Knowledge Management Framework in Offsite Construction

RYAN E. SMITH

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Dedication

This thesis is dedicated to Lindsey Joy, my partner in life, my best friend, my love.

Declaration

This thesis, nor any part thereof, has been submitted for any other degree or professional qualification.

Significant collaborations with the following researchers should be declared as concepts, theories, applications, testing, and assessment of results concerning offsite construction knowledge management have been inspired by such: Dr. Robert Hairstans, Professor, Edinburgh Napier University; Dr. Ivan Rupnik, Associate Professor, Northeastern University; and Tyler Schmetterer, Managing Director, MOD X.

While recognition and declaration of these collaborations are important to this work, the codification of this research specific to inter-organizational knowledge management in offsite construction represented in this thesis is my own as an independent scholar.

Signed: [redacted] Date: 01 December 2023

Ryan E. Smith, Professor and Director
School of Architecture
University of Arizona

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Academic Outputs

Published research significantly associated with this PhD thesis includes the following:

Smith, R.E. and National Institute of Building Sciences (2015) *Off-site Construction Industry Survey 2014*. National Institute of Building Sciences.

Smith, R.E. and Tarr, K. (2019) "Offsite Industry Survey 2018". *National Institute of Building Sciences.*

Smith, R.E. and Rice, T. (2017) "Permanent Modular Construction: construction performance". In *Offsite Architecture: constructing the future*. Smith and Quale (Eds.) Routledge Taylor and Francis: 123-142.

Smith, R.E., Griffin, G. and Rice, T. (2017) Mass timber: evaluating construction. *Journal of Architecture, Engineering and Design Management*. Vol 14:1-2.

Smith, Ryan E. and Rupnik, Ivan. (2018) *5 in 5 Growth Initiative: research roadmap recommendations*. Modular Building Institute. Final Report. May 2018.

Hairstans, R. and Smith, R.E. (2018) Offsite HUB (Scotland): establishing a collaborative regional framework for knowledge exchange in the UK, *Architectural Engineering and Design Management*, 14:1-2, 60-77.

Smith, R., Runpik, I., Schmetterer, T. & Barry, K. (2022). "HUD Offsite Construction for Housing Research Roadmap". Office of Policy Development and Research, US Department of Housing and Urban Development. June 2022. https://www.huduser.gov/portal/publications/Offsite-Construction-for-Housing-Research-Roadmap.html Accessed: 08 April 2023.

The following academic and professional engagements have influenced this thesis:

2013 – present. Offsite Construction Council – Past Chair, National Institute of Building Sciences. Washington DC. 150 person OSC council part of congressionally focused on knowledge management, advocacy, and education with OSC resources posted to web. www.nibs.org/oscc

2020 – 2022. Offsite Construction Task Force – Co-Chair. Housing Development Consortium. Seattle, King County. Exemplarily OSC program to demonstrate value of OSC and develop best practice case studies. 15 person government, academic and industry group. https://www.housingconsortium.org/offsite-construction/

2018 – present. MOD X Founding Partner. Research and education advisory focused on international knowledge management in offsite construction. OSC knowledge exchange activities between companies and stakeholders (MODX Network) in the US, UK (Scotland), Japan, Sweden, New Zealand, Australia and Canada. The advisory group has provided consulting services under non-disclosure to dozens of OSC supply related companies and organizations. MOD X has also developed and disseminated over 60 open access video interviews and webinars with their network at: http://www.modx.network.

2017 – present. Built Environment Exchange (BeX). I have participated in this platform authored by Dr. Robert Hairstans at Edinburgh Napier University for student training and placements in sustainable construction companies and organizations internationally to foster accelerating change in construction culture. I have exchanged students with Edinburgh Napier University and University of Alberta students for international research experiences.

