewees
- DP06. Engage in partnerships – 83% of the interviewees

- DP10. Develop training and knowledge management strategies – 92% of the interviewees
- DP08. Involve all the project stakeholders early in the process – 100% of the interviewees

It is important to note that the perceptions of Interviewee #9 regarding the adoption of the proposed principles in their firm were not focused on using or increasing the use of OSC in multifamily projects, but on other types of projects because their firm no longer works with multifamily projects.

The researcher generated a word cloud based on all interviewees' responses that were related to the proposed principles (coded as *Principles* by the researcher) by using specific software (NVivo) set up to display the 500 most frequent words and stemmed words grouped together. The size of a word is a representation of how frequently that word (or related words) was mentioned by the interviewees in the material coded as *Principles*. Figure 5.4 shows that the most frequent words cited were related to *Standards*, or more precisely *Standardization*, which suggested that the interviewees realized the importance of design and construction firms establishing and working with standardized processes and products for the success of OSC in the multifamily market. *Modular* were also frequently mentioned, suggesting that some interviewees associated the principles with the use of volumetric modules, or modular construction.

Following, the author presents interviewees' perceptions on each draft principle, discusses the results by comparing the interviewees' perceptions with the existing literature, and proposes changes when required. Additionally, the researcher presents the results related to two emerging principles (EP01 and EP02). These principles emerged during the interviews, as some interviewees presented relevant and well-founded justifications for their inclusion in the final set of principles.

Figure 5.4. Word cloud for the code Principles.

DP01. Shift towards digital transformation

The interviewees acknowledged the importance of this proposition, as emphasized by Interviewee #10: “If you, if you have digital integration and, all the, all the stakeholders are sort of working on the same platform, like, there's a power in that.” And Interviewee #9:

> … so, digital fabrication is absolutely key. No question about it. It is the tool that if it is being used correctly, it will help you with all of your MEP coordination. It will help the contractor understand how to make the connections and how all of the things that we call stitching and assembly at the site.

A total of three interviewees, however, do not see digital transformation as essential to firms interested in embracing OSC, especially when they focus on lower levels of OSC adoption (e.g., panelized walls): “… I don't know that it needs to fully be reliant on a digital platform, but it certainly is best practice.” (Interviewee #8), and:

> So, I always chuckle a little bit when people say: ‘Well we're not going to prefab because it's too expensive to implement BIM’. I mean people have been doing prefab for 50 years in a way, right? No doubt doing full modular, doing bathroom pods, doing things like that would be much more difficult in an analog world. But I don't think it's a prerequisite. (Interviewee #4)

Some of the participants associated digital transformation exclusively to BIM: “Yeah! Totally! And look, if you’re going to be in the offsite construction space, you have to be in Revit. I mean, you just have to, in order to integrate the fabricator.” (Interviewee #2).

> In today's world, I don't think you could, it would be very hard to do it [OSC] without [BIM], and it is the — safest is not the right word, but it manages everyone’s risk… So, I do think that it's almost a way of doing business, not an option anymore. (Interviewee #8)

However, the digital transformation principle encompasses more than BIM strategies. Some interviewees acknowledge the benefits of management software, digital platforms and even artificial intelligent to manage their projects and facilitate the workflow of information and documents:

> So, what we did was just have our system work with whatever format they're giving us. If they use Procore and it sends a very ugly email that doesn't translate well, and then there's an attachment, it doesn't matter. The software goes, looks for the attachment, pulls it out, scans it, gets the information, and puts it out in a way that we can read it… so it's pretty in depth. (Interviewee #1)

> Obviously, BIM is really beneficial, but even a lot of the other software out there for you: RFI responses and just organizing like you're saying schedules and tracking data and tracking information has been really helpful. (Interviewee #6)

And Interviewee #7 revealed interest in moving towards higher levels of digitization and digitalization:

> We are going to get [software company] involved and help us set up some computer software to help us not only manage the procurement flow but also manage the factory fabrication flow from station to station, so that we could track that in real time and see how we get fit to another level of detail that we can make sure that we're not going to be missing material or product as each station is being finished for each module.

Despite recognizing the importance of digital transformation to promote a higher level of adoption of OSC, some interviewees highlighted some challenges to be overcome, such as different levels of digital engagement among those involved in a project, interoperability, and the need to learn to work with new technologies.

> I do think the digital transformation is always going to be challenging because all of the stakeholders are at different places in their technology journey and especially in multifamily, you get people that don't even use technology. So, I

> do think that that's not as widespread as we think it is. That's always going to be a challenge for us and for everyone. (Interviewee #8)

Table 5.4 summarizes interviewees' perceptions on the implementation of digital transformation strategies in design and construction firms to facilitate the use of offsite construction in multifamily projects. A total of seven interviewees reported that their firms have engaged in digital transformation.

Table 5.4. Interviewees' perceptions on DP01

ID	Organization	Draft Principle 1	Implementation in the firm
1	Design	Important	Yes
2	Design	Important, but depending on the project it is difficult to be implemented	No
3	Construction	Important, but depending on the project it is difficult to be implemented	No
4	Construction	Important in higher levels of OSC, not essential in lower levels of adoption	Yes
5	Construction	Important in higher levels of OSC, not essential in lower levels of adoption – BIM is mostly for designers	In process
6	Design	Important for both OSC and site-built construction	Yes
7	Construction	Important, but not essential – less technology = more coordination	No
8	Construction	Not sure, but BIM is essential	Yes
9	Design	Important	Yes
10	Design	Important	Yes
11	Construction	Important	Yes
12	Design	Important, but the firm prefers not to change the way things are currently done	No

Note. Gray cells indicate interviewees working in firms that use volumetric modules. White cells indicate interviewees working in firms that only use non-volumetric components.

<u>Comments</u>

This principle was widely commented on by the interviewees, who recognized that it constitutes an important strategy to be implemented in companies that intend to advance in the adoption of OSC. Respondents with more experience in the use of volumetric modules expressed that they find it impossible to develop projects with a high degree of modularization if the company has not implemented the digitalization of its processes, including BIM adoption. However, respondents who work on projects with a low level of OSC adoption do not perceive this principle as critical. Research and practice reveal that this strategy is important for the AEC industry as a whole and even more fundamental for companies engaged in the use of OSC, since it allows for the integration and automation of the construction processes (Andersson & Lessing, 2020; Bertram et al., 2019; Saad et al., 2021). Considering the breadth of this strategy, the researcher renamed it: *Shift towards digital transformation and automation.*

DP02. Adopt enhanced planning and scheduling methods

Seven of the interviewees highlighted the significance of this proposition, while three of them did not mention the need to enhance planning and scheduling methods. Interviewee #6, a designer, provided a good overview of how planning and scheduling works in OSC projects, considering the different players involved in the process and the need to pay special attention to tasks that occur simultaneously:

> Modular, with the accelerated schedule and the fact that they're building modules while grading is going on, and that there's obviously a little bit of overlap there and the ability to get modular buildings in the ground quicker than a site build structure does complicate the schedule and it speeds things up a little bit… But a lot of those schedules overlap on how the site-built progress is going with modular and trying to coordinate that. So, it it's very, very intense and very, very much needs to be defined and coordinated yet. (Interviewee #6)

It is important to emphasize the need to fit the project schedule into the manufacturer production line schedule:

> So, that's a key element, and part of the pre-construction process scheduling too is that the factory has to say: "OK, we're going to do this job for you, but we can't start manufacturing for you until this date because of our production line". You got the offsite manufacturer tells you that they have a window for you, then you know they're managing their time properly, because that's the only way you can make it work, is planning a window and scheduling to fit that window because you don't have an opportunity to miss that window. (Interviewee #7)

Another point highlighted is the need to get some project reviewed and inspected by different jurisdictions, which impacts on planning and scheduling: "Yeah, absolutely, because the critical path, it is quite a bit different when you're doing modular because you need different sets of reviews from different jurisdictions in many cases." (Interviewee #10)

Table 5.5 summarizes interviewees' perceptions on the implementation of enhanced planning and scheduling methods in design and construction firms to facilitate the use of offsite construction in multifamily projects. A total of nine interviewees reported that their firms have enhanced planning and scheduling.

Table 5.5. Interviewees' perceptions on DP02

ID	Organization	Draft Principle 2	Implementation in the firm
1	Design	Important	Yes
2	Design	Important	No answer provided
3	Construction	No comment provided	No
4	Construction	Important	Yes
5	Construction	Important	No answer provided
6	Design	Important	Yes
7	Construction	Important	Yes
8	Construction	No comment provided	Yes
9	Design	Important	Yes
10	Design	Important	Yes
11	Construction	No comment provided	Yes, can be improved
12	Design	No comment provided	Yes

Note. Gray cells indicate interviewees working in firms that use volumetric modules. White cells indicate interviewees working in firms that only use non-volumetric components.

Comments

The interviewees acknowledged the importance of this principle to the success of OSC in multifamily projects, especially the interviewees involved in higher levels of OSC (volumetric modules). OSC requires the development of a detailed scope early in the planning stage and involves a more compressed schedule, which must be as reliable as possible throughout the phases of the project (Bertram et al., 2019). Therefore, the engagement of design and construction firms with lean construction techniques is recommended, since lean construction tools are much more collaborative and assertive than traditional planning and scheduling methods (Gusmao Brissi, Wong Chong, et al., 2021). After reviewing interviewees' perceptions and the literature focused on this topic, the researcher decided to redefine this principle to emphasize the focus on lean construction practices: *Adopt lean construction practices*.

DP03. Improve quality assurance and quality controls

Only two interviewees mentioned the importance of this proposition. Two interviewees stated that improved quality assurance and quality controls is equally important in both OSC and site-built construction, and seven interviewees did not attribute any relevance to this proposition as a strategy to be adopted by design and construction firms using OSC in multifamily projects. Interviewee #4 was emphatic in highlighting the importance of principle 3: "Improve quality assurance with QA/QC processes, obviously that is critical. … I would argue this one is actually a baseline requirement."

In addition to emphasizing the importance of this proposition, Interviewee #1 commented on the need to develop a specific QA/QC process for OSC projects: "If the firm is not set up for that, then they won't be able to deliver on the contract, so it's not just improving quality assurance/quality control, it's really having a volumetric modular specific design process…".

Although not highlighting the importance of this proposition, Interviewee #5 highlighted some problems identified on-site as a result of poor QA/QC processes in both design and manufacturing phases:

> That's definitely a huge, huge issue. I think we've actually found that getting everything engineered ahead of time, usually will take care of a lot more of those issues, but at the same time, a designer on a computer screen can mess up just the same as a framer in the field… It happens both on the prefab side and on the infield side, so that a huge part of the construction job is just trying to manage those discrepancies.

Strategies to ensure quality in projects using OSC comprise constant interaction between the design and construction team and the manufacturer. For designers, this process goes beyond checking their own documents, as it also involves detailed checks of shop drawings and manufacturing models, as stated Interviewee #6: "I think what where the QA/QC part would come in is when the factory is actually producing their shop drawings." For construction companies, QA/QC should include checking the components being manufactured, especially in volumetric modules "And then some companies, general contractors, will pay for someone to be in the factory full time, also to make sure that quality control is not overlooked." (Interviewee #7)

Table 5.6 summarizes interviewees' perceptions on the implementation of improved QA/QC processes planning and scheduling methods in design and construction firms to facilitate the use of offsite construction in multifamily projects. A total of 10 interviewees reported that their firms have improved QA/QC processes, even if not aiming at using or increasing the use of OSC in multifamily projects (Interviewees #2).

Table 5.6. Interviewees' perceptions on DP03

ID	Organization	Draft Principle 3	Implementation in the firm
1	Design	Important	Yes
2	Design	Important, but difficult to be implemented	Yes
3	Construction	No comment provided	No
4	Construction	Important	Yes
5	Construction	Not sure, same for site-built and OSC	No answer provided
6	Design	Not sure, same for site-built and OSC	Yes
7	Construction	No comment provided	Yes
8	Construction	No comment provided	Yes
9	Design	No comment provided	Yes
10	Design	No comment provided	Yes
11	Construction	No comment provided	Yes
12	Design	No comment provided	Yes

Note. Gray cells indicate interviewees working in firms that use volumetric modules. White cells indicate interviewees working in firms that only use non-volumetric components.

Comments

Few respondents commented on this principle, and the comments provided indicated that they associated the importance of this proposition mostly with the manufacturing phase of the OSC. However, the success of OSC depends on monitoring and identifying issues throughout the project phases, and feedbacking them to the design, manufacturing, and construction teams (Arashpour et al., 2020; Lessing et al., 2005). After reflecting on the comments provided by the interviewees and also in previous literature, the researcher acknowledged that this proposition should be renamed to better define its goal, focused on the development of a systematic performance measuring and quality control method, which would be more applicable for construction firms: "Improve monitoring and quality control".

DP04. Integrate logistics and supply chain management with AEC processes

Six interviewees acknowledge the importance of this proposition and five of them did not make any comment. One interviewee from a design firm was not sure about the importance of this principle and commented that it would apply only for construction firms. On the other hand, an interviewee from a design firm stated that this principle was one of the most important ones.

The interviewees noted that the role of designers in logistics involves the correct sizing and structuring of offsite-manufactured modules to facilitate transport and craning, as well as site staging.

> … obviously the architect, the factory and the engineer all work together to make sure the modules meet the design or the dimensional requirements before they ship, during design, to make sure we have no problems going down the road or anything like that. But, for us [structural engineers] I would say the only point we get involved with is identifying how the modules are constructed to make the safe craning of the modules easier. (Interviewee #6)

However, the role of designers goes beyond logistics, as it is necessary to define a design in line with production (offsite and on-site). Depending on the design, which contains different layers of components and installations to be assembled on the construction site in a defined order, construction companies can plan and schedule the allocation of workers and the delivery and assembly of components on the site.

> It's everything that we've spent four years learning, which is: ‘Let's not put the electrical, mechanical, plumbing, fire protection and low voltage persons and subs all on the site at the same time. Let's change the design’… You order it, so ductwork guy comes in and does his work first and then the plumber comes in and does his connections and then fire protection comes in. And so, you have to understand what you're doing, and it requires you to schedule it a little differently… they used to be trying to bring in 25 people to do the electrical work in a building, now they literally might be bringing 4 and so. (Interviewee #9)

Interviewee #8 suggested that this proposition is the most challenging to be successfully implemented in construction firms because “It's tracked on excel sheets. It's word of mouth. It's following up. There's a lot of layers of vendors, and terms and conditions that don't allow us to have certainty with deliveries and expectations.”

Table 5.7 summarizes interviewees’ perceptions on the integration of logistics and supply chain management into the processes of design and construction firms to facilitate the use of offsite construction in multifamily projects. A total of five interviewees reported that their firms have adopted this strategy.

<u>Comments</u>

While only half of respondents admitted the importance of this principle for the success of OSC, the literature demonstrates that logistics and supply chain management strategies must be planned early in the design stage, as it affects all phases of the project and can highly impair the project cost and completion time (Bertram et al., 2019; Lessing & Brege, 2015).

Table 5.7. Interviewees' perceptions on DP04

ID	Organization	Draft Principle 4	Implementation in the firm
1	Design	No comment provided	No answer provided
2	Design	Important	No
3	Construction	Important	No
4	Construction	Important	Yes
5	Construction	No comment provided	No answer provided
6	Design	Important	Yes
7	Construction	No comment provided	No answer provided
8	Construction	Important	Yes
9	Design	Important	Yes
10	Design	No comment provided	Yes
11	Construction	No comment provided	No (to be implemented)
12	Design	Not sure, mostly for the construction firms	No

Note. Gray cells indicate interviewees working in firms that use volumetric modules. White cells indicate interviewees working in firms that only use non-volumetric components.

DP05. Plan for new models of permitting and inspections

According to the interviewees' perceptions, this proposition is important when the firm plans to use volumetric modules, but it is not very relevant in the use of non-volumetric components, as expressed by Interviewee #4: "Where you get into permitting issues is when you're doing bathroom pods and modules, you know, full modules, in trying to review what are the requirements of the local city for inspections." Six interviewees deemed this principle as important and a total of five interviewees did not express their opinions about this proposition.

The interviewees revealed that according to each jurisdiction, there are many differences in permitting and inspections processes, in addition, conflicts between states and cities codes and requirements further complicate these. Strategies to facilitate permitting and inspections involve meetings with building inspectors at the beginning of the project to get them on board and hiring an independent third-party inspection company that is nationally recognized to lead the process: "On most cases, the first thing that we do when we find out we're doing a project, whether in Tampa, FL or Reno, NV is… we get on a plane and go meet with the building inspector". (Interviewee #9)

Table 5.8 summarizes the interviewee's perceptions on the integration of logistics and supply chain management into the processes of design and construction firms to facilitate the use of offsite construction in multifamily projects. A total of seven interviewees reported that their firms have adopted this strategy.

Table 5.8. Interviewees' perceptions on DP05

ID	Organization	Draft Principle 5	Implementation in the firm
1	Design	No comment provided	No answer provided
2	Design	Important	No
3	Construction	Important	No
4	Construction	Important	Yes
5	Construction	No comment provided	No
6	Design	Important	Yes
7	Construction	No comment provided	Yes
8	Construction	Important	Yes
9	Design	Important	Yes
10	Design	No comment provided	Yes
11	Construction	No comment provided	In process
12	Design	Not sure, mostly for the construction firms	Yes

Note. Gray cells indicate interviewees working in firms that use volumetric modules. White cells indicate interviewees working in firms that only use non-volumetric components.

Comments

Again, half of interviewees considered this strategy important. Based on the comments of interviewees and participants from other phases of this study, the researcher revised this principle, as although it is an important topic to be considered for the success of the OSC, research and practice revealed this principle is more important for vertically integrated companies manufacturers because they are responsible for licenses in volumetric modular OSC (Smith et al., 2015) and one alternative would be to certify modular manufacturers instead of individual modules (Stein, 2016). As for non-volumetric OSC, licenses, inspections and approvals work similarly to traditional construction.

Likewise other principles previously discussed, in this case, the part that would fit most to design and construction companies would be to work with governmental and non-governmental regulatory organizations and educate them on practices and protocols of OSC projects (Galante et al., 2017). Therefore, after such considerations, this principle was removed from the final set of principles.

DP06. Engage in partnerships

A total of 11 interviewees acknowledged this principle as important, as expressed by Interviewee #9: "… you know that to me is really number one. If I don't engage in partnerships with the right people at the beginning, then nothing else is going to matter." However, among them, one interviewee considered that engaging in partnerships is as important in OSC as in traditional construction. One of the interviewees did not provide any comments on this principle.

The interviewees highlighted that OSC demands more engagement in partnerships as they require more collaboration and integration between developers, designers, manufacturers and contractors not just in one project, but potentially in repeated projects, for in OSC, repetition results in improvements in the quality of processes and products: "Yes, we have several architects and factories that we work with all the time and those are to me the most successful projects." (Interviewee #6)

In addition to impacting the success of OSC projects, recurring partnerships help set standards for future projects: "But we are working with several factories trying to develop standards and trying to get into a more of a repetitive design …" (Interviewee #6)

Even partnerships with companies that support more intensive use of OSC are important, such as partnerships with software companies:

> … we were going to get [software company] involved and help us set up some computer software to help us not only manage the procurement flow but also manage the factory fabrication flow from station to station so that we could track that in real time… (Interviewee #7)

Table 5.9 summarizes interviewees' perceptions on design and construction firms engaging in partnerships to facilitate the use of offsite construction in multifamily projects. A total of seven interviewees reported that their firms have adopted this strategy.

Comments

Interviewees anticipated that partnerships contribute to the success of OSC in multifamily projects because it improves relationships and collaboration, facilitates the information flow and allows to share the risks and benefits of projects (Hu et al., 2019; Pan et al., 2007). Considering the synergies of this principle with innovative contractual models, the researcher decided to join those two principles and create the following principle: *Engage in partnerships and innovative contractual models.*

Table 5.9. Interviewees' perceptions on DP06

ID	Organization	Draft Principle 6	Implementation in the firm
1	Design	Important	Yes
2	Design	Important	No answer provided
3	Construction	Important	No
4	Construction	As important as in traditional construction	Yes
5	Construction	Important	No answer provided
6	Design	Important	Yes
7	Construction	Important	No answer provided
8	Construction	Important	Yes
9	Design	Important	Yes
10	Design	Important	Yes
11	Construction	No comment provided	In process
12	Design	Important	Yes

Note. Gray cells indicate interviewees working in firms that use volumetric modules. White cells indicate interviewees working in firms that only use non-volumetric components.

DP07. Adopt more innovative delivery and contracting models

Five interviewees acknowledge the importance – or somewhat importance – of this principle, including an interviewee who conveyed that this principle is only important if it includes the issue of financing OSC projects.

Only two interviewees have this principle implemented in their firms, one from a construction and the other from a design firm that no longer works with multifamily projects. Interviewee #7 expressed that they would adopt more innovative contract models because they have the potential to make OSC projects more cost effective: "Probably adopting more innovative delivery models. That's one of the things we want to try to change and find a different way of making it more cost effective."

Interviewee #8 indicated that this proposition is important for the implementation of other strategies important in OSC projects: "… then, the other thing you touched on is delivery methods, in IPD and design build it's going to be significantly easier to implement these things [other principles] because that forces the early collaboration."

Interviewee #9 highlighted the importance of been creative to created opportunities for the different stakeholders involved in the project, which includes setting pre-stablished values for scaled projects.:

And we say "[partner], we're going to give you 15 projects this year for [project X] and you're going to make $100,000 fee on every one of them. Then you are motivated to figure out how to drive down cost…

Some interviewees also commented on the importance of financial topics in construction contracts:

… on number 7 [from the list of draft principles]… is where I put the issues about bonding, bank draw schedules, the contract methodology, all of those different things that they don't talk about… I can have the greatest design and manufacture and construction team in the world, but if the bank says we're not going to lend you $10 million, then it doesn't matter.

Table 5.10 summarizes interviewees' perceptions on design and construction firms' adoption of more innovative contracting models to facilitate the use of offsite construction in their multifamily projects.

Table 5.10. Interviewees' perceptions on DP07

ID	Organization	Draft Principle 7	Implementation in the firm
1	Design	Not important	No
2	Design	Somewhat important	No
3	Construction	No comment provided	No
4	Construction	No comment provided	No answer provided
5	Construction	Not sure	No answer provided
6	Design	Not sure	No
7	Construction	Important	To be implemented
8	Construction	Important	Yes
9	Design	Important	Yes
10	Design	No comment provided	No answer provided
11	Construction	Important, but must include financing issues	In process
12	Design	No comment provided	No answer provided

Note. Gray cells indicate interviewees working in firms that use volumetric modules. White cells indicate interviewees working in firms that only use non-volumetric components.

Comments

Although less than half of respondents anticipated this strategy as important to the success of OSC, research and practice reveal that relational contractual models are central to the OSC ecosystem as it stimulates collaboration and transparency between the parties (KPMG, 2016; McKinsey Global Institute, 2017). One of the participants, who works in a vertically integrated company, pointed out that the company's contractual relationships with suppliers had to be completely revised to adapt to the new business model completely focused on the use of OSC. Interestingly, some participants have already experimented with adapted versions of the IPD with different partners, proving that, as indicated in the literature, contracts need to be based on trusting relationships between the parties involved, much more than on texts full of rules and punitive clauses (McKinsey Global Institute, 2017).

Here again, designers and construction professionals often do not have the power to decide on the type of contract that defines the delivery method, for as explored by Pullen et al. (2019), novel contractual models are dependent on owners and developers upfront decisions. So, in addition to educating owners and developers, designers and construction professionals can adopt innovative contract models to reduce friction with other partners, such as manufacturers, subcontractors, traders, etc., which would involve partnerships.

As explained in the previous draft principle, the researcher combined draft principle #6 and draft principle #7 into one new principle: *Engage in partnerships and innovative contractual models.*

DP08. Involve all the project stakeholders early in the process

This proposition was a consensus among the interviewees, since all of them found it important. Some interviewees pointed out that this decision is often not up to designers and construction companies: "… ultimately the consultants don't get the opportunity to present how the project should be managed, right? So, it ultimately relies on the owner's level of understanding." (Interviewee #1). Even acknowledging these difficulties, one of the interviewees highlighted the role of AEC professionals in educating developers and owners about the importance of this strategy.

> Involving stakeholders in the project early, that's something that I feel is most important in this process. And a developer I've worked work with, I've tried to get them to realize that they have to bring in more equity partners, bring in designers and bring in the off-site early on to make those processes important. I think that that's an area that can be improved. If you can explain in a way that shows the developer value in doing that. (Interviewee #7)

OSC resonates with standardization, thus, as acknowledged by the interviewees, OSC and modular construction, in particular, require an even earlier involvement of stakeholders to define the technical standards to be adopted in the project:

I would say it's good for the engineer to get involved pretty early with the factory or have a standard build method with the factories, so that a lot of those items can be worked out and addressed. (Interviewee #6)

The fabricator has to be in the process so early because the fundamental decisions: are you doing steel, are you doing wood? All of that, has to be decided by the client. It's almost in the due diligence stage, right? (Interviewee #2)

Table 5.11 summarizes interviewees' perceptions on the involvement of all the project stakeholders early in the design and construction processes to facilitate the use of offsite construction in their multifamily projects. A total of eight interviewees reported that their firms have adopted or are adopting this strategy.

Table 5.11. Interviewees' perceptions on DP08

ID	Organization	Draft Principle 8	Implementation in the firm
1	Design	Important	No answer provided
2	Design	Important	No answer provided
3	Construction	Important	No
4	Construction	Important	No answer provided
5	Construction	Important	Yes
6	Design	Important	Yes
7	Construction	Important	Yes
8	Construction	Important	Yes
9	Design	Important	Yes
10	Design	Important	Yes
11	Construction	Important	In process
12	Design	Important	Yes

Note. Gray cells indicate interviewees working in firms that use volumetric modules. White cells indicate interviewees working in firms that only use non-volumetric components.

<u>Comments</u>

This principle was clearly defended by all interviewees, but it was also commented that in many cases this is not an attribution of design or construction companies, but of the owners or developers, who may not have a clear perception of the benefits that this strategy can bring to the project as a whole (Hu et al., 2019; Peltokorpi et al., 2018). Therefore, considering the importance of this strategy to the use of OSC, it is paramount that designers and construction professionals educate owners, developers and manufactures on the benefits of all the stakeholders becoming involved in the early stages of the, as defended by Hu et al. (2019). After pondering on the interviewees' comments and comparing them with the literature, the researcher acknowledges that this strategy is more applicable to owners and developers, therefore it was not included in the final set of principles.

DP09. Adopt a sustainable approach for construction projects

Only Interviewee #10 perceived the engagement with sustainability principles as important for the growing use of OSC in multifamily projects:

> The one that sort of jumped out at me, and that is sort of due to my heart, and we're working hard at our firm to try to come to grips with this, is the sustainable approach, number 9 [from the list of draft principles]. Most of the reason why we're trying to embrace these new technologies is to save material, save time, save carbon, save money for our client.

Four interviewees did not even comment on this proposition and three interviewees perceived that this proposition is as important in OSC as it is in the traditional construction, so it cannot be considered conductive to OSC: "… for us, it wasn't a specific goal related to getting into modular. I think the industry itself needs to adopt these methods to be more sustainable." (Interviewee #6)

Some interviewees acknowledge this proposition as a result of embracing OSC, not as a strategy to engage in OSC: "Probably sustainability [is not important]. It's because that becomes not so much a methodology, it becomes a benefit of offsite construction." (Interviewee #2)

Table 5.12 summarizes interviewees' perceptions on design and construction firms' adoption of a sustainable approach to facilitate the use of offsite construction in their multifamily projects. A total of three interviewees reported that their firms have adopted, and seven interviewees reported that their firms have not adopted this strategy.

Comments

Considering the perception of respondents, design and construction companies consider sustainability to be of little relevance within the AEC industry and even more irrelevant as a strategy to boost the use of OSC in multifamily projects. Only one respondent stated that sustainability is fundamental in their company and a driver for the adoption of new technologies such as OSC. Research has demonstrated the benefits to sustainability resulting from the adoption of OSC (Aye et al., 2012; X. Cao et al., 2015; Quale et al., 2012; Wu et al., 2019).

However, as highlighted by some interviewees and by research on this topic, sustainability fits better as a result of the adoption of OSC, and not as a strategy for engaging in OSC, therefore, the researcher decided to withdraw this proposition from the set of principles.

Table 5.12. Interviewees' perceptions on DP09

ID	Organization	Draft Principle 9	Implementation in the firm
1	Design	Not important	No
2	Design	Not important	No
3	Construction	No comment provided	No
4	Construction	As important as in traditional construction	Yes
5	Construction	Not important	No
6	Design	As important as in traditional construction	No
7	Construction	Not important	No
8	Construction	No comment provided	No answer provided
9	Design	No comment provided	No
10	Design	Important	Yes
11	Construction	As important as in traditional construction	Yes
12	Design	No comment provided	No answer provided

Note. Gray cells indicate interviewees working in firms that use volumetric modules. White cells indicate interviewees working in firms that only use non-volumetric components.

DG10. Develop training and knowledge management strategies

Eleven interviewees acknowledge that design and construction firms need to develop specific training and knowledge management strategies to embrace OSC in multifamily projects, because "design teams need critical information about offsite construction prior to them completing their documents…" and:

> So, for the GC's and the architectural firms that sometimes minimize the differences in modular construction, there should be a training program and management strategies for that, not to mention BIM and everything else. (Interviewee #1)

According to the interviewees, such training strategies must be comprehensive and impact on the mindset of design and construction firms: "I mean, the emotional intelligence side of that it's not just training our new software, it's training to get your mind to work differently… (Interviewee #2).

The interviewees highlighted the importance of recording and disseminating the lessons learned in each project as a way to improve the design and construction processes, which is vital in OSC, since this construction technology implies repetition and standardization of processes and products:

> Data should be collected during all phases of the project and promptly fed back to all the parties involved in the project to solve eventual problems identified. On a team level, and internally, that is the most challenging because data does get collected, but it is not promptly fed back to all parties involved to solve eventual problems or to prevent problems. (Interviewee #1)

In addition, because it involves repetition and standardization, the processes will be improved as more projects are built, which allows for continuous improvement:

> And then you can work things out on the first one, and by the second one, if your team doesn't change, you're getting it down, and so it's like: OK, you've done this before, I know how it works. By the third one, it's a well-oiled machine and it just keeps getting more and more efficient. (Interviewee #2)

Table 5.13 summarizes interviewees' perceptions on design and construction firms' adoption of improved training and knowledge management strategies to facilitate the use of offsite construction in their multifamily projects. A total of eleven interviewees reported that their firms have adopted or are adopting this strategy.

Table 5.13. Interviewees' perceptions on DP10

ID	Organization	Draft Principle 10	Implementation in the firm
1	Design	Important	Yes
2	Design	Important	In process
3	Construction	Not important	No
4	Construction	Important	Yes
5	Construction	Important	In process
6	Design	Important	Yes
7	Construction	Important	In process
8	Construction	Important	Yes
9	Design	Important	Yes
10	Design	Important	Yes
11	Construction	Important	In process
12	Design	Somewhat important	Yes

Note. Gray cells indicate interviewees working in firms that use volumetric modules. White cells indicate interviewees working in firms that only use non-volumetric components.

Comments

Almost all interviewees acknowledged the necessity to equip design and construction firms with the appropriate knowledge and skills to advance OSC. Research on this topic has also identified a need to enhance skills on OSC for both designers and construction professionals (Hwang et al., 2018b) and pointed out the need to record and share the lessons learned within a project (Smith, 2011). Some of the interviewees recognized the importance of knowledge transfer between design, construction and manufacture firms involved in OSC, which also contribute to technology transfer (Sexton et al., 2006).

EP01. Develop product-oriented business models – Extra principle that emerged from the interviews

Product-oriented business models was not included in the draft principles, but it was enthusiastically defended by three of the interviewees as an overarching strategy that comprehends standardization, product platform and DfMA strategies. This topic had already been discussed in previous phases of this study and ranked by the online survey participants (change C15), but due to its low position in the ranking (rank position #14/17), it was not included in the drafted propositions.

Once the firms are product-oriented and no longer project-oriented, there are opportunities to scale the production of specific products. Interviewee #11 pointed out that this strategy is part of the goal of their firm:

> I mean, the one thing that that would be nice is being able to start to think of our multifamily projects as not a project-by-project scenario, but a program so that we could start building modules. And let's say we have an A type module, a B type module, a C type module and the combination of those could be used in multiple projects… So, that's what we're trying to get, is the idea of a product. So, that is a goal that's out there.

For design firms, this strategy would affect the way design documents are created:

> … it's a totally different mindset of how you build, put together a set of documents in the traditional AEC world versus that, and so, our sheets, our construction documents went from being a CD set to literally a station by station, by station set… (Interviewee #9).

Focusing on the role of standardization in this context, Interviewee #9 stated: "Really, I think it's going to help the industry more if we can standardize things and really have a similar way to build across the factories." (Interviewee #6)

Interviewees acknowledged that it is challenging to work with more standardized products and still develop creative designs:

> … I think the best way the industry could really go is that the architect can still design what they would like to see and that the factories themselves have built standards that will allow the architect to design what they want and still meet that requirement out of having to modify the architecture of the building … because an owner is going to want to see an architecture a certain way and not necessarily have to make it look boxy or in a way that you can tell is modular or volumetric. (Interviewee #6)

Table 5.14 summarizes interviewees' perceptions on design and construction firms' involvement with standardization, product platform and DfMA strategies to facilitate the use of offsite construction in their multifamily projects. Only four interviewees reported that their firms have adopted or are adopting this strategy, even if not aiming at using or increasing the use of OSC in multifamily projects (Interviewee #9).

Table 5.14. Interviewees' perceptions on EP01

ID	Organization	Extra Principle 01	Implementation in the firm
1	Design	No comment provided	No comment provided
2	Design	No comment provided	No comment provided
3	Construction	No comment provided	No comment provided
4	Construction	No comment provided	No comment provided
5	Construction	No comment provided	No comment provided
6	Design	Important	Yes
7	Construction	No comment provided	No comment provided
8	Construction	No comment provided	No comment provided
9	Design	Important	Yes
10	Design	No comment provided	No comment provided
11	Construction	Important	In process
12	Design	Somewhat important	In process

Note. Gray cells indicate interviewees working in firms that use volumetric modules. White cells indicate interviewees working in firms that only use non-volumetric components.

Comments

Although this principle has not been included in the set of draft principles due to the results of the previous phases of this study, in this phase some interviewees have properly defended the adoption of this strategy, a trend that has been identified in research and practice, as it demonstrates that the adoption of product-oriented strategies works well for niche-focused companies, such as companies focused on the multifamily housing market (Lessing & Brege, 2018). Once companies adopt a product-oriented business model they will no longer work with one-of-a-kind projects, but with innovative products that can be replicated in several projects, which results in benefits for companies and customers, as indicated in the literature. (Peltokorpi et al., 2018). Included in this principle are product standardization and customization strategies and, more specifically for designers, DfMA strategies, which have been highlighted in research and practice as paramount in higher levels of OSC (Dodge Data & Analytics, 2020b; Goulding et al., 2015).

EP02. Promote leadership and mindset engagement with OSC principles – Extra principle that emerged from the interviews

This proposition was not included in the draft principles but was cited by seven interviewees who drew attention to the importance of changing the mindset of design and construction organizations: "… that's really what I've spent my last year doing. It is just trying to adjust the mindset, particularly the leaders, so that they would not just accept it but not be against it, something that is different…" (Interviewee #11).

And then, building up a leadership compromised and excited about OSC: "… but you need someone passionate about it that wants to wake up every morning and go and do this and help raise the bar… a champion, or a leader, or someone that has ownership in the process." (Interviewee #8)

Promote leadership and mindset engagement with OSC principles Leadership has the potential to enable OSC, facilitating changes in the organizational mindset:

> If you have one or two leaders that can make that mindset shift and drive it, that can change things pretty quick, so, it truly is a leadership issue. After that, I'm not as convinced that, that, that, that's the hardest one. (Interviewee #11)

The way the champions promote the OSC principles within organizations can be decisive in the success of the project:

> It's not trying to sell someone that prefab is a good idea. It's showing them that: "Look how much time I'm going to save you. Look how much less rework you're going to have on this job. Look at how many hours you're going to save. Look how many fewer injuries you're going to have". It's all very powerful. (Interviewee #4)

Table 5.15 summarizes interviewees' perceptions on design and construction firms' leadership and mindset engagement with OSC principles to facilitate the use of offsite construction in their multifamily projects. A total of seven interviewees reported that their firms have adopted or are adopting this strategy.

Table 5.15. Interviewees' perceptions on EP02

ID	Organization	Extra Principle 02	Implementation in the firm
1	Design	No comment provided	No comment provided
2	Design	Important	In process
3	Construction	No comment provided	No comment provided
4	Construction	Important	Yes
5	Construction	No comment provided	No comment provided
6	Design	No comment provided	No comment provided
7	Construction	Important	Yes
8	Construction	Important	Yes
9	Design	Important	Yes
10	Design	No comment provided	No comment provided
11	Construction	Important	In process
12	Design	Important	No

Note. Gray cells indicate interviewees working in firms that use volumetric modules. White cells indicate interviewees working in firms that only use non-volumetric components.

<u>Comments</u>

This principle, although not included in the set of draft principles, was brought up for discussion by more than half of the respondents who considered it important for the success of OSC in design and construction companies. Therefore, the researcher assessed this topic and decided to include it in the revised set of principles.

Previous research revealed that changes in the mindset of design and construction companies in order to promote engagement with OSC principles allow such companies to better understand OSC and realize the benefits this technology can bring to their projects, as well as challenges to be overcome (N. Lu & Liska, 2008), which also helps companies make more informed decisions that may affect other strategies to be adopted (Zakaria et al., 2018). It is also important to form leaders and champions with extensive knowledge of OSC to advocate OSC strategies within the company and even with partners, owners and developers.

5.2.2.1 Discussion

The draft principles were revised and the final set of eight principles was organized according to the framework developed by the World Economic Forum industry report which focused on measures to transform the AEC industry (World Economic Forum, 2016) and are presented in Table 5.16.

Table 5.16. Principles to implement strategic changes in design and construction firms aiming at the successful adoption of OSC in multifamily projects – final format

Principles ID	Draft Principles ID	Final Principle	Topic
P01	EP01	Develop product-oriented business models	Strategy and business model
P02	EP02	Promote leadership and mindset engagement with OSC principles	People, organization, and culture
P03	DP06 DP07	Engage in partnerships and more innovative contractual models	Strategy and business model
P04	DP01	Shift toward digital transformation	Technology, materials, and tools
P05	DP10	Training and knowledge management strategies	People, organization, and culture
P06	DP02	Adopt lean construction practices	Processes and operations
P07	DP03	Improve monitoring and quality control	Processes and operations
P08	DP04	Integrate logistics and supply chain management with AEC processes	Processes and operations
-	DP05	*Eliminated:* Permitting and inspections	Processes and operations
-	DP08	*Eliminated:* Involve all the project stakeholders early in the process	Strategy and business model
-	DP09	*Eliminated:* Sustainable approach	

Interviewees' perceptions on the proposed principles varied depending on their experience with OSC. Hence, interviewees who had participated in projects with the adoption of volumetric modules realized that the proposed strategic changes are essential for design and construction companies to successfully engage in the growing use of OSC, evolving even to the adoption of volumetric modules. On the other hand, interviewees who only had experience with more basic levels of OSC, such as panelized systems, did not realize the need for major changes in design and construction companies in order to evolve with the use of OSC and did not grasp that a more intense and increasing adoption of OSC would benefit their firms' efficiency, as demonstrated in research and practice (Dodge Data & Analytics, 2020b; Lessing & Brege, 2018).

In addition, depending on the respondent's region of activity, the perception of the advantages and disadvantages of using OSC vary depending on the availability and qualification of the workforce, the customers/market's view on the use of OSC in multifamily projects, and even the codes and requirements required by state and local jurisdictions. There is a lack of research addressing these factors in the context of the use of OSC in the multifamily market across the US, so studies addressing this topic would be necessary.