2018 – present. Ivory Innovations Advisory Board. US based housing affordability and innovation NGO laboratory and consortium that hosts the Hack-A-House, student housing innovation competition, Ivory Prize for Industry Innovation, an industry awards program, and a housing innovation incubator and investor boot camp. I serve on the board as an advisor for housing innovation in design and construction. https://ivory-innovations.org/

2019 – 2021. Editorial Board. International Journal of Industrialized Construction board. Editor-in-Chief, Mohamed Al-Hussein, University of Alberta. and co-chair of Modular and Offsite Construction Summit, an academic and industry offsite construction conference hosted by Dr. Al-Hussein's lab at the University of Alberta in 2015.

Abstract

Offsite construction (OSC) has demonstrated considerable benefits and potential to improve housing construction affordability and access. Despite the benefits, OSC has waned in significant uptake and adoption in the US and UK, in part due to the lack of knowledge sharing among stakeholders in the OSC industry. Therefore, this research aimed to develop an applied framework for non-project-based inter-organizational knowledge management (KM) in OSC. As a theory building project, the research employed a constructivist grounded theory methodology, wherein the researcher was an active participant in the study. Four research community contexts served as testbed case studies in which qualitative data was gathered and analyzed through theoretical sampling, memoing and coding, and constant data comparisons to reach theoretical saturation. Themes, concepts, and categories formed core theories through inductive means. The case study analysis was contextualized in secondary and primary research. The secondary research consisted of literature review of KM theory and OSC knowledge categories, characterization, needs and priorities. To verify and clarify the OSC knowledge needs, data was mined from four primary research activities conducted by the researcher. The knowledge needs and priorities analysis proffered a discrete intellectual contribution of the work. In the main, the case studies, framed by the secondary and primary research, formed a theoretical framework named TM3 - type, mode, measure model – a non-project-based inter-organizational framework for KM in OSC housing.

Table of Contents

List of Abbreviations

AECO	architecture engineering construction owner
AHJ	authority having jurisdiction
BeX	Built Environment Exchange
CCG	Campbell Construction Group
CCP	context, content and process
CM	construction manager
CoP	community of practice
CS	case study
DfMA	design for manufacture and assembly
ENU	Edinburgh Napier University
GC	general contractor
GT	grounded theory
HUD	US Department of Housing and Urban Development
HVAC	heating ventilation air conditioning
IP	intellectual property
KB	knowledge broker
KDM	knowledge dimensions matrix
KM	knowledge management
MBI	Modular Building Institute
MEP	mechanical electrical plumbing
MMC	modern methods of construction
NIBS	National Institute of Building Sciences
OSC	offsite construction
OSCC	Off-Site Construction Council
OSM	offsite manufacturing
PR	primary research
PTC	Project Technical Committee
SMTS	Stewart Milne Timber Systems
SR	secondary research
TM3	type mode measure model
TOE	technology, organization, and environment

CH 01 – Introduction

The motivation for this research was to increase housing affordability in the US and UK. Offsite construction (OSC) has been identified as a solution to address housing affordability and access because its application has brought about improved productivity, performance, quality, scheduling, and cost control, amongst other benefits (Barbosa et al., 2017; Smith & Rice, 2015). Despite these benefits, OSC has continued to wane in market uptake and adoption in the US and UK. OSC for housing includes the processes to develop, finance, design, plan, permit, manufacture, inspect, transport, and assemble components and subassemblies that have been prefabricated offsite (Figure 1.1), or literally remote to the jobsite in an enclosed environment (Smith & Quale, 2017, p. 264). OSC is innovation - a relatively new process and product that combines manufacturing and construction and requires knowledge outside of conventional wisdom in traditional construction practice (Davenport, 1993; Goulding & Arif, 2013).

Figure 1.1. Onsite assembly of offsite manufactured volumes. Source: (KieranTimberlake, 2010)

One reoccurring barrier to OSC growth is the lack of knowledge sharing across the sector, with barriers to knowledge exchange between organizations in the OSC industry, outside of project-based knowledge (Firestone & McElroy, 2003; Quintas, 2005). Knowledge management (KM) is "the process of creating, sharing, using and managing the knowledge and information of an organization(s)" (Girard & Girard, 2015, p.14). The research aim of this thesis was to overcome this gap in knowledge exchange by developing a non-project-based framework for inter-organizational KM in OSC for housing.