Some interviewees were comfortable with the situation of their companies, "… complacency also sets in, in the sense like, it's easy to just work with what we have done before and just move on, right? So that … we don't want to change some certain things." (Interviewee #12). But as suggested in the literature review, the AEC industry practitioners are aware of their inefficiencies and the opportunities for improvement that arise within the AEC industry (Hoover & Snyder, 2018), which was confirmed by the interviewees "… because we spend a lot of time updating drawings… BIM in that regard, kind of corrects itself in many ways, and not only that." (Interviewee #12)

The interviewees did not deem the sustainability-related principle important and some of them noted that sustainability might be more of a result, rather than a principle or driving force for the higher use of OSC. Finally, most respondents (6 out of 8 that expressed their opinions) acknowledged that the strategies for using OSC in multifamily projects are applicable to other markets as well, such as healthcare, hospitality, or any other market that are well-suited for the use of OSC, which is aligned with the findings of the recent study by Dodge Data & Analytics (2020b).

5.2.3 Interviewees' perceptions on the factors affecting the use of OSC in their firms

As the purpose of this phase of the study was mainly to validate the previously proposed principles, the interviewees were not explicitly asked about the factors affecting the use of OSC in their firms, but they were asked why their firms were using or not using OSC in their multifamily projects. In addition to providing their responses to that question, during the interviews some interviewees provided general comments on their perceptions about the benefits and challenges of adopting OSC in multifamily projects in the US.

5.2.3.1 Challenges – why interviewees' firms were not using OSC in multifamily projects

Three interviewees explained that their firms were no longer adopting OSC in multifamily projects due to three main reasons that are explained as follows. Learning and training requirements was highlighted by Interviewee #2 as a current barrier to OSC adoption by the firm: "… because the architects need to learn to do something different and something new, and it has an entirely different set of challenges than designing for stick builder." However, Interviewee #2 indicated that the company can get involved with OSC thanks to scalability opportunities of some potential multifamily projects.

Interviewee #3 observed that their firm's decisions on the use of OSC in multifamily projects varies according to the multifamily market of the different regions of the US, so that in the specific area where Interviewee #3 works, the firm decided not to use OSC in multifamily projects because "… unfortunately, there's not enough of a market to sustain". He also highlighted that modest savings in cost does not justify the risk to use OSC in a skeptical and challenging market.

Interviewee #9 explained that not using OSC in multifamily projects was a strategic decision in their firm, because the multifamily market is very competitive and works with very tight margins in comparison to other markets: "The multifamily is so competitive that it makes it very difficult to compete, so, we chose [to work only with] healthcare because there are bigger margins, there is higher risk, there is more complexity, and we had no competition."

5.2.3.2 Drivers and benefits – why interviewees' firms were using OSC in multifamily projects

The reasons highlighted for the use of OSC were usually associated to savings in costs and time. In addition to benefits in terms of cost savings, Interviewee #12 acknowledged that OSC also reduces problems in the construction site both due to poor design coordination and issues related to exposure to weather:

> … you basically save on labor costs because a lot of the work is not affected by the elements because they [the modules or components] are kind of

> manufactured in a shelter. So, you don't have to worry about bad weather or something like that … The other thing is that a lot of flaws are actually found when they are manufacturing the wall panels because if there are some errors in geometry or details, they will catch on before the construction starts.

Interviewee #8 acknowledged benefits in safety, quality, and stakeholders' alignment: resulting from the adoption of OSC,

> … holistically and nationwide doing work offsite in a controlled environment is safer, and there's an increased level of quality control and quality assurance when things are done offsite. There's a better opportunity to set expectations with clients and design teams when things can be done offsite as well, because they are able to be reviewed prior to getting to the site.

Focusing on the drivers to an increasing adoption of OSC in multifamily projects, two interviewees stated that their companies are taking advantage of the market momentum, marked by an increasing interest of some customers in OSC adoption in their multifamily projects: "So, as the opportunities arise with different clients, we just kind of followed the industry and have done that." (Interviewee #6).

Labor and experience issues such as labor shortage and workforce skills to work with OSC were also identified as drivers to OSC adoption, as acknowledged by Interviewee #11:

> The overall line I would just say is both the shortage currently and the future anticipated shortage of labor, on-site labor. And so … offsite construction tends to allow for a larger workforce base with maybe less skills than you would need for on-site, so that's the overriding theme.

Still focusing on workforce skills, Interviewee #8, from a company with nationwide presence, stated that the adoption of OSC by the company varies from one region to another, mostly due to the availability and quality of the workforce:

> … in Chicago the workforce is so great and production rates are so high that nine times out of ten offsite construction is not faster or cheaper in Chicago. It's actually more expensive and sometimes slower. And it's really just in Boston, New York and Chicago [where this happens]. Probably where you have strong workforces. But if you go down South, to Arkansas, or Nebraska, Florida, where you have less skilled workforce, ten out of ten times offsite construction makes sense and, in many cases, [OSC] come from up here [interviewee region].

Other factors less discussed by interviewees included: the involvement of companies with new technologies, the opportunity to standardize the AEC industry through the adoption of standardized products and processes that are already being adopted in OSC, and opportunities to scale some projects with repetitive characteristics.

5.2.3.3 Discussion

Even though the goal of the interviews was not to evaluate factors, the researcher included this section to illustrate the factors mentioned by participants during the validation interviews, which could be considered the most important factors at the company level.

Table 5.17 summarizes the interviewees' perceptions on the factors affecting the use of OC in their firms. The factors were named according to the consolidated list of factors presented by the end of Phase 2 (see Table 4.12).

Table 5.17. Interviewees' perceptions on the factors affecting the use of OC in their firms

ID	Firm	Factors affecting the use of OSC in the interviewees' firms	
		Positive factors	Negative factors
1	Design	costs, time, planning/processes & business	-
2	Design	planning/processes & business	labor & experience
3	Construction	time, climate/weather & resilience	customer's/social attitude and market culture, costs
4	Construction	costs, time	-
5	Construction	costs, time	-
6	Design	customer's/social attitude and market culture, technology and innovation, planning/processes & business, labor & experience	-
7	Construction	costs, time	-
8	Construction	safety & healthy, stakeholder's alignment, quality & product value, transportation and logistics	transportation and logistics
9	Design	labor & experience	costs, planning/processes & business, customer's/social attitude and market culture
10	Design	technology and innovation, customer's/ social attitude and market culture, quality & product value, labor & experience	-
11	Construction	labor & experience, costs, time, quality & product value	-
12	Design	costs, design & coordination, quality & product value, climate/weather & resilience	-

Note. Gray cells indicate interviewees working in firms that use volumetric modules. White cells indicate interviewees working in firms that only use non-volumetric components.

Among the 18 revised factors (RF) listed in Table 4.12 eleven were mentioned by the interviewees as a factor driving or hindering the adoption of OSC in their firms, plus one factor, which was cited in the interviews, but had been removed from the revised list of factors (Table 4.12), namely *stakeholder's alignment* (see Figure 5.5). Again, the economic factors were the most frequent with *cost* (*n*=8) and *time* (*n*=6) ranking in the two first positions, followed by the social factor *labor and experience* (*n*=5) as the third most cited factor.

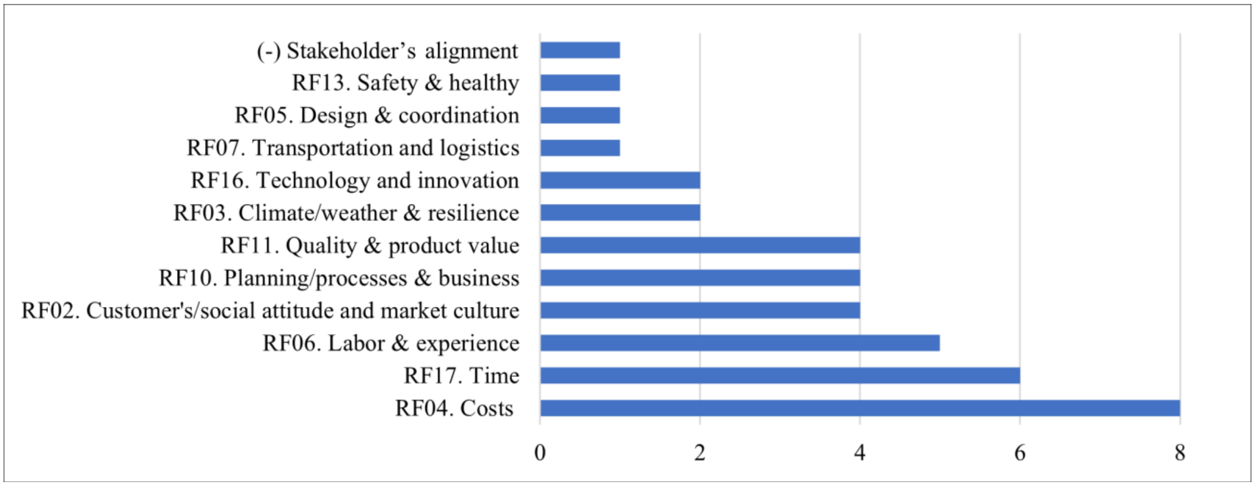


Figure 5.5. Frequency of factors affecting the use of OSC in the interviewees' firms (n=12)

The interviewees considered some factors conducive to the use of OSC, such as *safety and health, time* and *quality and product values*, which was mentioned by previous literature to improve when OSC is used (Galante et al., 2017; Velamati, 2012). Other factors were considered both beneficial and detrimental to the use of OSC. This is the case of *customer's/social attitude and market culture*, for some markets and customers still have a negative view of buildings built using OSC technologies, while others are incentivizing the use of OSC in multifamily projects, as demonstrated by the literature (Gusmao Brissi, Debs, et al., 2021).

Confirming what has been identified in the literature (Galante et al., 2017; Stein, 2016), *cost* is a controversial factor, also identified as both a hindrance and an enticement to the adoption of OSC in the interviewees' firms. Some respondents emphasized that upfront costs or financing issues when using OSC in multifamily projects make its adoption challenging, while others reported real savings resulting from standardization of processes and products, in addition to economies of scale, savings reduced to reduced schedule, etc. *Planning, processes and* *business, labor & experience* and *transportation and logistics* were factors also identified as both beneficial and challenging to the adoption of OSC, for there are many subfactors under those main groups, some of them positive and some of them negative for OSC – see subsection 4.2.3.1 and Research Article 1 (Gusmao Brissi, Debs, et al., 2021).

One interviewee presented an environmental factor as a driver to the adoption of OSC in their firm: *Climate, weather, and resilience*, which actually has an economic side resulting from less dependency on weather conditions affecting work progress, and a social side as well, for workers will be less exposed to extreme weather conditions, which impacts on labor performance and workers' health and safety (Velamati, 2012).

Similar to what was verified among Delphi survey participants (see Table 4.13), the interviewees suggested that some factors are important regardless of the project's location or geographic region – costs, planning, processes and business, technology and innovation, time, quality and product value, and safety and health in construction – while others are more relevant at the local level – local costumer's preferences and market culture, local codes and requirements, local labor market and suppliers, etc. Therefore, each interviewee highlighted different factors that contributed to the use or increase in the use of OSC in their firms.

It is important to note that the interviewees considered that the factors affecting the use of OSC in multifamily projects are similar to the factors that affect the use of OSC in other projects suitable for OSC (hospitality, healthcare, etc.).

5.2.4 Relationships: principles, changes and factors

The identification of factors and the ranking of changes was important to define the principles outline, but while revising the principles, the researcher noted that some changes occupying lower rankings were identified as directly related to the final set of principles. In addition, the researcher revised the relationships between the changes and the factors identified in Phase 2 (see Table 4.15) and analyzed how they connected with the validated principles, which is presented in Table 5.18. The table focuses on the direct relationships between the principles, the changes and the factors, but there are multiple indirect connections between them. The factors functioned as structural elements within the principles' framework and were useful to identify the necessary changes, which in turn shaped the principles. Given the characteristics of the interviews, it is important to emphasize that the interviewees' discussions regarding the factors were mostly focused on the company level, so that factors more generic, related to the market, society, environment and even the government were not widely discussed.

The proposed principles directly connect to 11 of the 18 factors previously identified in this study (see Table 4.12), namely: design and coordination, labor and experience, management and productivity, planning/processes and business, quality and product value, risks and financing, supply chain and procurement, technology and innovation, time, transportation and logistics, and waste and pollution. However, indirectly, the proposed principles affect the other seven factors and vice-versa – aesthetics, costs, climate/weather and resilience, customer's/social attitude and market culture, materials and practices, safety and health in construction, and site disruption. For example, costs issues are connected to all the principles and projects' aesthetics is affected by the product-oriented approach of the company.

As for the changes, with the exception of the change associated to principle #7, all changes in the table were part of the list presented in Phase 3 (see Table 4.16), but the order of importance is no longer relevant here. It is important to note that the relationships between the *changes* and the *draft principles* identified in Phase 4 (see Table 5.1) were adjusted as presented in Table 5.18, so that each final *principle* is linked to one of the *changes* previously consolidated in Phase 3.

It is interesting to note that change *C06. Design for OSC since the project conceptualization*, ranked 1st in the rankings of changes from Phase 3 and associated with the draft principle #8 (eliminated), was not associated with any of the revised principles because, despite its importance, it depends on owners' and developers' decisions. On the other hand, change *C12. Plan for maximum waste reduction* (ranked 17th – last position), which had not been linked to any of the draft principles, is directly linked to principle #4, as it relates to lean construction principles, which focus on eliminating waste in production processes and maximizing value to the product.

Table 5.18. Relationships between the principles, the changes, and the factors

Principle	Change	Factor
Strategy and business model		
P01. Develop product-oriented business models	C15. Promote the standardization and simplification of processes and products by engaging in product platform and DfMA strategies.	Planning/processes & business Design & coordination
P03. Engage in partnerships and more innovative contractual models	C02. Adopt more innovative contracting models sharing responsibilities, risks, profits, and expenses. C07. Develop partnerships and collaboration with experienced manufacturers and suppliers in OSC that work to create value to the product.	Planning/processes & business Risks &financing
People, organization, and culture		
P02. Promote leadership and mindset engagement with OSC principles	No change associated with this principle	Labor and experience
P05. Training and knowledge management strategies	C08. Establish continuous training and knowledge management strategies for the different hierarchical levels of the company.	
Technology, materials, and tools		
P04. Shift toward digital transformation	C10. Implement BIM technologies and adopt a higher level of detail for all projects to promote digital fabrication strategies and to improve delivery methods, procurement process, logistics, and even installation monitoring.	Technology & innovation
Processes and operations		
P06. Adopt lean construction practices	C01. Adopt enhanced management techniques, including lean construction practices.	Management & productivity
	C04. Allocate more time for improved design coordination, submittals analysis, planning and scheduling.	Design & coordination
	C11. Plan for a reduced schedule with OSC and commit to the deadlines for the delivery of the various phases of the project (design, planning, preconstruction, construction, and close-out).	Time
	C12. Plan for maximum waste reduction.	Waste and pollution
P07. Improve monitoring and quality control	C03. Adopt more strict quality control standards for all the phases of the project, similar to the ones used in the manufacturing industry.	Management & productivity Quality & product value
P08. Integrate logistics and supply chain management with AEC processes	C13. Plan logistics carefully considering size restrictions for transportation and travel distances from manufacturing facilities to the jobsite.	Supply chain & procurement Transportation & logistics

As for change *C15. Promote the standardization and simplification of processes and products by engaging in product platform and DfMA strategies*, it was previously ranked 14th and was not associate to any of the draft principles, but it was now linked to principle #1.

According to the interviewees, this is one of the most important changes to be implemented in design and construction firms working with OSC if they are interested in engaging in higher levels of OSC adoption, which is aligned with the literature (Lessing & Brege, 2018). These discrepancies are likely due to differences between participants in the different phases of the study, because in Phases 2 and 3 of is study, the participants had more experience with the use of non-volumetric components, while in Phase 5 – interviews, half of the participants had experience with volumetric modules.

Resuming the identification e validation of factors at the company level of design and construction firms, the combination of factors discussed by the interviewees as presented in Figure 5.5 with the list of factors linked to the principles (Table 5.18) resulted in a consolidated list with the most important factors that affect the use of OSC in multifamily projects in the US (see Table 5.19), focusing on the company level of design and construction firms. The 15 factors included in the *Final list of the most important factors – company level* were the combination of both lists.

Table 5.19. Final list of the most important factors affecting the use of OSC in multifamily projects in the US – company level

Factors discussed by the interviewees (Phase 5)	Factors linked to the Principles (Phase 5)	Final list with the most important factors – company level
Customer's/social attitude and market culture	-	Customer's/social attitude and market culture
Climate, weather, and resilience	-	Climate, weather, and resilience
Costs	-	Costs
Design and coordination	Design and coordination	Design and coordination
Labor and experience	Labor and experience	Labor and experience
	Management and Productivity	Management and Productivity
Planning, processes, and business	Planning, processes, and business	Planning, processes, and business
Quality and product value	Quality & product value	Quality and product value
	Risks &financing	Risks and financing
Safety and health	-	Safety and health
	Supply chain and procurement	Supply chain and procurement
Technology and innovation	Technology and innovation	Technology and innovation
Time	Time	Time
Transportation and logistics	Transportation and logistics	Transportation and logistics
	Waste and pollution	Waste and pollution
Stakeholder's alignment		(Included in "Planning, processes, and business")

5.3 Chapter Summary

This chapter presented major results for the last two phases of this study. In Phase 4 the researcher proposed a set with ten draft principles to implement strategic changes in design and construction companies aiming at the successful use of OSC in their multifamily projects in the United States.

In Phase 5 the researcher conducted interviews with experienced professionals from design and construction firms to validate the proposed principles. The interviewees' comments were used to revise the draft principles and a final set with 8 principles was presented.

The interviewees' perceptions also provided a better understanding of the factors affecting the use of OSC in multifamily projects in the US and how those factors connect to the required changes to be implemented in design and construction firms to adjust them to successfully use OSC in their multifamily housing projects. Focusing on the company level, a total of 15 factors were identified as the most important factors affecting the use of OSC in multifamily projects in the US. As for the changes, a total of 11 changes out of the 17 changes ranked in Phase 3 were linked to the principles, and therefore identified as the most important to be implemented in design and construction companies interested in the successful use of OSC in multifamily projects in the US.

In the following chapter, the researcher will present an overall discussion of findings, conclusions, limitations, and recommendations for future research regarding the factors affecting the adoption of OSC and the changes to be implemented in design and construction firms aiming at using OSC in their multifamily projects.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

This chapter presents the conclusions of this dissertation. A brief discussion is presented on how the combined results of all five phases fit into the prior literature investigated. Then, the researcher presents specific conclusions regarding the use of OSC in multifamily projects, focusing on the main factors that affect the use of OSC and on how to implement strategic changes in design and construction firms interested in using OSC. The final result of this study is a set of principles and associated changes to be adopted by design and construction firms interested in using OSC in multifamily projects in the United States.

Before the conclusions the researcher enumerates the limitations found during the course of the research, which should be considered by the readers of this study. To conclude, recommendations for future research that may add value to the knowledge generated and discussed in this study are presented.

6.1 Discussion of Results

The final discussion of the results focuses on the revised set of principles to implement strategic changes in design and construction firms interested in using OSC in multifamily projects in the United States. While discussing the principles, the researcher discusses the connections between the principles and the changes, how they connect to the resilience principles and how they promote the emergence of new roles for design and construction companies. The researcher also presents a brief discussion on the main factors that affect the use of OSC in multifamily projects in the US within the company level, which were validated in Phase 5 of this study. The

6.1.1 Principles to implement changes in design and construction firms adopting OSC in multifamily projects

Based on the results of the previous phases and analyses performed by the researcher, the researcher developed, validated, and revised the principles to implement changes in design and construction firms adopting OSC in multifamily projects. The revised set of eight principles were organized according to the framework developed by the World Economic Forum industry report which focused on measures to transform the AEC industry (World Economic Forum, 2016) and are presented in Figure 6.1.