In identifying the research aim, the following research questions emerged:

- What is KM?
- Why is KM needed in OSC?
- What are the OSC knowledge categories and needs to be used in KM?
- How can knowledge be exchanged in OSC?

To answer these questions and develop the KM framework, this research had five objectives by which the research was structured and undertaken:

- Objective 01: Identify the research aim and methodology.
- Objective 02: Perform a literature review of KM theory and OSC knowledge from secondary research (SR).
- Objective 03: Mine data from primary research (PR) activities on OSC KM.
- Objective 04: Engage in case study (CS) analysis through grounded theory (GT) contextualized in objective 02 and 03.
- Objective 05: Develop a KM theoretical framework for OSC.

The first objective was to identify the research aim and research methodology. Leading up to identifying the research aim, the researcher participated in an inter-organizational KM research community through the National Institute of Building Sciences Off-site Construction Council (NIBS OSCC) and observed the need for improvement of knowledge sharing between OSC stakeholders. The researcher sought to support OSC industry participants to address the lack of knowledge exchange by studying the way to improve KM between organizations. After preliminary literature review of the character of construction knowledge and KM practices, the goal to develop a framework for OSC knowledge sharing and exchange was identified. Constructivist GT was selected as the research methodology (Glaser & Strauss, 2017), due to the nature of the research aim to develop a theoretical framework, the experience of the researcher using qualitative methods, and CSs of ongoing KM communities in which the researcher was participating. Chapter 04 covers the research methodology and tactics in detail.

The second objective for the research was to perform a literature review of SR sources. Following a systematic approach outlined by Jesson et al. (2011), the literature review occurred in two parts. SR01 is a literature review of KM theory (Chapter 02) that identifies the extant literature on KM foundations, strategies, tactics, and tools. SR02 OSC knowledge (Chapter 03) treats how OSC can address housing needs in the US and UK and how KM can support the uptake and adoption of OSC, including OSC knowledge characterization, categories, needs and priorities.

The third objective was to data mine PR of four projects conducted by the researcher as follows: PR01 - OSC Industry Surveys, PR02 - OSC Performance Studies, PR03 - OSC Strategic Growth Plan, and PR04 - OSC Housing Research Roadmap. This data mining effort triangulated the OSC knowledge types and needs from the SR02 literature review. Together, the literature review and data mining were conducted to confirm and contextualize the primary vehicle for this research – CS analysis. Chapter 05 reports on the outcomes of this third objective.

Objective four was to analyze four KM socialization contextual CSs (CS01 – CS04) using GT tactics. The cases were OSC research communities of practice (CoPs) in which the researcher was participating. The research used theoretical sampling, constant data comparisons, and theoretical saturation. Memos and coding techniques were employed to discover core theories considering concepts, context, and processes (CCP) (Pettigrew, 1985) of the CS environments. The CS findings were confirmed and contextualized in the PR and SR of the SR01 and SR02 literature review and PR01 – PR04 data mining. Chapter 06 covers the CS analysis findings.

Lastly, objective five was theory building. During the application of the CS GT tactic, referencing literature and data from concurrent research on OSC knowledge, a theorical framework emerged. This framework, named the Type, Mode, Measure Model (TM3), was intended for use in inter-organizational KM communities of practice for OSC housing. The framework was reviewed by the participants in the CS and peer researchers. In the end, the framework is a theory, developed through a constructivist GT research methodology. The framework is explained in Chapter 07 – Theoretical Framework.