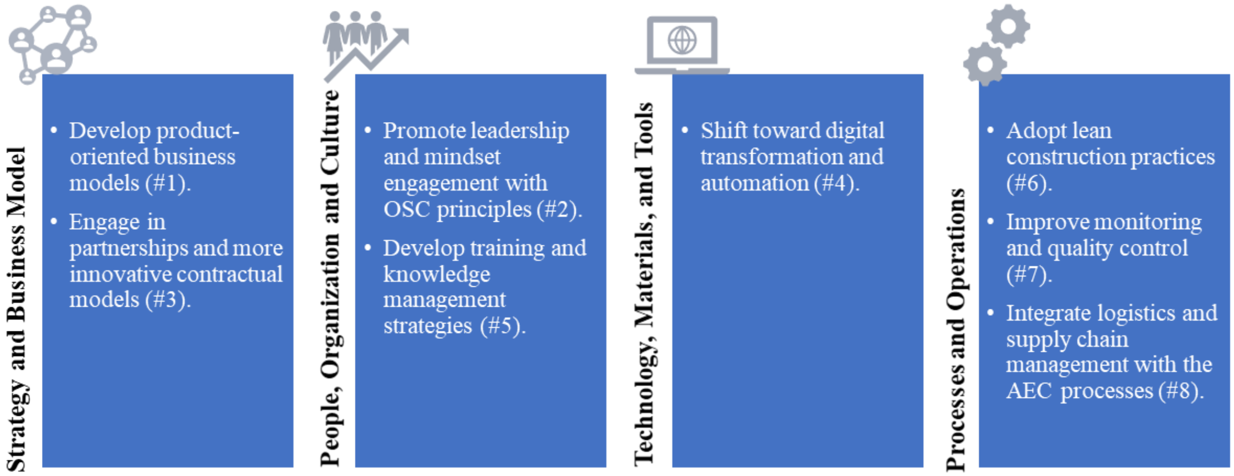


Figure 6.1. Final set of principles

Under each principle are the associated main strategic changes to be implemented in design and construction companies, which are based on the changes previously identified and validated. Upon further elaboration and research, some *changes* not previously identified by the participants of the study were included, and some of them were reworded:

<u>Principle #1 – Develop product-oriented business models</u>

- Develop a business focused on products that can be replicated in several projects.
- Promote the standardization and simplification of processes and products by engaging in product platform and DfMA strategies.
- Adapt the company's products to the multifamily market, following standardized models, but allowing mass customization strategies to meet customers' needs and still guarantee economies of scale.

<u>Principle #2 – Promote leadership and mindset engagement with OSC principles</u>

- The mindset for working with OSC needs to permeate the different levels of design and construction companies.

- Form leaders and champions with extensive knowledge of OSC to advocate OSC strategies within the company and even with partners, owners and developers.

Principle #3 – Engage in partnerships and more innovative contractual models

- Identify partner companies and reinforce the relationship and collaboration with such companies focusing on sharing projects' risks and benefits.
- Adopt relational and innovative contracts to strengthen partnerships and increase productivity.
- Adopt collaborative delivery methods (such as IPD) that support early engagement between parties, reduce adverse relationships, and encourage true inter-and multidisciplinary collaboration and transparency throughout the process.

Principle #4 – Shift toward digital transformation

- Define and implement a comprehensive strategy of ICT improvement involving digitization (the conversion of information and data to digital format) and digitalization, (improving processes by taking advantage of digital technologies and digitized data) to ensure access to good quality systems and equipment and secure a seamless information flow.
- Implement BIM technologies and adopt a higher level of detail for all projects to promote digital fabrication strategies, which are important in OSC, and to improve delivery methods, procurement process, logistics, and even installation monitoring.

Principle #5 – Develop training and knowledge management strategies

- Enhance the skills on OSC for both design and construction professionals.
- Prepare teams to work with OSC's complementary concepts and technologies such as lean construction, BIM, project management platforms.
- Develop and implement strategies to facilitate information sharing and knowledge dissemination – lessons learned – encompassing all the company levels.

Principle #6 – Adopt lean construction practices

- Employ lean construction tools, which are enhanced management techniques, more collaborative and assertive than traditional planning and scheduling methods, working better with OSC compressed schedules.
- Allocate adequate time for more detailed design coordination, which are paramount in OSC projects.
- Focus on maximizing value and reducing waste, in terms of work, materials and time.

Principle #7 – Improve monitoring and quality control

- Adopt more strict quality control standards for all the phases of the project – design, production, transportation and on-site work – similar to the ones used in the manufacturing industry.
- Work collaboratively (design teams, construction team and manufacturers) to streamline collection, feedback, and analysis of project data, especially data focused on the quality of processes and products.
- Deploy tools that allow real-time monitoring and data collection and the integration of the collected data with the project information – BIM, project management platforms.

Principle #8 – Integrate logistics and supply chain management with AEC processes

- Acknowledge logistical issues as an integral part of the project process since the project onset, as it highly impacts the cost and duration of OSC projects.
- Promote collaboration between design and construction teams to define the dimensions of modules and components, temporary reinforcements, lifting points, etc.- DfMA strategies.
- Extend processes monitoring to logistics and supply chain management, including manufacturing, transportation, delivery/storage e assembly strategies.

The eight principles and associated changes identified above are connected and, if applied as a group, will contribute to design and construction companies' success in using OSC in their multifamily projects, evolve towards the use of higher levels of OSC and become more resilient. That is, once companies adopt a product-oriented business model (principle #1) they will no longer work with one-of-a-kind projects, but with innovative products that can be replicated in several projects, which can improve the efficiency of design and construction firms (Peltokorpi et al., 2018). Such products need to be tailored to the multifamily market, following standardized models, but research and practice has demonstrated that mass customization strategies are required to meet customers' needs and still guarantee economies of scale (Andersson & Lessing, 2019; Lessing & Brege, 2018; Peltokorpi et al., 2018). Ideally, this should be the first step for companies embracing OSC.

The next step involves promoting leadership and mindset engagement with OSC principles (principle #2). The mindset for working with OSC needs to permeate the different levels of design and construction companies and to achieve this goal it is important to have a robust leadership operating as enablers of innovation in construction and more precisely of OSC, as highlighted in the literature (Ozorhon et al., 2014).

With the leadership acting to promote OSC, it is possible to develop partnerships and new models of contracts (principle #3) that favor the use of the OSC to benefit all the project's stakeholders. Research and practice has demonstrated that this strategy, although involving sharing risks and benefits, will create a favorable environment for all stakeholders by promoting trust, collaboration, and knowledge dissemination (Hu et al., 2019; KPMG, 2016; Pan et al., 2007).

Another essential strategy to be implemented in design and construction firms to enable full collaboration between the project's stakeholders is the digital transformation and automation (principle #4). Digitization and digitalization will promote a seamless, reliable, and traceable information flow and process integration, which is essential in OSC (Bertram et al., 2019; Razkenari et al., 2020). Furthermore, it will allow the automation of repetitive processes, reducing errors and execution time, which is also aligned with manufacturing processes and lean construction principles (Gusmao Brissi, Wong Chong, et al., 2021). BIM, digital platforms, software, computer system, automated equipment, IoT, among other tools are an integral part of this strategy (Gusmao Brissi, Wong Chong, et al., 2021; Sacks et al., 2010).

To enable some of the aforementioned strategies, design and construction companies need to develop training and knowledge management strategies (principle #5) to prepare the team to work with concepts and technologies such as lean construction, BIM, project management platforms, and above all, enhance skills on OSC for both design and construction professionals, which is line with Hwang et al (2018b). According to previous studies, equally important is the need to record and share lessons learned within a project based on a knowledge management method that encompasses all levels of the company (Lessing et al., 2015; Smith, 2011)

Lean construction practices (principle #6) are based on the relationship and collaboration between those involved in the construction processes. As lean construction involves a much more collaborative and thorough project planning and scheduling this strategy improves efficiency and productivity in OSC (Goh & Goh, 2019). Previous research has also indicated that schedule updates and planning adjustments are facilitated when lean construction techniques are combined with digital tools (Gusmao Brissi, Wong Chong, et al., 2021; Sacks et al., 2010).

In line with lean practices, improved monitoring and quality control (principle #7) result in continuous improvement, which is once again a common practice in the manufacturing industry and therefore more easily applicable to OSC than traditional construction. Previous literature has suggested that design and construction companies should work together and also involve manufacturers to streamline collection, feedback, and analysis of project data, especially data focused on the quality of processes and products (Sacks et al., 2010). Considering the more compressed schedule of OSC projects, it is fundamental, to deploy tools that allow real-time monitoring and data collection – RFID, IoT, etc. – and the integration of the collected data with the project information – BIM, project management platforms (C. Z. Li et al., 2018).

Because OSC involves more logistics and supply chain management (principle #8) considerations, monitoring of processes in OSC should be extended to these processes as well. In addition, as commented above and addressed by Lessing & Brege (2015), partnerships established in advance will contribute to reduce problems with delivery schedules. Therefore, logistical issues must be an integral part of the project process since the project onset (Bertram et al., 2019; Lessing & Brege, 2015), with design and construction teams collaborating to define the dimensions of modules and components, temporary reinforcements, lifting points, etc., for these issues impact the transport and handling of the components (Hwang et al., 2018b).

It is important to note that early stakeholders' involvement would promote (1) the exchange of inputs and alignment of customer's and technical requirements since the project onset, optimizing planning, time savings, and cost certainty, and even contributing to the balance between standardization and some level of customization, (2) reduced adversarial interactions throughout the project development.

Figure 6.2 shows the relationships between the principles to fully enable the changes. It should be noted, however, that the principles are not a ‘one-size-fits-all’ solution for design and construction companies, and it is essential to consider the importance of each company's context in terms or organizational network, direction and capability (Sexton et al., 2006).

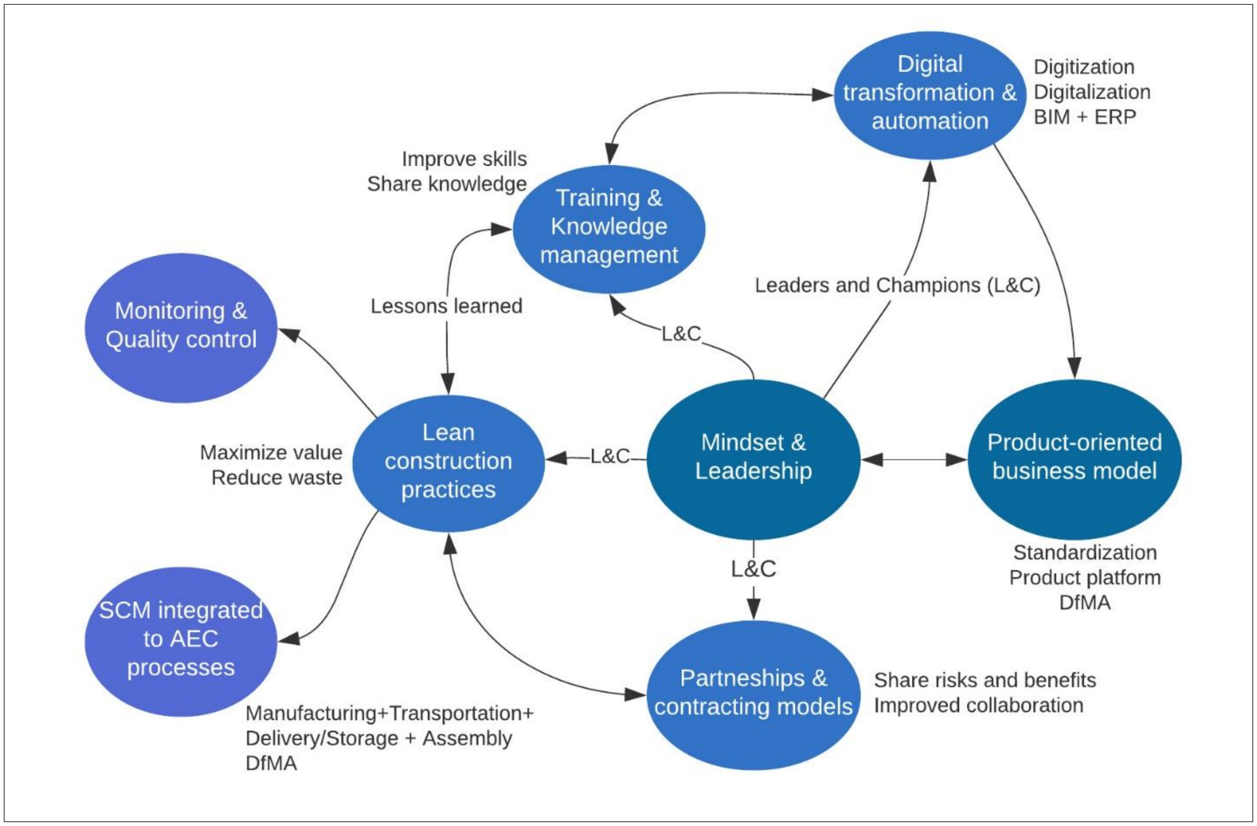


Figure 6.2. Scheme showing the interactions between the principles and keywords related to the changes

These principles allow design and construction companies in the US, especially small companies, to adjust to start using or increase the use of OSC in their multifamily housing projects, which is an innovative construction method with the potential to improve the efficiency and productivity of these companies (Bertram et al., 2019).

The final set of proposed principles is in line with the practices identified in the study developed by the WEF (2016) and indicates that such practices are even more relevant within OSC, as it involves a higher level of industrialization within the AEC industry. In fact, the data provided by the professionals who participated in the different phases of the research and the literature investigated corroborated the importance of the practices identified in the WEF study, more specifically in the OSC universe, but the data also indicated that although the AEC professionals were aware of the need for changes, they recognized that changes are taking place relatively slowly as it is difficult for companies (especially SMEs) to adapt to a dramatically different reality.

6.1.2 Emergence of new roles for design and construction companies

An industrialized housing construction process shares some similarities with making automobiles (Gann, 1996). This way, the role of a construction company would be quite similar to an automobile manufacturer. The car manufacturing process is developed during model design and the project already defines what type of equipment will be used and how the production flow on the assembly line will be. When a car design is completed, the factory already has a plan for how it will be produced. It is possible to assess the number of models manufactured per hour, the number of employees needed and also what types of equipment will be used.

Large construction companies adopting higher levels of OSC would act more like assemblers, managing the supply chain and just assembling or monitoring assembly on site (Bock & Linner, 2010). The construction companies would be involved in a more industrialized process, in which they would be responsible for bridging the gap between component manufacturers and designers, working with both from the beginning to define the component/module production process and the on-site assembly process. This entire process involves a "production and assembly system" that is defined jointly by the designers, manufacturers, and assemblers – GCs/CMs (Bock & Linner, 2010), hence the importance of the partnership between all involved parties. Because they are large, such companies will influence their partner supplier's strategies and will work together to achieve the standardization and interchangeability of projects, essential to allow a wide range of components to be assembled in different combinations to satisfy customer choices (Gann, 1996).

Smaller construction companies, which are more ‘craft-based’ and usually self-perform most of the construction work, would need to partner with component/module manufacturers that have a defined system, to improve their capabilities, work with their partners’ technology and focus more on assembling the systems on the construction site. This cooperative approach is based on trust and collaboration (Girmscheid, 2012)

Design companies would develop projects with well-defined manufacturing and assembly specifications, that is, strategies of design for manufacturing and assembly (DfMA) would be an essential part of the design. Working with product platforms and systems, designers would have to use design flexibility strategies to allow for mass customization of products without sacrificing aesthetics and functionality (J. Cao et al., 2021).

As noted by some participants of the study, the advance of industrialized construction, which begins with the growing use of OSC, may lead to the emergence of more vertically integrated companies, that is, the processes of design, engineering, manufacturing of construction parts, as well as the control of logistics and assembly on-site will all be performed by a single company (Lessing & Brege, 2018; Pullen et al., 2019).

6.1.3 More resilient design and construction companies

In addition to bringing innovation to their businesses, by implementing the changes recommended in the principles, design and construction companies will adjust four fundamental facets of a company: (1) strategy and business model, (2) people, organization, and culture, (3) technology, materials, and tools, and (4) processes and operations, which will increase their resilience to the turbulences of the construction market focused on multifamily projects.

Table 6.1 shows how the proposed principles allow the implementation of changes in line with the principles to promote resilience discussed in Chapter 2 (see 2.4.1).

Table 6.1. Alignment between the proposed principles and the principles to promote resilience

Principles	Companies' strategic changes	Resilience principle
Develop product-oriented business models	Develop a business focused on products that can be replicated in several projects.	Maintain diversity and redundancy
Promote leadership and mindset engagement with OSC principles	Leadership and trust facilitate interactions that result in social capital.	Foster social capital
Engage in partnerships and more innovative contractual models	Identify partner companies and reinforce the relationship and collaboration along the value-chain	Manage connectivity
	Partnerships with some selected partners provides alternatives in case of disturbances.	Maintain diversity and redundancy
	Adopt relational and innovative contracts and collaborative delivery methods	Foster social capital
Shift towards digital transformation	Implement a comprehensive strategy of ICT improvement involving digitization and digitalization, to streamline the information flow, ensure access to good quality systems and equipment, and secure alternatives when disturbances occur in a system.	Maintain diversity and redundancy Manage connectivity
Develop training and knowledge management strategies	Engage in knowledge and learning sharing that involves different professionals from different levels of the AEC industry	Manage connectivity Foster social capital Encourage learning and experimentation
Adopt lean construction practices	Focus on management approaches that increase the reliability of companies' processes while keeping efficiency.	Maintain diversity and redundancy
	Promote collaborative engagement and trust among the multiple parties of a project.	Manage connectivity Foster social capital
	Adopt continuous improvement strategies.	Encourage learning and experimentation
Improve monitoring and quality control	Work collaboratively in monitoring products and processes.	Manage connectivity
	Feedback data to project teams to identify and fix problems - adaptive management.	Encourage learning and experimentation
Integrate logistics and supply chain management with the AEC processes	Promote collaboration between design and construction teams to define the dimensions of modules and components, temporary reinforcements, lifting points, etc.	Manage connectivity Foster social capital
	Extend processes monitoring to logistics and supply chain management, including transportation, storage, and assembly strategies.	Encourage learning and experimentation

6.1.4 Sustainability as a result of higher OSC adoption

It is interesting to note that the professionals who participated in the different phases of this study made few references to the socio-environmental aspects of sustainability in the multifamily housing sector, both with regard to the factors that affect the use of OSC, and with regard to the changes to be implemented in design and construction companies. Focusing on the changes, some interviewees highlighted that sustainability would be a result of the adoption of OSC, not a driver to the adoption of OSC.

On the one hand, this confirmed what was investigated *specifically* in the literature on the use of OSC in multifamily projects, which focused much more on the importance of economic issues (Gusmao Brissi, Debs, et al., 2021); but on the other hand, it diverged from the trend of adopting more environmentally sustainable practices, which has been identified in several industrial sectors, including the AEC industry (Dodge Data Analytics, 2018), and more specifically the housing market (Dodge Data & Analytics, 2020a). As for OSC, research has demonstrated the benefits to sustainability resulting from its adoption (Aye et al., 2012; X. Cao et al., 2015; Quale et al., 2012; Wu et al., 2019).

6.1.5 Factors affecting the use of OSC in multifamily projects in the US at the Company level

The factors affecting the use of OSC in multifamily projects in the US were addressed in 3 phases of this study – Phase 1, 2 and 5. The factors identified in the literature review (Phase 1), which were refined during the Delphi Survey (Phase 2) were factors more generic, involving the company level, the market, and the society, and even the government. The factors discussed on the interviews (Phase 5) focused mostly on the company level of design and construction firms, so a total of 15 factors were identified as important at the company level of design and construction companies, affecting the use of OSC in multifamily projects in the US. The results are relatively well aligned with the study by Dodge & Analytics (2020b) that investigated the status of the use of prefabrication and modular construction in the US – not focused only on multifamily projects – Table 6.2.

Table 6.2. Comparison of most important factors validated in Phase 5 with the factors identified in the study by Dodge & Analytics (2020b)

Present Study	**Dodge & Analytics (2020)**	
Final list with the most important facts – company level	Positive Factors	Negative Factors
Customer's/social attitude and market culture	Increased client satisfaction + Owner demand	Owner is not interested in a modular approach
Climate, weather, and resilience	Enables year-round construction	-
Costs	Improved cost predictability and performance + Decreases construction costs	Costs too much
Design and coordination	-	-
Labor and experience	Workforce shortages Helps deal with skilled labor shortages	Availability of trained workforce to install prefabricated or modular components + Familiarity with modular construction
Management and Productivity	Improved productivity	-
Planning, processes, and business	Remaining competitive	Project types not applicable for prefabrication or modular construction Project delivery method prevents effective prefabrication or modular use planning Prefabrication not part of project design
Quality and product value	Improved quality	Quality concerns
Risks and financing	-	-
Safety and health	Improved safety performance	-
Supply chain and procurement	-	Availability of prefabrication shop locally or modular component manufacturers
Technology and innovation	-	-
Time	Increased schedule certainty + Improved project schedule performance	-
Transportation and logistics	-	-
Waste and pollution	Reduced waste generated	-

Note. (1) Based on the following results from Dodge &Analytics survey (2020b)*: Top Factors That Influenced Use of Prefabrication and Modular Construction/ Impact of Prefabrication and Modular Construction on Seven Key Performance Factors/ Top Factors That Will Influence Use of Prefabrication and Permanent Modular Construction in Next Three Years. (2) Based on the following results from Dodge &Analytics survey* (2020b)*: Obstacles to Increasing Number of Projects That Use Prefabrication and Permanent Modular Construction*

Costs, time and quality were among the most important factors discussed in this study and were practically a consensus when considering the use of OSC in multifamily projects, which is not different from traditional construction (McKinsey

Global Institute, 2017). This result was expected, as the literature has shown that the decisions on the method of construction to be adopted in a project are too often based on direct costs and not on value (Blismas et al., 2006), and that the production time of projects using OSC is certainly reduced, while the quality of products and processes is enhanced (Bertram et al., 2019; Dodge Data & Analytics, 2020b; Lessing et al., 2015).

Labor and experience were also identified as important factors by most participants from the different phases of this study. While OSC is more efficient and can help to deal with the workforce shortage in the construction industry, there is a concern about the experience and preparedness of professionals – such as designers and consultants – and suppliers to work with OSC (Fannie Mae, 2020; Stein, 2016). Still about experience and skills, the literature suggested that less skilled labors can perform offsite work that would require highly-skilled on-site subcontractors (Galante et al., 2017). It was also noted that, based on the results of phases 2 and 3, this factor varies in importance depending on the location of the project or the location of the design and construction company because, particularly in the construction phase, more remote places in the US suffers with shortage of skilled work (Dodge Data & Analytics, 2020b). However, there is a lack of literature focused on the impact of labor and experience on the adoption of OSC across the US.

Customer's/social attitude and market culture are among the main factors affecting the use of OSC adoption in multifamily projects (Gibb & Isack, 2003). As identified in previous research, "the owner's willingness to accept modular construction is one of the most critical decision-making factors for OSC projects" (Gusmao Brissi, Debs, et al., 2021, p. 16), which was acknowledged by the interviewees. In addition, to satisfy the needs of several dwellers of a building and minimize the lack of flexibility in OSC it is necessary to adopt strategies of mass customization (Gibb, 2001).

Supply chain and procurement was another important factor discussed in this study because OSC projects requires a higher level of integration between construction activities carried out in a factory with the on-site activities (Bertram et al., 2019; Niu et al., 2017). Therefore, procurement must involve suppliers early in the process, to ensure a close collaboration with the suppliers of OSC components (Lessing et al., 2015, 2005).

According to research and practice focused on OSC, to deal with factors related to *planning, processes, and business* in multifamily projects, it is important to adopt product-oriented business models (Bertram et al., 2019; Lessing et al., 2015) and more innovative and collaborative contractual and delivery models (Bertram et al., 2019).

As for factors related to *management and productivity*, the opportunities to improve productivity using OSC are massive, but due to the similarities between OSC and the manufacturing industry, AEC companies must engage in lean contruction practices to eliminate waste and to ensure the continuous improvement of their processes (Gusmao Brissi, Wong Chong, et al., 2021; Lessing et al., 2005). In addition, by adopting lean construction practices, problems related to *waste and pollution* are also tackled, further contributing to reducing the environmental impact of construction processes (Jaillon & Poon, 2014; Lessing et al., 2005).

6.2 Limitations

In addition to the limitations mentioned in Chapter 1 (Introduction) of this document, the following unexpected limitations were found during the course of this dissertation:

- The researcher had to interrupt the Delphi survey before an adequate level of agreement between participants was reached due to the high mortality in the sample participating in the survey and the low level of engagement of the remaining participants.
- Results from the Delphi survey, the online survey and the interviews might have been affected due to the fact that AEC professionals had their routines hardly affected by the COVID-19 pandemics.

6.3 Conclusions

The main purpose of this study was to develop principles to implement strategic changes in design and construction companies aiming at the successful use of OSC for delivering more affordable and sustainable multifamily buildings in the United States, which was achieved through a methodology that comprised five phases (1) literature review, (2) Delphi survey, (3) online survey, (4) proposition of principles, and (5) validation interviews. The results of this study support the advancement of the AEC industry by proposing strategies that will allow design and construction companies, particularly SMEs, to advance in the adoption of the OSC, which is a constructive method capable of boosting the performance of the AEC industry.

The eight proposed principles highlight the need for design and construction companies to shift towards product-oriented business models, which will require a change in the company's mindset and engagement in strategic partnerships. Digitalization and automation associated with training and appropriate knowledge management will facilitate the implementation of changes and prepare the teams for new business models, and processes and operations involving lean construction principles, efficient quality control and monitoring methods extendable to logistics and supply chain management, which is an integral part of OSC projects. The main changes associated to the principles were identified and are aligned with the principles to promote resilience.

It was interesting to note that the sustainability related principle was not deemed important during the validation phase. The interviewees noted that sustainability might be more of a consequence, rather than a principle or driving force for a higher use of OSC.

In addition to developing the principles and associated changes, the study also identified 18 factors as the most relevant factors affecting OSC adoption in multifamily projects in the United States, and also identified 15 of them as the most important at the company level – companies of design and construction, which are (in alphabetical order): customer's/social attitude and market culture, climate/weather/resilience, costs, design and coordination, labor and experience, management & productivity, planning/processes/ business, quality and product value, risks and financing, safety and health, supply chain and procurement, technology and innovation, time, transportation and logistics, and waste and pollution.

Besides helping to shape more efficient and resilient construction companies, by focusing on the multifamily housing market, the application of the proposed principles will contribute to building more affordable and sustainable housing in the United States. Finally, despite focusing on the multifamily housing market, which has its peculiarities, the proposed strategies can serve as initial reference for design and construction companies of other building sectors looking to improve their use of OSC in the United States.

6.4 Recommendations for Future Research

This study contributes to the advancement of the AEC industry but also raises questions to be explored in future research. Among the topics to be explored, the researcher highlights the following:

- Develop a cross-sectional study to evaluate the implementation of the proposed principles on the performance of design or construction companies and their projects. The performance evaluation would be based on the analysis of key performance indicators (KPIs) measured before and after the implementation of the changes.
- Investigate the role of BIM as a facilitator in the implementation of the eight principles, considering a large number of design and construction companies, especially small and medium-sized companies, still do not use BIM in multifamily projects.
- Further evaluate the difference in perceptions between professionals that had modular volumetric and those that had only non-volumetric OSC experience.
- Further investigate how the regional differences across the United States affect the use of OSC within the multifamily market of each region.
- Evaluate the applicability of the developed principles to other building sectors and other countries.

APPENDIX A. IRB EXEMPTION LETTER

IRB-2020-481 - Modification: 1. COVID-19 EXEMPT (MODIFICATION) Approval

do-not-reply@cayuse.com <do-not-reply@cayuse.com>

Fri 4/9/2021 3:06 PM

To: de Cresce El Debs, Luciana <ldecresc@purdue.edu>; Sara Gusmao Brissi <sgusmaob@purdue.edu>

PURDUE
UNIVERSITY

*****THIS LETTER IS BEING ISSUED DURING THE FACE TO FACE RESTRICTION ON HUMAN SUBJECTS RESEARCH STUDIES RELATED TO COVID-19. THIS DOCUMENT SERVES AS PROTOCOL APPROVAL FROM THE HRPP/IRB, BUT DOES NOT PERMIT FACE TO FACE RESEARCH UNTIL AN APPROVED UNIVERSITY COVID-19 RESEARCH SPACE SOP PERMITS RESEARCH OPERATIONS. ******

This Memo is Generated From the Purdue University Human Research Protection Program System, Cayuse IRB.

Date: April 9, 2021
PI: LUCIANA DE CRESCE EL DEBS
Re: Modification - IRB-2020-481
An analysis of the changes in design and construction firms using offsite construction in multifamily housing in the United States

The Purdue University Institutional Review Board has approved the modification for your study "*An analysis of the changes in design and construction firms using offsite construction in multifamily housing in the United States* . " The Category for this Exemption is listed below. This study maintains a status of exempt and an administrative check-in date of May 22, 2023. The IRB must be notified when this study is closed. If a study closure request has not been initiated by this date, the HRPP will request study status update for the record.

Specific details about your modification approval appear below.
Decision: Exempt
Research Notes: Keep in mind, all recruitment material must contain: the study title, IRB protocol number, name of PI, and contact information for research team.

What are your responsibilities now, as you move forward with your research?

Document Retention: The PI is responsible for keeping all regulated documents, including IRB correspondence such as this letter, approved study documents, and signed consent forms for at least three (3) years following protocol closure for audit purposes. Documents regulated by HIPAA, such as Release Authorizations, must be maintained for six (6) years.

Site Permission: If your research is conducted at locations outside of Purdue University (such as schools, hospitals, or businesses), you must obtain written permission from all sites to recruit, consent, study, or observe participants. Generally, such permission comes in the form of a letter from the school superintendent, director, or manager. You must maintain a copy of this permission with study records.

Training: All researchers collecting or analyzing data from this study must renew training in human subjects research via the CITI Program (www.citiprogram.org) every 4 years. New personnel must complete training and be added to the protocol before beginning research with human participants or their data.

Modifications: Change to any aspect of this protocol or research personnel must be approved by the IRB before implementation, except when necessary to eliminate apparent immediate hazards to subjects or others. In such situations, the IRB should still be notified immediately.

Unanticipated Problems/Adverse Events: Unanticipated problems involving risks to subjects or others, serious adverse events, and
noncompliance with the approved protocol must be reported to the IRB immediately through an incident report. When in doubt, consult with the HRPP/IRB.

Monitoring: The HRPP reminds researchers that this study is subject to monitoring at any time by Purdue's HRPP staff, Institutional Review Board, Research Quality Assurance unit, or authorized external entities. Timely cooperation with monitoring procedures is an expectation of IRB approval.

Change of Institutions: If the PI leaves Purdue, the study must be closed or the PI must be replaced on the study or transferred to a new IRB. Studies without a Purdue University PI will be closed.

Other Approvals: This Purdue IRB approval covers only regulations related to human subjects research protections (e.g. 45 CFR 46). This determination does not constitute approval from any other Purdue campus departments, research sites, or outside agencies. The Principal Investigator and all researchers are required to affirm that the research meets all applicable local/state/ federal laws and university policies that may apply.

If you have questions about this determination or your responsibilities when conducting human subjects research on this project or any other, please do not hesitate to contact Purdue's HRPP at irb@purdue.edu or 765-494-5942. We are here to help!

Sincerely,

Purdue University Human Research Protection Program/ Institutional Review Board
Login to Cayuse IRB

See Purdue HRPP/IRB Measures in Response to COVID-19
https://www.irb.purdue.edu/docs/IRB%20Covid-19%20Recommendations.pdf

APPENDIX B. DELPHI QUESTIONNAIRES – PHASE 2

Questionnaire 1 – Phase 2

1) Select from the list below all the relevant factors affecting the adoption of OSC in affordable and sustainable multifamily housing in the United States. You may include in your selection any factor you consider relevant and is not included in the list provided. Provide an explanation of the importance of each factor listed.

Material Provided: Table as shown below – columns in grey to be filled by the participants.

Factors	Factors selected by the participant	Explanation
Economic Factors		
Costs		
Time	XXX	XXX
Logistics	XXX	XXX
Quality	XXX	XXX
Design		
Risks		
Planning, strategy and processes		
Supply chain, manufacturing and procurement		
Productivity		
Technology and innovation		
Management		
Environmental Factors		
Environmental issues	XXX	XXX
Waste and pollution		
Materials	XXX	XXX
Energy and water efficiency	XXX	XXX
Site disruption		
Building IEQ and resilience		
Climate and weather conditions		
Social Factors		
Labor	XXX	XXX
Safety and health	XXX	XXX
Experience	XXX	XXX
Regulations and government incentives	XXX	XXX
Social attitude and market culture		
Client's attitude		
Aesthetics		
Value-added products		
Stakeholders alignment		
Influence on society and local communities		

2) List at least six relevant changes required to adjust design and construction firms to successfully adopt OSC for delivering affordable and sustainable multifamily buildings in the United States. Provide an explanation of the importance of each change listed.

Material Provided: Table as shown below – columns in grey to be filled by the participants.

Changes selected by the participant	Explanation
XXX	XXX
XXX	XXX
XXX	XXX
XXX	XXX
XXX	XXX
XXX	XXX
XXX	XXX

Organization and Respondent Profile

3) Describe your organization type *(select one)*:

☐ General contractor/ construction company ☐ Offsite construction manufacturer

☐ Architect firm ☐ Other (specify): ________________

☐ Engineering firm

4) Annual revenue of the company:

☐ less than $100 million ☐ $100–500 million ☐ $500–1000 million

☐ more than $1 billion ☐ do not know ☐ prefer not to disclose

5) How many years have you worked in the engineering/construction industry?

☐ 14 years or less ☐ 15–20 ☐ 21–25 ☐ more than 25

6) Approximately how many construction projects with significant use of OSC components has your company worked on (including present projects / proposed projects)?

☐ less than 5 ☐ 5–10 ☐ 10–20 ☐ more than 20

7) Approximately how many construction projects with significant use of OSC components have you worked on (including present projects / proposed projects)?

☐ less than 5 ☐ 5–10 ☐ 10–20 ☐ more than 20

8) Type of construction projects your organization has undertaken that involved modular components *(select all the apply)*:

☐ Infrastructure (roads, bridges) ☐ Commercial Buildings

☐ Institutional Buildings (schools, hospitals) ☐ Residential

☐ Other (please specify):___________________

Questionnaire 2 – Phase 2

1) Select the 10 most relevant factors from the list provided below (factors presented in order of frequency), which shows the results of my analysis based on your previous responses and the factors you have previously selected, so that you can compare them to the factors chosen by the other participants. Feel free to select factors different from the ones you have selected in the first questionnaire, but, please, provide explanations to justify your new selection. Feel free to also comment on the explanations presented in column 7 - Explanations aggregated based on the group comments. Note that the "factors" refer to the most relevant factors affecting the adoption of offsite construction for delivering more affordable and sustainable multifamily housing in the United States.

Material Provided: (i) an exact copy of the participant's responses to Q1; (ii) a table as shown below – column in grey to be filled by the participants.

Results based on the analysis of Questionnaire 1 + your answers to Questionnaire 1.

Table explanation: 1. The 3 sustainable categories/ 2. Factors Selected in order of frequency/ 3. Number of participants who selected each factor / 4. Number of participants who associated each factor to advantages to multifamily projects/ 5. Number of participants who associated each factor to challenges to multifamily projects/ 6. Number of participants who associated each factor with neither advantages nor challenges or that associated a factor with both advantages and challenges / 7. Explanations I have aggregated based on the group comments/ 8. Your Previous Selection/ 9. Here you will indicate the 10 factors you consider the most relevant and add your comments + explanations.

1. Category	2. Factors Selected	3. Frequency (n=15)	4. Advantages	5. Challenges	6. Neutral	7. Explanations	8. Your Previous Selection	9. Participant's Selection of Factors + Comments and Explanations
TBD	TBD					TBD	TBD	If you agree this is a relevant factor, make an "X" in this field and add your comments as desired.
TBD	TBD					TBD	TBD	If you agree this is a relevant factor, make an "X" in this field and add your comments as desired
TBD	TBD					TBD	TBD	
TBD	TBD					TBD	TBD	

2) Select the 10 most relevant changes from the list provided below, which shows the results of my analysis based on your previous responses and the changes you have previously selected, so that you can compare them to the factors chosen by the other participants. Feel free to select changes different from the ones you have selected in the first questionnaire, but, please, provide explanations to justify your new selection. Feel free to also comment on the

explanations presented in column 2 - Changes interpretation based on the participants responses and comments. The "changes" refer to the most relevant changes required to adjust design and construction firms to successfully adopt offsite construction for delivering more affordable and sustainable multifamily residential buildings in the United States.

Notes.

a. The changes listed by the participants in the 1st Questionnaire were analyzed and interpreted by the researcher. Therefore, similar changes were translated into the same nomenclature.
b. The changes listed by the participants in the 1st Questionnaire did not refer only to design and construction firms. Therefore, the researcher identified the different players related to the proposed changes.
c. The changes must focus on design and construction firms.

Material Provided: (i) an exact copy of the participant's responses to Q1; (ii) a table as shown below – column in grey to be filled by the participants.

Results based on Questionnaire 1 + your answers to Questionnaire 1

Table explanation: 1. Player that should promote change / 2. My interpretation of the changes based on the participants responses and comments/ 3. Your Previous Answers/ 4. Here you will indicate the 10 changes you consider the most relevant and add you comments + explanations.

1. Player	2. Changes interpretation based on the participants responses and comments	3. Your Previous Answers	4. Participant's Selection of Changes + Comments and Explanations
Designer	TBD	TBD	If you agree this is a relevant change, make an "X" in this field and add your comments as desired
Designer	TBD	TBD	If you agree this is a relevant change, make an "X" in this field and add your comments as desired
Designer/ GC	TBD	TBD	If you agree this is a relevant change, make an "X" in this field and add your comments as desired
GC	TBD	TBD	If you agree this is a relevant change, make an "X" in this field and add your comments as desired
GC	TBD	TBD	If you agree this is a relevant change, make an "X" in this field and add your comments as desired

Questionnaire 3 – Phase 2

1) Rank in order of importance each of the factors from the factors list below, by numbering each factor in order of importance, with "1" being the most important and "n" (highest number to be defined according to the total number of factors) the least important. Ties are not allowed. Provide comments explaining your rankings. Note that the "factors" refer to **the most relevant factors** affecting the adoption of offsite construction for delivering more affordable and sustainable multifamily housing in the United States.

Material Provided: (i) an exact copy of the participant's responses to Q3; (ii) a table as shown below (one for each panel) – columns in grey to be filled by the participants.

EXAMPLE: One Pared list of factors for each group based on Q2.

List with a maximum of 20 factors - one from each panel (1, 2 and 3)		
Pared list of factors based on group's responses to Q2 (varies according to each panel)	Factors rank (numbers indicating the importance, 1 = most important / "n" = least important)	Explanation
TBD	XX	XXX
TBD	XX	XXX
TBD	XX	XXX
TBD	XX	XXX
TBD	XX	XXX
TBD	XX	XXX
TBD	XX	XXX
…	…	…
TBD	XX	XXX

2) Rank in order of importance each of the changes from the changes list below, by numbering Rank in order of importance – most important at the top – each of the changes from the changes list below. Ties will not be allowed. Provide comments explaining your rankings. The "changes" refer to the **most relevant changes** required to adjust design and construction firms to successfully adopt offsite construction for delivering more affordable and sustainable multifamily residential buildings in the United States.

Material Provided: (i) an exact copy of the participant's responses to Q2; (ii) a table as shown below (one for each panel) – columns in grey to be filled by the participants. EXAMPLE:

List with a maximum of 20 changes - one from each panel (1, 2 and 3)		
Pared list of changes based on group's responses to Q2(varies according to each panel)	Changes rank (numbers indicating the importance, 1 = most important / "n" = least important)	Explanation
TBD	XX	XXX
TBD	XX	XXX
TBD	XX	XXX
TBD	XX	XXX
TBD	XX	XXX
TBD	XX	XXX
…	…	…
TBD	XX	XXX

Questionnaire 4 – Phase 2

1) Analyze the results, review your previous ranking of factors as you wish, and provide comments on eventual modifications. Note that the "factors" refer to **the most relevant factors** affecting the adoption of offsite construction for delivering more affordable and sustainable multifamily housing in the United States.

Material Provided: (i) an exact copy of the participant's responses to Q3; (ii) a table as shown below (one for each panel) – columns in grey to be filled by the participants. EXAMPLE:

Ranking of factors - one from each panel (1, 2 and 3)				
Rank position	Factors based on group's responses to Q3 (varies according to each panel)	Explanations aggregated based on the group comments in Q3	Rank position proposed by the participant in Q3	Modifications to previous responses + Comments
1	TBD	TBD	TBD	XXX
2	TBD	TBD	TBD	
3	TBD	TBD	TBD	
4	TBD	TBD	TBD	XXX
5	TBD	TBD	TBD	
…	…	…	…	XXX
n	TBD	TBD	TBD	

(iii) table with summary of statistics for the factors results.