The conclusion of the thesis, Chapter 08, outlines the findings from this research, with the associated knowledge contributions, potential impact, and shortcomings. The assumptions and limitations of the research are conveyed. The next step is discussed to confirm the credibility, applicability, transferability, dependability of the theory through continued application in various socialized contexts engaging OSC KM, thereby critiquing and refining the framework. In addition to proposing a framework for KM in OSC, this work provided additional intellectual contributions as follows:

- Demonstrated a precedent constructivist GT methodology, with its accompanying objectives and research design, that may be applied to construction and other inter-organizational domains.
- Provided a precedent of multiple CS analyses leveraging GT methodology and tactics.
- Identified knowledge types (tacit and explicit) and conversions that can be applied to construction and OSC.
- Qualified KM mode strategies and tactics that can be used to create and manage inter-organizational CoPs.
- Proposed ways to measure KM effectiveness and performance.
- Characterized, categorized, and prioritized OSC knowledge for US housing.

CH 02 – KM Theory Literature Review

The literature review of SR for this thesis is in two parts, with Chapter 02 covering KM and Chapter 03 OSC. Specifically, Chapter 02, this chapter, is a literature review of KM theory including KM foundations, strategies, tactics, and tools. Chapter 03, the next chapter, is a literature review regarding OSC in addressing housing affordability, KM specific to OSC, and OSC knowledge characterization, needs and priorities.

The present chapter is a literature review of SR concerning inter-organizational KM theory. In the first section, KM is introduced. The chapter then covers inter-organizational KM, a particular field of KM and the contingency dimensions of KM: type, mode, and measure. Knowledge types and conversion research are reviewed, and then modes of KM are discussed with a review of mode strategies, tactics, and tools. The section concludes with the concept of measuring the effectiveness of KM.

2.1 Knowledge Management Cycle

Paul Quintas (2005) states, KM “has been discovered rather than invented”. This signifies the dynamic nature of KM and that its emergence and evolution has been pulled into existence and maturity, not pushed as an invention or innovation to create value in the knowledge economy. KM is not to be confused with information. It is much more than codified knowledge, which might be more appropriately connected to the field of information management (Spender & Grant, 1996) or commercialized knowledge such as a product or process improvement that can be sold (Siegel et al., 2004) although these are both aspects of KM. Moreover, while we tend to consider knowledge a commodity or “thing” in western culture, there are various ways to understand and consider knowledge as a process, or more aptly put, “knowing”. KM from this perspective is less a noun to be exchanged on the market and more a series of verbs – personal, community, or organizational actions of continuous development and improvement. Therefore, KM involves several activities and steps (Firestone & McElroy, 2003), from discovering new knowledge to clarifying existing knowledge; categorizing, or codifying knowledge;

communicating, disseminating, and in some instances commercializing, knowledge; and finally, maintaining knowledge.

Established as a discipline since the early nineties (Nonaka et al., 1995), KM can be found in higher education courses taught in business administration, information systems, management, library studies, and information science (Nonaka & von Krogh, 2009). Furthermore, KM in research is used in fields of information and media, computer science, public health, and public policy, and several universities have KM master's degrees (Bellinger et al., 2004). Large companies, public institutions, and non-government organizations have KM efforts as part of their business. IT and human resources departments and consultants are emerging to advise organizations on establishing and maintaining KM practices. The goal of KM efforts is to improve performance, innovate for competitive advantage, share lessons learned, integrate, and continuously improve (Gupta et al., 2004). KM has a strategic emphasis on sharing knowledge across an organization and enableing organizational learning (Sanchez, 2006). The emergence of KM, in the context of supply chain involving multiple companies and horizontal ownership of knowledge through trans-organizational or inter-organizational KM, is relatively new and is spurred by the digital transformation of society that increases the speed of knowledge production and knowledge flow (Easterby-Smith et al., 2008).

Holsapple and Joshi (1999) performed a comparative analysis of ten KM frameworks and concluded that there is not a common or standard way of characterizing knowledge manipulation activities or the influences on the conduct of KM and that no individual KM framework subsumes others. Heisig (2009) compared 160 KM frameworks internationally across different industry sectors from 1995, when KM started appearing in publications, to 2003, when the quantitative and qualitative literature survey was performed by the scholar. Heisig's goal was to find commonalities and harmonization in a framework for KM. He found that the six more frequently (reaching 50% or more response) discussed groups of KM activities included, in order of priority: share (97), create (87), use (79), store (66), and identify (65).

Mohajan (2016) performed a comprehensive analysis of KM “cycles” (activities and frameworks) analyzing five unique proposals by Meyer and Zack (1996), Bukowitz and Williams (2000), McElroy (1999), Wiig (1993) and Dalkir (2005). Table 2.1 outlines the KM cycles from Mohajan (2016) with the associated activities in the cycle.

Table 2.1. KM cycles – activities. Adapted from: (Dalkir, 2011; Mohajan, 2016).

[redacted]

The published literature on KM generally is extensive. However, the literature on KM in construction is more modest, and KM in OSC is even more scant (Egbu & Robinson, 2005; Lindgren, 2020; Rezgui & Miles, 2011). The limited KM literature in construction outlines several activities that frequently exist in KM general practices as identified in Table 2.2.

Table 2.2. KM activities, sometimes referred to as sub-processes, and their associated descriptions. Adatped from: (Egbu & Robinson, 2005; Rezgui & Miles, 2011).

[redacted]

[redacted]

These activities are not necessarily sequential, although many KM practices suggest a natural progression of developing knowledge that is then solidified, disseminated, and applied to another context. Some KM activities may be more relevant to a KM iteration than others. The steps outlined should be viewed as a continuous cycle of KM improvement (Evans et al., 2015). According to KM researchers Davenport and Prusak (1998), "Knowledge management is an evolving practice. Even the most developed and mature knowledge management projects we studied were unfinished works in progress". Once knowledge is created or clarified, and then codified, communicated, and contextualized, it needs to be maintained continually. KM ensures that knowledge is not stagnant, rather dynamically improved upon by further study through research and/or practice. This cycle (Figure 2.1) also explains that KM is fundamentally concerned with the evolution of knowledge.

[redacted]

Figure 2.1. KM Activity Cycle. Source: (Egbu & Robinson, 2005; Rezgui & Miles, 2011).

2.2 Inter-Organizational KM

Literature in KM focuses on both intra-organizational and inter-organizational KM (Easterby-Smith et al., 2008). Further, research in KM in business, including design and construction, emphasizes the co-production of knowledge in action, and less on the development of knowledge that comes through traditional research outside of its application (Gibbons et al., 1994). These concepts will be evaluated in the following sections to define and operationalize KM for OSC.

KM literature emphasizes intra-organizational knowledge production and sharing within a single company or organization (Lobbecke et al., 2016). This is because KM, in the knowledge economy, emphasizes resource-based knowledge that is developed and shared within a discrete company or firm as a function of the need for unique competencies to gain competitive advantage and differentiation in the market (Penrose, 1959). Knowledge is key to innovation for enterprise, "building and creating knowledge as a necessary condition to survive" (Matusik & Hill, 1998). Therefore, in the knowledge economy, construction firms distinguish themselves from one another as heterogenous organizations. Much of the literature focuses on IT-enabled KM within a firm, building a culture of knowledge sharing, databases of knowledge and structures for personnel to exchange knowledge through workshops, groups, and lunch information sessions (Yang & Maxwell, 2011).

Construction, and OSC in particular, is an innovation domain with unique types of knowledge being fostered and created everyday through building design, manufacture, and construction practice. Therefore, OSC requires a level of inter-organizational coordination, collaboration, and even business partnership and business models that redefine what it means to be a distinct and heterogenous entity delivering a product or service for housing (Easterby-Smith et al., 2008). There has been an increase in recent years of research to investigate knowledge development and sharing processes across organizations and companies (Gerlach et al., 2015; Loebbecke et al., 1999; Newell, 2015). This inter-organizational knowledge co-development and sharing, or knowledge partnering, has increasingly become a competitive advantage of its own (Caldwell & Howard, 2010; Foss et al., 2010). Inter-organizational KM has been accelerated in recent years due to the advancement of information and communication technologies for both horizontal level knowledge exchanges in an industry (Feller et al., 2013; Hardy et al., 2003) as well as vertical supply chain knowledge partnership and alignments (Rollins et al., 2011).