Ranking of factors / changes - one from each panel (1, 2, 3 and 4)				
	Round 4 (n= TBD)			
Rank number	Percentage who mentioned	Mean rank (MR)	SD	Variance of rank $(MR - GM)^2$
1				
2				
3				
4				
5				
6				
7				
8				
9				
…				
n				
Totals				Round 4
Number of respondents (n)				
Grand Mean (GM)				
Kendall's coefficient of concordance (W)				
Chi-squared test (χ^2)				
Degree of freedom (df)				
Significance level (p)				

2) Analyze the results, review your previous ranking of changes as you wish, and provide comments on eventual modifications. The "changes" refer to the **most relevant changes** required to adjust design and construction firms to successfully adopt offsite construction for delivering more affordable and sustainable multifamily residential buildings in the United States.

Material Provided: (i) an exact copy of the participant's responses to Q3; (ii) a table as shown below (one for each panel) – columns in grey to be filled by the participants.

Ranking of changes - one from each panel (1, 2 and 3)				
Rank position	Changes based on group's responses to Q3 (varies according to each panel)	Explanations aggregated based on the group comments in Q3	Rank position proposed by the participant in Q3	Modifications to previous responses + Comments
1	TBD	TBD	TBD	XXX
2	TBD	TBD	TBD	
3	TBD	TBD	TBD	
4	TBD	TBD	TBD	XXX
5	TBD	TBD	TBD	
6	TBD	TBD	TBD	
7	TBD	TBD	TBD	
8	TBD	TBD	TBD	
9	TBD	TBD	TBD	
…	…	…	…	XXX
n	TBD	TBD	TBD	

(iii) table with a summary of statistics for the changes results: idem table from question 1, item (iii).

APPENDIX C. ONLINE SURVEY

Online survey instrument – imported from Qualtrics

Changes to be implemented in design and construction firms to successfully use offsite construction

Important note

Before you start, we would like to clarify that we are seeking input from AEC industry professionals **with experience in multifamily projects and offsite construction in the United States**. Examples of offsite construction include exterior prefabricated panels, prefabricated columns, and beams, bathroom pods, prefabricated MEP racks, volumetric modules of rooms, and even entire apartment units.

The study

This study is part of a Ph.D. dissertation whose purpose is to identify and provide principles on how to implement structural changes in design and construction companies aiming at the successful use of offsite construction for delivering more affordable and sustainable (see definitions below) multifamily residential buildings in the United States. To achieve this purpose, this phase of the research aims to rank the most relevant changes required to adjust design and construction firms to successfully use offsite construction in multifamily residential projects. The changes to be ranked have been identified by experts from the AEC industry in a previous phase of the research. Those participants have previous experience working with multifamily projects and offsite construction.

Definitions To ensure that all participants will have the same level of understanding of some terms used in the study, some definitions will be provided to the participants at the beginning of the survey.

<u>Affordable housing:</u> the study focuses on ways to make housing more affordable, especially rental housing in metropolitan areas of the United States, so this term includes the traditional affordable housing market, and market-rate housing as well.

<u>Multifamily buildings:</u> residential buildings with five or more housing units. They may include market-rate apartments, affordable housing units, student housing, senior housing, and even mixed-use buildings with residential units.

<u>Offsite construction:</u> offsite construction is the manufacture and pre-assembly of components, or modules in a manufacturing facility before installation into the construction site.

<u>Sustainable housing:</u> residential buildings that stand out for being economic, social, and environmentally sustainable, that is, they excel in minimizing the consumption of resources while fully meeting the needs of the dwellers.

What will I do if I choose to be in this study?

If you choose to participate in the study, you will be asked to confirm your participation by clicking on the YES bottom below and answering 10 questions.

How long will I be in the study?

The survey should last 10-15 minutes.

What are the possible risks or discomforts?

The risk in participating in this study should be no greater than you would encounter in daily life as an industry professional.

Are there any potential benefits?

There are no direct benefits to participating in this study. Indirect benefits to the architecture, engineering, and construction (AEC) industry include: supporting design and construction companies interested in implementing structural changes required to the effective use of offsite construction in multifamily residential projects in the United States and assist stakeholders in managing the factors that affect the adoption of offsite construction for delivering more affordable and sustainable multifamily housing projects.

Will information about me and my participation be kept confidential?

Yes, information about you and your participation in this study will be kept confidential. This project's research records may be reviewed by departments at Purdue University responsible for regulatory and research oversight.

What are my rights if I take part in this study?

Your participation in this study is voluntary. You can withdraw your participation at any time or skip any question you do not wish to answer.

Who can I contact if I have questions about the study?

Please contact Dr. Luciana Debs (ldecresc@purdue.edu), (765) 494-9196 with any questions.

To report anonymously via Purdue's Hotline see www.purdue.edu/hotline

If you have questions about your rights while taking part in the study or have concerns about the treatment of research participants, please call the Human Research Protection Program at (765) 494-5942, email (irb@purdue.edu) or write to:

Human Research Protection Program - Purdue University

Ernest C. Young Hall, Room 1032

155 S. Grant St.

West Lafayette, IN 47907-2114

Decision Do you want to participate in this survey?

○ I Agree

End of Block: Default Question Block

Start of Block: Block 1

Q1 Have you ever worked with multifamily projects in the United States?

○ Yes

○ No

Skip To: End of Survey If Q1 = No

Q2 Have you ever worked with offsite construction in the United States?

○ No, never and never worked on a project that has considered using it.

○ No, but worked in project(s) that have considered using it before.

○ Yes, I have worked with offsite construction before - between 1 and 5 projects).

○ Yes, I have worked with offsite construction - more than 5 projects.

Skip To: End of Survey If Q2 = No, never and never worked on a project that has considered using it.

End of Block: Block 1

Start of Block: Block 2

Q3 Based on your knowledge of offsite construction, please take the time to order **all the 18** changes below from **most (top) to least (bottom)** significant so that design and construction firms adapt to the successful use of **offsite construction (OSC)** in your multifamily buildings' projects.

______ Adopt enhanced management techniques, including lean construction practices.

______ Adopt more innovative contracting models sharing responsibilities, risks, profits and expenses.

______ Adopt more strict quality control standards for all the phases of the project, similar to the ones used in the manufacturing industry.

______ Allocate more time for improved design coordination, submittals analysis, planning and scheduling.

______ Design and build sustainable and efficient buildings, comprehending sustainable building materials specs, energy and water efficiency, higher indoor environmental quality.

______ Design for OSC since the project conceptualization.

______ Develop partnerships and collaboration with experienced manufactures and suppliers in OSC that work to create value to the product.

______ Establish continuous training and knowledge management strategies for the different hierarchical levels of the company.

______ Focus on the three dimensions of sustainability (social, economic, environmental) to improve the overall business performance.

______ Implement BIM technologies and adopt a higher level of detail for all projects to promote digital fabrication strategies and to improve delivery methods, procurement process, logistics, and even installation monitoring.

______ Plan for maximum waste reduction.

______ Plan for a reduced schedule with OSC and commit to the deadlines for the delivery of the various phases of the project (design, planning, preconstruction, construction, and close-out).

______ Plan logistics carefully considering size restrictions for transportation and travel distances from manufacturing facilities to the jobsite.

______ Plan to deal with labor unavailability and develop a strategy to deal with labor issues such as crew reduction, union trades, workers training.

______ Promote the standardization and simplification of processes and products by engaging in product platform and DFMA strategies.

______ Promote wider acceptance and understanding of OSC among AEC professionals and stakeholders and the government.

______ Understand OSC limitations and characteristics, how they affect the flexibility and creativity of design and work to improve the aesthetics and technical aspects of projects, and align them with owners' and customers' expectations.

______ Work with government, institutions and the AEC industry to incentivize the market by reviewing tax codes and creating incentives.

End of Block: Block 2

Start of Block: Block 3

Q4 How would you evaluate your knowledge of offsite construction?

- ○ Extremely familiar
- ○ Very familiar
- ○ Moderately familiar
- ○ Slightly familiar

Q5 How many years have you worked in the engineering/construction industry?

- ○ 5 years or less
- ○ 5–10 years
- ○ 10–15 years
- ○ 15–20 years
- ○ more than 20 years

Q6 How involved are you with decisions about use of offsite construction on projects of your company?

- ○ Main decision maker
- ○ Involved in decision making process, but not main decision maker
- ○ Provide information, but make no decisions
- ○ Not involved

Q7 Describe your organization type (select one):

- ○ Architecture firm
- ○ Engineering firm
- ○ General contractor/ construction company
- ○ Subcontractor
- ○ Other (specify): ____

Q8 In the last 5 years, approximately how many construction projects with significant use of offsite construction has YOUR COMPANY worked on? Consider significant use if the percentage of offsite construction is greater than 30% of the total contracted work for the construction project. Examples of offsite construction: exterior prefabricated panels, prefabricated columns and beams, bathroom pods, prefabricated MEP racks, volumetric modules of rooms and even entire apartment units.

- none
- less than 5 projects
- 5-10 projects
- 10-20 projects
- more than 20 projects

Q9 Provide **your work** location in the United States:

- Region 1: Northeast - Division 1: New England (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont)
- Region 1: Northeast - Division 2: Mid-Atlantic (New Jersey, New York, and Pennsylvania)
- Region 2: Midwest - Division 3: East North Central (Illinois, Indiana, Michigan, Ohio, and Wisconsin)
- Region 2: Midwest - Division 4: West North Central (Iowa, Kansas, Minnesota, Missouri, Nebraska, North Dakota, and South Dakota)
- Region 3: South - Division 5: South Atlantic (Delaware, Florida, Georgia, Maryland, North Carolina, South Carolina, Virginia, District of Columbia, and West Virginia)
- Region 3: South - Division 6: East South Central (Alabama, Kentucky, Mississippi, and Tennessee)
- Region 3: South - Division 7: West South Central (Arkansas, Louisiana, Oklahoma, and Texas)
- Region 4: West - Division 8: Mountain (Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming)
- Region 4: West - Division 9: Pacific (Alaska, California, Hawaii, Oregon, and Washington)

Q10 Provide the annual revenue of the company:

- less than $50 million
- $50- $100 million
- $100–500 million
- $500–1000 million
- more than $1 billion

- do not know
- prefer not to disclose

End of Block: Block 3

APPENDIX D. INTERVIEWS INSTRUMENT

Definitions

To ensure that all participants will have the same level of understanding on some terms used in the study, some definitions will be provided to the participants at the beginning of each interview.

Affordable housing: involves the traditional affordable housing market, and market-rate housing as well, focusing on ways to make housing **more affordable**, especially rental housing in metropolitan areas of the United States.

Offsite construction: offsite construction is the manufacture and pre-assembly of components, or modules in a manufacturing facility before installation into the construction site.

Sustainable housing: residential buildings that stand out for being **economic, social and environmentally** sustainable, that is, they excel in minimizing the consumption of resources while fully meeting the needs of the dwellers.

Important

The researcher will provide the interviewee in advance with a summary of the principles to support design and construction companies interested in adopting offsite construction in their multifamily projects in advance. The principles will be sent by email.

Organization and Respondent Profile

1) Select your organization type (select one):

☐ Architect firm ☐ General contractor/ construction company

☐ Engineering firm ☐ Other (specify): ______________________

2) How many years have you worked in the engineering/construction industry?

☐ 5 years or less ☐ 5–10 ☐ 10–15 s☐ 15–20 ☐ more than 20

3) Approximately how many construction projects with significant use of offsite construction has your company worked on (including present projects / proposed projects)?

☐ none ☐ less than 5 ☐ 5–10 ☐ 10–20 x☐ more than 20

If you answered "NONE" in the previous question, in how many projects has your company **considered** to use offsite construction (including present projects / proposed projects)?

☐ none ☐ less than 5 ☐ 5–10 ☐ 10–20 ☐ more than 20

4) How many of the projects from question 4 or 5 where multifamily projects (including mixed-use with multifamily units)?

☐ none ☐ less than 5 ☐ 5–10 ☐ 10–20 x☐ more than 20

Questionnaire

1) Does your company work with offsite construction in its multifamily projects? Why or why not?

Possible follow-up questions:

   a. Were the reasons for not adopting OSC in their multifamily projects related to the need to promote changes in the company?

2) Do you think the proposed principles (previously sent to the interviewee) cover the most important changes to be implemented in design and construction firms to facilitate the use of offsite construction in their multifamily projects?

Possible follow-up questions:

   a. Which propositions do you consider the most relevant? Why?

   b. Which ones to you think are the more difficult to be implemented?

3) **A. For companies using OSC in multifamily projects:** Has your company implemented or tried to implement any of those changes to adapt to working with offsite construction in its multifamily projects? If so, please discuss which ones were more aligned with the proposed principles.

Possible follow-up questions:

   a. Is there any important change implemented in your company that was not included in the principles?

   B. For companies not using OSC in multifamily projects: Which of those changes do you think would favor the use of OSC in your company's multifamily projects?

Possible follow-up questions:

   b. Which ones do you consider more aligned with your company's philosophy?

4) Do you think the use of offsite construction in **multifamily projects** requires companies to implement adjustments different from those that would be necessary in the case of using offsite construction **in other types of projects**? Why?

5) Do you think the changes implemented/ or that would be implemented in your firm to facilitate the use of offsite construction were/ or would be beneficial to the company as a whole, even if the company ended up not adopting OSC in its multifamily projects?

6) Do you think there are changes that should have been implemented, but that have not yet been or will be implemented in the next 5 years to allow the company:

   A. For companies using OSC in multifamily projects: to keep up with the increasing use of offsite construction?

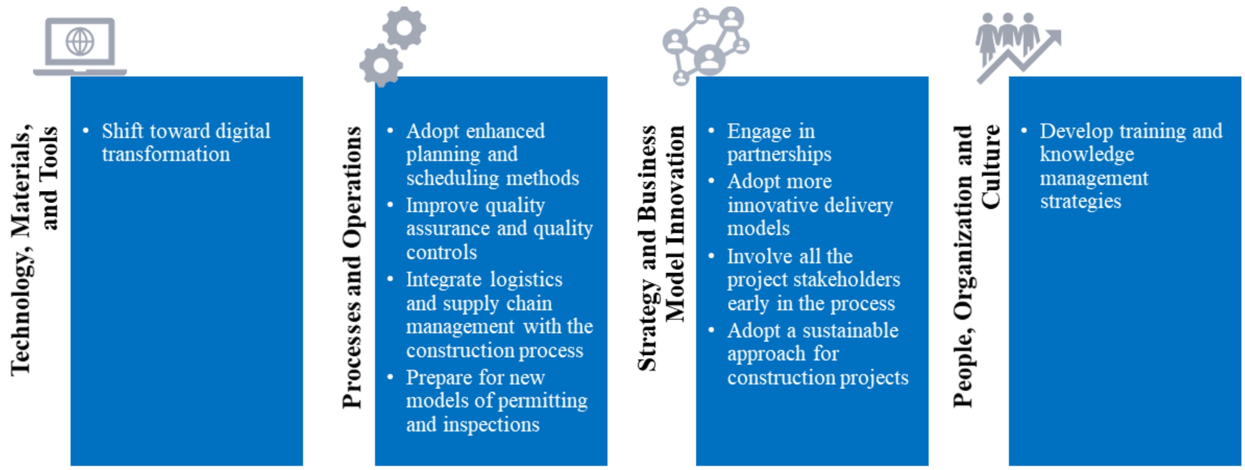
   B. For companies not using OSC in multifamily projects: to start using offsite construction in its projects?

7) Is there anything else you would like to add related to the use of offsite construction in multifamily projects?

APPENDIX E. DRAFT PRINCIPLES – SUMMARY SENT TO INTERVIEWEES

Draft principles to support design and construction firms in adopting offsite construction (OSC) in multifamily projects in the US

Below is a summary of the 10 principles drafted by the researcher, which consist of the most important strategies to be implemented in design and construction firms interested in adopting OSC in multifamily projects in the US. These draft principles are based on the results of 2 previous phases of this research. The principles focus on the company level and are grouped according to 4 topical areas defined by the World Economic Forum [1] : (1) technology, materials, and tools, (2) processes and operations, (3) strategy and business model, and (4) people, organization and culture – see the figure below. The principles are not presented in order of importance.



[1] World Economic Forum, & The Boston Consulting Group. (2016). Shaping the future of construction - A breakthrough in mindset and technology (Issue May). World Economic Forum.

1. Shift toward digital transformation

- This strategy would be implemented in both design and construction firms. It encompasses (1) digitization, that is, the conversion of information and data to digital format, and (2) digitalization, which involves improving processes by taking advantage of digital technologies and digitized data.
- BIM is a fundamental part of the digital transformation in design and construction firms, but a comprehensive strategy of ICT improvement should be implemented to ensure access to good quality systems and equipment, which would ensure a seamless real time information flow.

2. Adopt enhanced planning and scheduling methods

- OSC requires the development of detailed planning. In addition, the schedule should be as reliable as possible throughout the phases of the project.
- Design and construction teams should improve design-construction coordination to avoid late design changes, which would require more time than in conventional projects.
- Construction companies should deal with further aspects of supply chain management to ensure optimized logistics involving transportation, but mainly receiving, handling, and storing components.
- Adoption of an efficient project management software/platform by design and construction firms.

3. Improve quality assurance and quality control (QA/QC) processes

- Design teams should ensure the project is fully prepared to be manufactured and support manufacturing teams in prototyping parts of the project.
- Construction teams should ensure the quality of the on-site work to avoid serious problems of incompatibility/tolerances between the elements built on-site and the prefabricated components.
- Data should be collected during all phases of the project and promptly fed back to all the parties involved in the project to solve eventual problems identified. In addition, this data should be used to evaluate the performance of the project according to pre-defined key performance indicators (KPIs).

4. Integrate logistics and supply chain management with AEC processes

- Construction companies should integrate construction activities carried out in a factory with the on-site activities by carefully planning the project logistics since the pre-construction phase.
- Site logistics for OSC should include more detailed site layout, paying special attention to the placement of cranes or other heavy lift equipment, and areas to deliver and store large components.

5. Prepare for new models of building permitting and inspections

- Because of the integrative nature of OSC, designers, manufactures and GCs should work collaboratively in preparing the permitting packet.
- Depending on the level of OSC adoption and local regulations, most of the inspection could be performed in the factory, which can facilitate the process for construction companies.

6. Engage in partnerships

- Partnerships would facilitate the development and coordination of projects, improving the flow of information, and reducing problems that are common in the design – manufacturing – assembly process, which ultimately would impact on the duration, cost and quality of the final product.
- Focusing more specifically on the pre-construction phase, partnerships and collaboration with experienced manufacturers and suppliers, involving long-term contracts, would ensure an optimized supply process.
- Partnerships with software companies would benefit design and construction companies interested in engaging in the digital transformation process.

7. Adopt more innovative delivery models

- A special focus on delivery methods is paramount because the adoption of OSC requires a much more collaborative process that involves the project's multiple parties since the project onset.
- Integrated Project Delivery arises as the most appropriate type of delivery method for projects adopting high levels of OSC because it requires stakeholders to collaborate throughout the project, including an agreement on shared risks and rewards.

8. Involve all the project stakeholders early in the process

- Early stakeholders' involvement would promote exchange of inputs and alignment of customer's and technical requirements since the project onset, optimizing planning, time savings and cost certainty.
- Early information exchange between project participants would allow for a balance between standardization and some level of customization.
- This would also reduce adversarial interactions throughout the project development.

9. Adopt a sustainable approach for construction projects

- Design and construction firms should perceive OSC as an important ally to help companies to comply with the growing requirements of environmental sustainability.
- OSC is aligned with environmental sustainability initiatives: (1) reduces materials consumption, (2) reduces waste generation, (3) improves building quality, and (4) improves building performance.

10. Develop training and knowledge management strategies

- Designers and construction professionals should understand how to use prefabricated modular components: understand how modular prefabricated systems work, its restrictions, and how to adapt them to different projects.
- Designers should be trained to develop new designs using OSC components, complying with standards and code requirements.
- AEC professionals should be trained to use technology that support the adoption of OSC, like BIM and management platforms.
- Construction professionals should be trained to deal with new models of planning, procurement, job site management, and on-site installation.
- Design and construction firms should create strategies to facilitate information sharing and knowledge dissemination encompassing all the company levels.

APPENDIX F. PERMISSIONS

WORLD ECONOMIC FORUM

COMMITTED TO IMPROVING THE STATE OF THE WORLD

DATA USE AGREEMENT (the "**Agreement**")

Is made by and between:

WORLD ECONOMIC FORUM, a not-for-profit organization headquartered at 91-93 Route de la Capite, CH-1223 Cologny/Geneva, Switzerland, represented by its legal representatives (hereinafter the "**Forum**"),

and

SARA GUSMAO BRISSI, headquartered at 2804 Wyndham Court, West Lafayette, IN, USA, represented by its legal representatives (hereinafter referred to as the "**Company**").

Whereas the Forum publishes a comprehensive series of reports on its key events and standalone publications such as the Global Competitiveness Report, the Global Risks Report and the Global Gender Gap Report, which examine in detail the broad range of global issues, it seeks to address with stakeholders as part of its mission of improving the state of the world;

Whereas the Company wishes to use data from the Forum's published reports for its own publication(s);

Now therefore, the following has been agreed:

1. **Purpose:** The Forum has agreed to grant to the Company the right to use the below described data from one of the Forum's published report. In return, the Company agrees to use the data in strict compliance with the terms and conditions set forth in this Agreement and only for the non-commercial purposes unless the Data will be used for educational purposes.

Name of the report featuring the data (hereinafter the "**Report**")	**Shaping the future of construction - A breakthrough in mindset and technology**
Data requested (hereinafter the "**Data**")	**Figure 1: Industry Transformation Framework, p.9. The figure will be included in a PhD Dissertation, which will be published**

2. **Authorized Use of Data:** The Company is hereby granted the right to use, reproduce, compile, and integrate the Data in its own publication(s).

   The Company shall not use the Data for any other purpose than permitted by this Agreement. Any use by the Company of the Data outside the scope of this Agreement is subject to the Forum's prior written consent on the form, content and context, in each instance.

   The Company commits to provide to the Forum a copy of each of its publications and/or any other material using the Data, for the Forum's records.

3. **Intellectual Property.** The Forum retains the ownership of the Data and related rights. There is no transfer of intellectual property pursuant to this Agreement.

   The Company undertakes to source the use, reproduction, compilation or integration of the Data as follows: "Source: Shaping the future of construction - A breakthrough in mindset and technology, World Economic Forum, Switzerland, 2016" and to provide to the Forum a copy of any publication using the Data.

4. **No Warranty.** The Forum does not warrant the accuracy or completeness of the Data. The Forum disclaims any and all liability that may be based on the Data, errors therein or omissions therefrom. The Forum published data that is believed to be true and verifiable in good faith; however, the Company shall not be entitled to rely on the accuracy or completeness of the Data.

5. **Confidentiality.** The Company will treat the conditions of this Agreement as confidential and will not disclose the information contained herein to any third party without the prior written consent of the Forum.

   The Company shall keep confidential the Information related to the Forum Entities and/or entrusted to them by their members, partners and/or constituents, which are not in the public domain or which are not generally accessible. "Confidential Information" as used herein, means any and all information (including, but not limited to commercial, financial, technical and operational) which is disclosed to or otherwise obtained by the Company through or in connection with this Agreement.

   The obligation to maintain confidentiality shall be effective as of the first day the Forum made the Confidential Information available to the Company. The Company shall advise its staff and/or any third parties engaged by it of the confidential nature of the Confidential Information and shall be responsible for any breach by any of its staff and/or third parties. The Company will promptly notify the Forum of any unauthorized disclosure or release of Confidential Information and the Company will use its best efforts to retrieve the same and to otherwise mitigate or limit damages resulting from such unauthorized disclosure.

   The Company acknowledges that the breach of this clause by the Company or any of its staff and/or third parties engaged by it will cause irrevocable and irreparable prejudice to the Forum. Accordingly, in addition to any other remedy to which the Forum may be entitled, at law or in equity.

6. **Data Privacy.** "Personal Data" includes any information relating to (i) an identified or identifiable natural person and (ii) an identified or identifiable legal person that is protected under any and all applicable data protection laws or regulations, including without limitation the General Data Protection Regulation (EU) 2016/679 and/or Swiss Federal Act on Data Protection of 19 June 1992 (Status as of 1 January 2014) (hereinafter "**Data Protection Laws**") to the extent applicable. Both parties hereby commit to duly comply with all its obligations with respect to the Personal Data under the applicable Data Protection Laws as applicable to it as data processor and/or data controller, which arise in connection with the Agreement.

7. **Disclaimer.** The Forum does not endorse the content of the Company's publications using the Data and shall not be responsible or liable, directly or indirectly, for any damage or loss caused or alleged to be caused by or in connection with any such publication to third parties.

8. **Liability.** The Company shall be liable for the performance or non-performance of its obligations under this Agreement (in particular, the Company shall ensure that it does not infringe any third party's rights when publishing material using the Data).

9. **Legal Contingencies.** The Forum may take any legal measures it deems necessary and appropriate, including termination of this Agreement, if the Company violates the obligations and conditions of this Agreement.

10. **No exclusivity.** The Company acknowledges that no exclusivity is granted by the Forum regarding the use of the Data.

11. **The Forum's independence and intellectual integrity.** As a not-for-profit foundation, the Forum enters into agreements for the purpose of fulfilling the Forum and the World Economic Forum LLC's mission and not for the purpose of entering into a commercial relationship. As a result, thereof, the Company expressly acknowledges and recognizes this principle as key to interpreting its rights and obligations hereunder and to guide its conduct with respect to the use of the Data.

    The Forum's independence and intellectual integrity are of utmost importance to the preservation of the Forum's unique status and its close relationship with the entirety of its members, partners and constituents. The Company agrees to safeguard these principles and to refrain from any initiative linked to this relationship and the use of the Data that would conflict with these central principles.

    The Company shall cause its directors, employees, agent or subcontractors involved in the use of the Data to comply with the obligations set forth in this Agreement.

12. **Communication to third parties.** Due to the independent and non-commercial nature of the Forum, the Company agrees to coordinate with the Forum and obtain the Forum's prior written consent before entering into publicity initiatives linked to this Agreement and/or making any type of information related to the Forum to third party, including media.

13. **Use of the Forum's logo.** With the exception of the use of the Data authorized under this Agreement, the use of the Forum's name and/or logo by the Company on any type of document or in its promotional, marketing, advertising and/or public relations activities, whether printed or in electronic format, is not permitted.

14. **"No Partnership" Clause.** Nothing in this Agreement or in the business relationship between the parties shall be construed as creating or implying a joint venture, employment, franchise, agency, or any other form of legal association between the parties.

15. **Forum's events.** This Agreement does not grant any rights to the Company in relation to any of the Forum's events.

16. **Term.** This Agreement between the Company and the Forum shall be effective as of 31/07/2020 and is valid for a period of 12 (twelve) months.

17. **Termination**. This Agreement may be terminated, without cause and before the expiration of the term, by the Forum by giving a 30 (thirty) days written notice to the Company. Should the Company be in breach with any of its contractual obligations herein (whether partial or total breach), the Forum reserves the right to terminate this Agreement by sending a termination letter with acknowledgement of receipt, provided that the Company has not in the meantime corrected the default in a manner acceptable to the Forum. Should the Forum terminate this Agreement, the Company shall immediately (i) cease using the Data, (ii) use its best effort to retrieve all distributed published materials using the Data and (iii) destroy all such materials and provide the Forum with a proof of destruction acceptable to the Forum.

18. **Survival**. The provisions for "Intellectual Property", "Confidentiality", "Disclaimer", "Data Privacy", and "Use of the Forum's logo" shall survive the term of the Agreement.

19. **Governing law and jurisdiction.** The Agreement shall be governed by and interpreted in accordance with the substantive laws of Switzerland, under the exclusion of any international treaty and under the exclusion of any conflicts of laws principles. Exclusive place of jurisdiction shall be Geneva.

By signing this Agreement, the Forum and the Company conclusively evidence their consent to the terms and conditions stated herein.

WORLD ECONOMIC FORUM

Date: June 22, 2020 | 14:32 CEST

Signature: DocuSigned by: saadia zahidi A6C0BB32160F4CB...

Name: saadia zahidi

Position: Managing Director

THE COMPANY

Date: June 16, 2020 | 22:59 EDT

Signature: DocuSigned by: FC4831E8BE39459...

Name: Sara Gusmao Brissi

Position: PhD. Student at Purdue University

Date: June 17, 2020 | 07:41 CEST

Signature: DocuSigned by: Olivier Schwab 71AC41E0BAC14F3...

Name: Olivier Schwab

Position: Managing Director

APPENDIX G. DELPHI PANEL – PARTIAL RESULTS

Delphi survey – first round

The objectives of the first round were to (1) validate the list with all the factors affecting the adoption of OSC in multifamily housing in the United States, which were identified in the literature and provided to the participants by the researcher, and (2) identify the most significant changes required to adjust design and construction firms to successfully adopt OSC for delivering more affordable and sustainable multifamily buildings in the United States. Questionnaire 1 was sent to the 14 participants (see APPENDIX B) that agreed to participate and all of them provided their responses.

Factors

The list provided to participants of the first round of the Delphi survey was based on a preliminary list of factors from phase 1, which was slightly modified by the end of Phase 1 – review of the literature. The researcher decided to use the preliminary results of Phase 1 due to time constraints and also because the experts were asked to suggest the inclusion or removal of factors, which would require changes in the list of factors anyway. The participants would include in their selection as many factors as they wanted, and the result of the responses of round one was a list with 28 factors – only one factor was added to the original list: Financing (Table G1).

Table G1. Most significant factors selected by the participants – Delphi round 1 (*n*=14)

ID	Factors	Frequency
1	Time	13
2	Labor	13
3	Costs	13
4	Logistics	12
5	Quality	11
6	Waste and pollution	11
7	Design	11
8	Client's attitude and market culture	10
9	Planning, strategy and processes	11
10	Risks	10
11	Supply chain, manufacturing and procurement	10
12	Productivity	9
13	Safety and health	9
14	Aesthetics	9
15	Technology and innovation	9
16	Materials	8
17	Site disruption	8
18	Management	8
19	Climate and weather conditions	7
20	Experience	7
21	Regulations and government incentives	7
22	Energy and water efficiency	4
23	Building IEQ and resilience	3
24	Stakeholders' alignment	5
25	Influence on society and local communities	4
26	Environmental issues	3
27	Business model	1
28	Financing	1

Changes

Each participant listed a minimum of six changes required to adjust design and construction firms to successfully adopt OSC in multifamily buildings in the United States. As this first round worked as a brainstorming, a long list with 88 changes were suggested by the participants. The researcher analyzed and consolidated the changes resulting in a list with 55 changes (Table G2). The changes were grouped according to the different players to implement each change: designers, general contractors, manufacturers, owners/developers. Some changes that were only applicable to manufacturers and owners / developers were included in the consolidated list because they were selected by the participants, even though they had been warned that they should only select changes to be implemented in design and construction companies.

Table G2. Most significant changes selected by the participants – Delphi round 1

	Changes - interpretation based on the participants responses and comments – Delphi round 1
1	Adopt differentiated procurement strategies to reduce costs and simplify the logistics.
2	Adopt digital fabrication strategies, including tools like computer numerical control (CNC), 3D printing, etc.
3	Adopt enhanced management techniques, including lean construction practices.
4	Adopt more innovative contracting models sharing responsibilities, risks, profits and expenses.
5	Adopt quality control standards similar to the manufacturing industry.
6	Adopt strategies for just in time (JIT) supply chain and delivery model.
7	Adopt strategies for mass customization.
8	Align Architect/Engineer of Record (AOR/EOR) documentation with the required factory production documentation.
9	Align AOR/EOR documentation, fabrication and assembly with life safety and code requirements.
10	Align expectations and promote collaboration between the stakeholders.
11	Align lenders requirements with owner's schedule to ensure financing of early off-site fabrication expenses.
12	Allocate more time for improved design coordination, submittals analysis, planning and scheduling.
13	Commit to delivery deadlines for project's drawings and documentation.
14	Create a knowledge base that allows the team to obtain essential information for accurate design and detail OSC projects.
15	Create a knowledge base that allows your team to obtain essential information for accurate pricing, planning and scheduling in OSC projects.
16	Define standards and unit scales to create projects attending different income groups.
17	Demand changes in AEC educational and training programs, so as to foster the next generation of technology-enabled and industrialized construction minded workers and professionals.
18	Design and build sustainable and efficient buildings: sustainable building materials specs, energy and water efficiency, higher Indoor Environmental Quality (IEQ).
19	Design for OSC since the project conceptualization.
20	Detail design taking into account structural tolerances, joints and connections requirements.
21	Develop a strategy to deal with labor issues such as crew reduction, union trades, workers training.
22	Develop partnerships and collaboration with large material suppliers that work to create value reaching up into the supply chain and owning more manufacturing for OSC.
23	Develop partnerships and collaboration with the information technology industry which work to provide supply chain and integration tools that promote productivity in vertical or horizontal alignments.
24	Engage in vertical integration to better control the supply chain.
25	Ensure a detailed mechanical, electric, plumbing (MEP) and structural coordination.
26	Establish continuous training and knowledge management strategies.

Table G2 continued

	Changes - interpretation based on the participants responses and comments – Delphi round 1
27	Establish partnerships and build a network of experienced trades/subs in OSC. Cooperate with partners training.
28	Evaluate the learning curve of getting OSC expertise.
29	Focus on the three dimensions of sustainability to improve the business performance
30	Identify multiple regional suppliers.
31	Implement technology (BIM) to improve the procurement process and logistics and installation monitoring.
32	Involve suppliers and subcontractors in planning the job site work.
33	More intense use of control and monitoring technologies such as radio-frequency identification (RFID), internet of things (IoT), smart construction objects (SCOs), etc.
34	More intense use of robotics and automated equipment offsite and on-site.
35	Plan for maximum waste reduction.
36	Plan for reduced schedule with OSC.
37	Plan logistics carefully considering size restrictions for transportation and travel distances from manufacturing facilities to the jobsite.
38	Plan to deal with labor unavailability
39	Plan to deal with manufacturers unavailability.
40	Promote a wider collaboration and alignment among the project stakeholders: meetings, planning, expectations, contracts, schedule.
41	Promote the standardization and simplification of processes and products by engaging in product platform and design for manufacturing and assembly (DfMA) strategies.
42	Promote wider acceptance and understanding of OSC among construction professionals and firms by providing information on the characteristics, limitations, and potential benefits of OSC.
43	Promote wider acceptance and understanding of OSC among owners, developers, users and AEC professionals by providing information on the characteristics, limitations and potential benefits of OSC.
44	Research on OSC, investigate the market and the demand, calculate costs and benefits, and develop a business plan before transitioning or investing or adopting OSC.
45	Restructure business platforms to vertical or horizontal integration.
46	Review processes: procurement, logistics, construction/ installation, monitoring, and planning.
47	Support owners and developers in developing Total Cost of Ownership models based on the use of OSC.
48	Transition to digital delivery methods (3D models) with a more intense use of BIM and higher level of details (LOD 400) in 3D models to facilitate the manufacturing and construction/ assembly process.
49	Understand OSC characteristics and their interactions with manufacturing theory and practices.
50	Understand OSC limitations and characteristics and align them with owners' and customers' expectations.
51	Understand the limitations and characteristics of the OSC, how they affect the flexibility and creativity of design and work to improve the aesthetics and technical aspects of projects.
52	Work with government, institutions, and organizations to review government requirements, local codes and regulations as a way to promote OSC and create a national standard involving the International Code Council.
53	Work with government, institutions, and the AEC industry to incentivize the market by reviewing tax codes and creating incentives.
54	Work with municipalities to educated them on the characteristics and benefits of OSC.
55	Work with owners, developers, and suppliers to develop strategies of production scale, focusing on volume, repeatability, and affordability.

Delphi survey – second round

Questionnaire 2 (see APPENDIX B) was sent to the 14 participants but only 9 participants responded. The goal of this round was to reduce the number and validate the most important factors and changes according to the perceptions of the various experts' groups. Therefore, in this round the experts were grouped into three distinct panels. Due to the low number of participants in this round, panel 3 had only one participant (Table G3).

Table G3. Number of participants by panel – Delphi round 2 (*n*=9)

Group/ Panel	Participants field	Number of participants
1	Designers – Architects and Engineers	4
2	Construction professionals	4
3	Consultants and academics [1]	1

Note. (1) Only the professor participated in this round.

None of the lists of factors and changes resulting from the consolidated responses from each of the three panels had more than 16 factors and 12 changes.

Factors

The participants of each panel selected a maximum of 10 factors they considered the most relevant ones affecting the adoption of OSC in multifamily housing in the United States, from the consolidated list provided to them. The results are presented in Table G4.

Table G4. Pared list with the most significant factors by panel

Panel 1 - Designers		
Factor	Frequency	%
Time	4	100
Labor	4	100
Costs	4	100
Design	4	100
Technology and innovation	3	75
Risks	3	75
Quality	2	50
Logistics	2	50
Planning, strategy, and processes	2	50
Waste and pollution	2	50
Productivity	2	50
Panel 2 - Construction professionals		
Factor	Frequency	%
Time	4	100
Labor	4	100
Quality	3	75
Logistics	3	75
Planning, strategy, and processes	3	75
Safety and health	3	75
Client's attitude and market culture	3	75
Site disruption	3	75
Costs	2	50
Technology and innovation	2	50
Waste and pollution	2	50
Management	2	50
Climate and weather conditions	2	50
Experience	2	50
Aesthetics	2	50
Materials	2	50
Panel 3 - Professor		
Factor	Frequency	%
Time	1	100
Labor	1	100
Quality	1	100
Costs	1	100
Management	1	100
Climate and weather conditions	1	100
Experience	1	100
Design	1	100
Supply chain, manufacturing, and procurement	1	100
Business model	1	100

Changes

The participants of each panel selected up to 10 most relevant changes required to adjust design and construction firms to successfully adopt OSC in multifamily buildings in the United States. The changes were selected from the consolidated list with 55 changes provided to them. The results are presented in Table G5.

Table G5. Pared list with the most significant changes by panel

Panel 1 - Designers Change	Frequency	%
Promote the standardization and simplification of processes and products by engaging in product platform and DFMA strategies.	4	100
Design for OSC since the project conceptualization.	3	75
Implement BIM technologies and adopt a higher level of detail for all projects to promote digital fabrication strategies and to improve delivery methods, procurement process, logistics, and even installation monitoring.	3	75
Allocate more time for improved design coordination, submittals analysis, planning, and scheduling. Coordination focusing on MEP and structural coordination; alignment of AOR/EOR documentation with the required factory production documentation, assembly requirements and code requirements.	2	50
Develop partnerships and collaboration with large material suppliers and experienced trades/subs in OSC that work to create value reaching up into the supply chain and owning more manufacturing for OSC. Cooperate with partners training and involve suppliers and subcontractors in planning work.	2	50
Understand OSC limitations and characteristics, how they affect the flexibility and creativity of design and work to improve the aesthetics and technical aspects of projects and align them with owners' and customers' expectations.	2	50
Promote wider acceptance and understanding of OSC among AEC professionals and stakeholders by providing information on the characteristics, limitations and potential benefits of OSC. Align expectations and promote collaboration between the stakeholders.	2	50
Adopt enhanced management techniques, including lean construction practices.	2	50
Align lenders requirements with owner's schedule to ensure financing of early off-site fabrication expenses.	2	50
Work with government, institutions and the AEC industry to incentivize the market by reviewing tax codes and creating incentives.	2	50
Panel 2 - Construction professionals **Change**	**Frequency**	**%**
Allocate more time for improved design coordination, submittals analysis, planning, and scheduling. Coordination focusing on: MEP and structural coordination; alignment of AOR/EOR documentation with the required factory production documentation, assembly requirements and code requirements.	3	75

Table G5 continued

Change	Frequency	%
Develop partnerships and collaboration with large material suppliers and experienced trades/subs in OSC that work to create value reaching up into the supply chain and owning more manufacturing for OSC. Cooperate with partners training and involve suppliers and subcontractors in planning work.	3	75
Understand OSC limitations and characteristics, how they affect the flexibility and creativity of design and work to improve the aesthetics and technical aspects of projects and align them with owners' and customers' expectations.	3	75
Plan to deal with labor unavailability and develop a strategy to deal with labor issues such as crew reduction, union trades, workers training.	3	75
Promote wider acceptance and understanding of OSC among AEC professionals and stakeholders by providing information on the characteristics, limitations, and potential benefits of OSC. Align expectations and promote collaboration between the stakeholders.	2	50
Adopt more innovative contracting models sharing responsibilities, risks, profits, and expenses.	2	50
Plan for reduced schedule with OSC. Commit to delivery deadlines for project's drawings and documentation.	2	50
Adopt quality control standards similar to the manufacturing industry.	2	50
Plan logistics carefully considering size restrictions for transportation and travel distances from manufacturing facilities to the jobsite.	2	50
Work with municipalities to educated them on the characteristics and benefits of OSC.	2	50
Panel 3 - Professor		
Change	Frequency	%
Allocate more time for improved design coordination, submittals analysis, planning, and scheduling. Coordination focusing on: MEP and structural coordination; alignment of AOR/EOR documentation with the required factory production documentation, assembly requirements and code requirements.	1	100
Plan for reduced schedule with OSC. Commit to delivery deadlines for project's drawings and documentation.	1	100
Promote the standardization and simplification of processes and products by engaging in product platform and DFMA strategies.	1	100
Adopt enhanced management techniques, including lean construction practices.	1	100
Design and build sustainable and efficient buildings: sustainable building materials specs, energy and water efficiency, higher IEQ.	1	100
Plan for maximum waste reduction.	1	100
Focus on the three dimensions of sustainability to improve the business performance	1	100
Establish continuous training and knowledge management strategies.	1	100

Delphi survey – third round

Questionnaire 3 (see APPENDIX B) was sent to the 14 participants and 12 participants responded. The goal of this round was to rank the most important factors and changes according to the perceptions of the various experts' groups. Once again, the experts were grouped into three distinct panels (Table G6).

Table G6. Number of participants by panel – Delphi round 3 (*n*=12)

Group/ Panel	Participants field	Number of participants
1	Designers – Architects and Engineers	5
2	Construction professionals	5
3	Consultants and academics	2

Factors

The researcher provided the participants of each group with the correspondent pared lists of the most relevant factors affecting the adoption of OSC in multifamily housing in the United States and the participants in each group ranked these factors according to their perceptions. Based on the participants responses, the researcher performed statistical analysis using the software SPSS to get the descriptive statistics for the factors. The preliminary rank of the factors within each panel was obtained according to the mean values and was dependent on the level of agreement among the participants of each panel.

<u>Panel 1 - Designers</u>

The results and the preliminary rank of the factors affecting the adoption of OSC in multifamily housing in the United States according to the participants from panel 1 are presented in Table G7.

Table G7. Descriptive Statistics – Round 3 – Factors Panel 1 (*n*=5)

Factors	Rank position	Minimum	Maximum	Mean	Std. Dev.	Variance
Time	1	1.00	4.00	2.000	1.225	1.500
Costs	2	1.00	8.00	4.000	2.915	8.500
Quality	3	1.00	7.00	4.400	2.408	5.800
Risks	4	1.00	11.00	4.600	4.037	16.300
Productivity	5	4.00	11.00	6.600	3.578	12.800
Labor	6	5.00	9.00	6.600	1.817	3.300
Technology and innovation	7	3.00	10.00	6.800	2.490	6.200
Planning, strategy and processes	8	2.00	11.00	7.000	3.536	12.500
Logistics	9	4.00	10.00	7.400	2.408	5.800
Design	10	3.00	10.00	7.800	2.775	7.700
Waste and pollution	11	5.00	11.00	8.800	2.683	7.200
Kendall's coefficient of concordance (W)						0.363

Note. Lower ranks represent more significant factors.

The statistical results revealed that the Kendall's coefficient of concordance (Kendall's *W*) was low, which indicated a weak agreement among the participants responses and a low level of confidence in the ranks (Schmidt, 1997). According to Schmidt (1997) a strong agreement and a high level of confidence in ranks is obtained when Kendall's *W* is equal or above 0.7. Therefore, it was necessary to perform another round of Delphi survey to try to increase consensus among the participants.

Panel 2 - Construction professionals

The results and the preliminary rank of the factors affecting the adoption of OSC in multifamily housing in the United States according to the participants from panel 2 are presented in Table G8.

Table G8. Descriptive Statistics – Round 3 – Factors Panel 2 (*n*=5)

Factors	Rank position	Minimum	Maximum	Mean	Std. Dev.	Variance
Time	1	1.00	11.00	4.000	4.062	16.500
Planning, strategy and processes	2	1.00	11.00	4.200	4.324	18.700
Quality	3	3.00	12.00	5.000	3.937	15.500
Costs	4	2.00	13.00	5.600	4.336	18.800
Safety and health	5	1.00	15.00	7.200	5.215	27.200
Logistics	6	4.00	12.00	7.200	3.564	12.700
Client's attitude and market culture	7	1.00	16.00	7.600	7.301	53.300
Site disruption	8	3.00	14.00	8.800	4.147	17.200
Technology and innovation	9	8.00	12.00	9.200	1.789	3.200
Aesthetics	10	6.00	15.00	9.800	4.324	18.700
Materials	11	4.00	14.00	10.000	4.637	21.500
Labor	12	9.00	13.00	10.600	1.517	2.300
Waste and pollution	13	7.00	16.00	11.000	4.583	21.000
Experience	14	6.00	15.00	11.600	3.507	12.300
Management	15	9.00	15.00	11.800	2.387	5.700
Climate and weather conditions	16	7.00	16.00	12.400	4.159	17.300
Kendall's coefficient of concordance (W)						0.337

Note. Lower ranks represent more significant factors.

The statistical results for this panel's responses also revealed that the Kendall's coefficient of concordance (Kendall's *W*) was low, so it was necessary to perform another round of Delphi survey to try to increase consensus among the participants.

Panel 3 – AEC Consultants and academics

The results and the preliminary rank of the factors affecting the adoption of OSC in multifamily housing in the United States according to the participants from panel 3 are presented in Table G9.

Table G9. Descriptive Statistics – Round 3 – Factors Panel 3 (*n*=2)

Factors	Rank position	Minimum	Maximum	Mean	Std. Dev.	Variance
Design	1	1.00	3.00	2.000	1.414	2.000
Costs	2	2.00	2.50	2.250	0.354	0.125
Business model	3	1.00	6.00	3.500	3.536	12.500
Management	4	4.00	5.00	4.500	0.707	0.500
Time	5	2.50	9.00	5.750	4.596	21.125
Quality	6	4.00	8.00	6.000	2.828	8.000
Experience	7	6.00	7.00	6.500	0.707	0.500
Supply chain, manufacturing, and procurement	8	5.00	8.00	6.500	2.121	4.500
Labor	9	7.00	9.00	8.000	1.414	2.000
Climate and weather conditions	10	10.00	10.00	10.000	0.000	0.000
Kendall's coefficient of concordance (W)						0.688

Note. Lower ranks represent more significant factors.

The statistical results for this panel's responses indicated an almost strong agreement among the participants responses, since the Kendall's *W* was 0.688. However, the researcher decided to perform another round of Delphi survey to try to achieve an even higher level of consensus among the participants.

Changes

The researcher provided the participants of each group with the correspondent pared lists of the most relevant changes required to adjust design and construction firms to successfully adopt OSC in multifamily buildings in the United States and they ranked these changes according to their perceptions. The preliminary rank of the changes within each panel was obtained according to the mean values and were dependent on the level of agreement among the participants of each panel. It is important to emphasize that the lower the mean value, the higher the rank position of each change.

<u>Panel 1 - Designers</u>

The results and the preliminary rank of the changes required to adjust design and construction firms to successfully adopt OSC in multifamily buildings in the United States according to the participants from panel 1 are presented in (Table G10).

Table G10. Descriptive Statistics – Round 3 – Changes Panel 1 (*n*=5)

Changes	Rank position	Min.	Max.	Mean	Std. Dev.	Var.
Design for OSC since the project conceptualization.	1	2.00	5.00	3.200	1.304	1.700
Understand OSC limitations and characteristics, how they affect the flexibility and creativity of design and work to improve the aesthetics and technical aspects of projects and align them with owners' and customers' expectations.	2	1.00	9.00	4.200	3.421	11.700
Allocate more time for improved design coordination, submittals analysis, planning and scheduling. Coordination focusing on: MEP and structural coordination; alignment of AOR/EOR documentation with the required factory production documentation, assembly requirements and code requirements.	3	1.00	8.50	5.100	2.702	7.300
Transition to digital delivery methods (3D models) with a more intense use of building information modeling (BIM) and higher level of details (LOD 400) in 3D models to facilitate the manufacturing and construction/ assembly process.	4	2.50	9.00	5.700	2.540	6.450
Align lenders requirements with owner's schedule to ensure financing of early off-site fabrication expenses.	5	3.00	9.00	6.000	2.550	6.500
Develop partnerships and collaboration with large material suppliers and experienced trades/subs in OSC that work to create value reaching up into the supply chain and owning more manufacturing for OSC. Cooperate with partners training and involve suppliers and subcontractors in planning work.	6	1.00	10.00	6.000	3.536	12.500
Promote wider acceptance and understanding of OSC among AEC professionals and stakeholders by providing information on the characteristics, limitations, and potential benefits of OSC. Align expectations and promote collaboration between the stakeholders.	7	1.00	10.00	6.200	3.564	12.700
Promote the standardization and simplification of processes and products by engaging in product platform and DFMA strategies.	8	2.50	11.00	6.500	4.213	17.750
Adopt enhanced management techniques, including lean construction practices.	9	2.00	10.00	7.200	3.271	10.700
Implement technology (BIM) to promote digital fabrication strategies (including tools like computer numerical control (CNC) and 3D printing) and to improve the procurement process, logistics and installation monitoring.	10	3.00	11.00	7.500	2.915	8.500
Work with government, institutions, and the AEC industry to incentivize the market by reviewing tax codes and creating incentives.	11	2.00	11.00	8.400	3.782	14.300
Kendall's coefficient of concordance (W)						0.198

Note. Lower ranks represent more significant factors.

The low value of Kendall's coefficient of concordance indicated a very weak agreement among the participants responses, therefore it was necessary to perform another round of Delphi survey to try to increase consensus among the participants.

Panel 2 - Construction professionals

The results and the preliminary rank of the changes required to adjust design and construction firms to successfully adopt OSC in multifamily buildings in the United States according to the participants from panel 2 are presented in Table G11.

Table G11. Descriptive Statistics – Round 3 – Changes Panel 2 (*n*=5)

Changes	Rank position	Min.	Max.	Mean	Std. Dev.	Var.
Allocate more time for improved design coordination, submittals analysis, planning and scheduling. Coordination focusing on: MEP and structural coordination; alignment of AOR/EOR documentation with the required factory production documentation, assembly requirements and code requirements.	1	1.00	5.00	2.800	1.483	2.200
Develop partnerships and collaboration with large material suppliers and experienced trades/subs in OSC that work to create value reaching up into the supply chain and owning more manufacturing for OSC. Cooperate with partners training and involve suppliers and subcontractors in planning work.	3	1.00	6.00	4.200	2.490	6.200
Understand OSC limitations and characteristics, how they affect the flexibility and creativity of design and work to improve the aesthetics and technical aspects of projects and align them with owners' and customers' expectations.	2	1.00	9.00	4.200	3.962	15.700
Plan logistics carefully considering size restrictions for transportation and travel distances from manufacturing facilities to the jobsite.	4	3.00	9.00	5.400	2.510	6.300
Promote wider acceptance and understanding of OSC among AEC professionals and stakeholders by providing information on the characteristics, limitations and potential benefits of OSC. Align expectations and promote collaboration between the stakeholders.	5	1.00	9.00	5.400	3.647	13.300
Adopt quality control standards similar to the manufacturing industry.	6	3.00	10.00	5.600	2.881	8.300
Plan for reduced schedule with OSC. Commit to delivery deadlines for project's drawings and documentation.	7	2.00	9.00	6.200	2.775	7.700
Plan to deal with labor unavailability and develop a strategy to deal with labor issues such as crew reduction, union trades, workers training.	8	5.00	8.00	6.600	1.517	2.300
Adopt more innovative contracting models sharing responsibilities, risks, profits and expenses.	9	4.00	10.00	7.000	2.550	6.500
Work with municipalities to educated them on the characteristics and benefits of OSC.	10	4.00	10.00	7.600	3.286	10.800
Kendall’s coefficient of concordance (W)						0. 231

Note. Lower ranks represent more significant factors.

The low value of Kendall's coefficient of concordance indicated a very weak agreement among the participants responses, therefore it was necessary to perform another round of Delphi survey to try to increase consensus among the participants.

Panel 3 – AEC Consultants and academics

The results and the preliminary rank of the changes required to adjust design and construction firms to successfully adopt OSC in multifamily buildings in the United States according to the participants from panel 3 are presented in Table G12.

Table G12. Descriptive Statistics – Round 3 – Changes Panel 3 (*n*=2)

Changes	Rank position	Min.	Max.	Mean	Std. Dev.	Var.
Allocate more time for improved design coordination, submittals analysis, planning and scheduling. Coordination focusing on: MEP and structural coordination; alignment of AOR/EOR documentation with the required factory production documentation, assembly requirements and code requirements.	1	1.00	2.00	1.500	0.707	0.500
Establish continuous training and knowledge management strategies.	2	3.00	3.00	3.000	0.000	0.000
Promote the standardization and simplification of processes and products by engaging in product platform and DfMA strategies.	3	1.00	5.00	3.000	2.828	8.000
Adopt enhanced management techniques, including lean construction practices.	4	2.00	5.00	3.500	2.121	4.500
Plan for reduced schedule with OSC. Commit to delivery deadlines for project's drawings and documentation.	5	4.00	4.00	4.000	0.000	0.000
Design and build sustainable and efficient buildings: sustainable building materials specs, energy and water efficiency, higher IEQ.	6	6.00	7.00	6.500	0.707	0.500
Focus on the three dimensions of sustainability to improve the business performance	7	6.00	8.00	7.000	1.414	2.000
Plan for maximum waste reduction.	8	7.00	8.00	7.500	0.707	0.500
Kendall's coefficient of concordance (W)						0. 810

Note. Lower ranks represent more significant factors.

The high value of Kendall's *W* (0.810) indicated a strong agreement among the participants responses and high level of confidence in the rankings of factors, therefore it was not necessary to perform another round of Delphi survey.

Factors – Consolidated list and explanation

Table G13. Consolidated list based on all ranked factors – alphabetical order

Revised factors	ID	Cat.	What it involves
Costs		ECO	Initial costs; lower labor rates; cost reductions due to time savings; triple constraints Scope x Cost x Time with Quality; economies of scale; factory costs lower than field labor; total cost of ownership (TCO); labor, equipment and material costs; accelerated schedules increasing costs; efficiencies through automation in fabrication and erection yielding cost savings; cost certainty; reduced rework costs
Design and coordination		ECO	Suitability of design for OSC; flexibility to accommodate design changes; detailed design and construction coordination; DFMA strategies to realize industrialized construction; higher involvement of designers; higher level of details; alignment between design and shop drawings; standardization; passive solar and/or other innovative sustainable design strategies; module types and sizes; complexity of project design; interfaces, junctions, connections, and constructions tolerances; design affects time, cost and quality
Transportation and logistics		ECO	Transportation of large dimension components (size restrictions, regulations); transport infrastructure; delivery; site location, conditions, access, limitations, and approvals required; site layout (storage and equipment location); on-site and off-site storage; equipment requirements and availability; craning or hoisting requirements; urban infill work; effective timing/sequencing of operations and assembly; just in time delivery
Management and productivity		ECO	Collaborative management; involvement of top management in decisions (upfront support); integrated management; site management adjusted for OSC (team size, technology); production monitoring strategies; management and coordination across trades; integrated with technology to ensure coherent communication flows and minimize rework, productivity improvement through controlled environments, minimizing trade conflicts, overlaps through controlled JIT delivery and assembly; crew size vs production time; extra work in the field reducing efficiencies in the factory
Planning, processes, and business		ECO	Extensive and time-consuming planning; planning with expertise; well-defined and timely strategies; standardized processes; simplified construction processes; process integration; early key decisions; stakeholder's alignment, company's structure and culture; company's strategies and involvement with technology; business models; organizational readiness; project scope; project characteristics; vertically integrated or horizontally integrated companies, project repetitiveness and scalability; contracts and project delivery models
Risks and financing		ECO	Financing barriers; funding strategies; risks of volatility and escalation in projects costs; risks associated to safety and health; risks associated to severe weather conditions; single source for manufacturing (factory shutdown); bonding and insurance; stakeholders' risk profiles; balance between bold design and educated risks; contractual risks; uncertainty in lead time; capacity and reliability of delivery; risk profile of projects; contracts and project delivery models
Supply chain and procurement		ECO	Supply chain developed for large scale offsite fabrication; dependence on supplier demand; suppliers and manufacturers in the project area or within economical transport distance; factory production monitoring; understanding the supply chain and manufacturing resources; complex procurement process and coordination; manufacture and supply integration
Technology and innovation		ECO	Factory settings fosters innovation and implementation of technology; innovative construction methods; connected to the use of relevant information and communication technology; BIM and automation tools required to manage industrial scale of OSC programs; systems to track procurement and installation procedures; OSC favors the emergence of a niche industry that will improve the digital flow in construction involving management, DFMA and blockchain; investment in research and development; testing new materials; impact of adoption of new technologies

Table G13 continued

Revised factors	ID	Cat.	What it involves
Time		ECO	Time savings; reduced schedule; triple constraints Scope x Cost x Time with Quality; upfront time required; time in the field; concurrent scheduling; solving problems in the field (connections) are time consuming; efficiencies through automation in fabrication and erection can yield time savings; projects with schedule and time constraints/restrictions; lead time; completion time certainty
Climate, weather, and resilience		ENV	Reduced on-site work: less dependency on weather conditions affecting work progress, labor performance and workers' health and safety; no weather impacts on factory work; safety and security conditions of prefabricated and modular buildings - weather resistance (wind, storm, etc.)
Materials and practices		ENV	Materials damage; materials consumption and savings; recycled, reusable and renewable materials; material waste; standardization of material; rethink materials under an ecologically framed model; efficient purchasing and material use; material durability (important when transporting and handling finished modules); use of environmentally preferable materials; use of regional materials (reduction of negative impacts of transportation)
Site disruption		ENV	Strategies to minimize site disruption, noise, and pollution; impact on surrounding local communities' disturbance; impacts on environmentally sensitive sites; traffic congestion: just-in-time deliveries of large volume components have a negative impact on the traffic in the jobsite surrounding area; imposition of specific hours to on-site work
Waste and pollution		ENV	Waste management including recycling and reuse strategies; waste and pollution reduction; waste monitoring and control in a factory; strategies for minimizing and capturing waste streams and waste disposal; on-site noise and air pollution reduction
Aesthetics		SOC	Aesthetic solutions; constraints and limitations; depends on the designers innovative and opportunistic approach; lack of exciting design; monotony and repetitiveness in the aesthetics of buildings; depends on the project
Customer's/ social attitude and market culture		SOC	Clients requirements; customer's perceptions and image of OSC; reaction to innovative suggestions (owners, developers, etc.); depends greatly on design; stakeholder's principles, cultural perceptions and acceptance/resistance to changes and innovation due to a lack of knowledge and evidence that value is created; consumer-focused; culture of late design changes and modifications; OSC enthusiasts (younger society) vs OSC oppositionists (current workforce); if more sustainable, OSC can be well regarded by the market
Labor and experience		SOC	Changes in the role of workers (less masters in craftwork and more assembly workers); workers shortage; level of knowledge and expertise of the professionals; availability and accessibility of experienced/skilled professionals, suppliers, contractors and teams; experience based on overseeing experienced group leaders; training, preparing and developing workforce; union agreements; work conditions; tuning among laborers; increase gender participation through controlled work and safety environments; more permanent local hires; more qualified labor
Quality and product value		SOC	Improved quality and consistency (factory environment, repetitive work); higher precision; strict requirements for QA/QC programs; triple constraints Scope x Cost x Time with Quality; testing in a production environment; performance predictability; reduction of defects and damages; inspection and supervision requirements; issues with systems integration and components connections; quality defects cannot be readily solved in the field; field assembly process highly impact on quality; durability; integrity of the building and call backs; customer-driven values; poor quality results in the lack of market trust
Safety and health in construction		SOC	Safety and health in the production environment (factory); less work in the jobsite; issues associated with use of equipment to manage large loads; issues related to repetitive work

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