Inter-organizational KM is not without challenges. There is still a need to balance the commercial interests of the individual organizations managing knowledge and the value that co-knowledge can provide for the end user and market (Gnyawali & Park, 2011). Although much of the current literature on inter-organizational KM is focused on strategic and social particulars of how knowledge partners create value, there is little that addresses the inherent competitive paradox of inter-organizational KM. However, there are frameworks emerging for inter-organizational KM in product development and software design literature that have been collected by Loebbecke et al. (2016) in “Managing inter-organizational knowledge sharing”. These frameworks demonstrate knowledge sharing “within an organization, while coordinating and controlling knowledge sharing between organizations” (p. 5). These frameworks can be applied to OSC industry, business, and practice to balance inter-organizational KM conflicting interests. The three “contingency dimensions” that emerged from this literature include the following:

1) Type - identifying the types of knowledge
2) Mode - determining the mode or method of knowledge transfer including sub-processes
3) Measure - evaluating the outcomes of the knowledge transfer

Milagres and Burcharth (2018), in "Knowledge Transfer in interorganizational partnerships: what do we know?", performed a literature review of ten articles on inter-organizational KM and found that there are three themes to KM between organizations. Theme 1 is the type of knowledge being transferred and its "macro-context". The context, according to the authors, comprises the factors of the macro environment that affect the motivation to form partnerships and transfer knowledge. Theme 2 is impacting factors to transfer. These include the drivers, structures, routines, relations, and absorption of the connection between organizations in the transfer. The authors also point out that organizations themselves and the individuals that make up the organizations have unique characteristics, motivations, and ways of learning that affect the knowledge transfer. Lastly, theme 3 is consequences, or how knowledge transfer is evaluated and how it affects the organizational performance of the participants. This article reaffirms the three contingency dimensions of inter-organizational KM proposed by Loebbecke et al.(2016) to identify the type of knowledge to be transferred, determine the mode (processes and subprocesses) of knowledge transfer, and then measure or evaluate the outcomes of the knowledge transfer. These three dimensions are situated in the context of the organizations proper and the macro-context of the market in which the intersecting organizations operate (Figure 2.2).

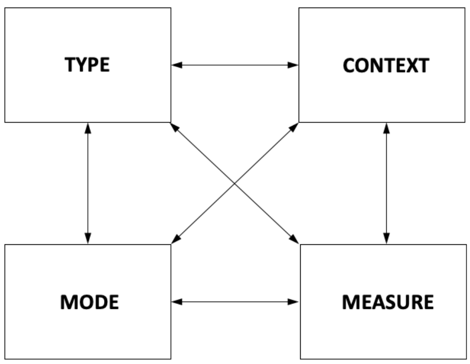

Figure 2.2. Type, mode and measure: contingency dimensions of KM related to the macro and organizational context. Adapted from: (Loebbecke et al., 2016).

The authors diagram their findings across the type, mode, and measure dimensions following on Bengtsson and Raza-Ullah (2016) and Oliver and Ebers (1998) (Figure 2.3). Under the type dimension, the researchers suggest six “anteceding” transfer processes: knowledge attributes, the macro context, inter-organizational factors, the source organization (supply), the recipient organization (receive), and individual factors. The process or mode of transfer is determined by “procedural governance” and “relational governance”. The measures of outcomes of the transfer include the effectiveness of the transfer itself (flow) and the performance effects for the participating organizations (impact). The authors suggest that “time” is a critical factor in the KM enterprise (Dyer and Hatch, 2006; Kotabe et al., 2003). KM and knowledge integration within the participating organizations can take a significant amount of time and are closely linked to culture, identity, trust, and interpersonal reliance. The actual KM process and mode that are used is not outlined by the authors; rather, they suggest that processes and subprocesses of KM need to be determined by the framework, including the knowledge type (attributes), participating organization make up, and structure and relations of the KM enterprise.

Interestingly, however, the authors claim that the antecedent (type) variables in their framework are more central or important than the outcomes (measure) and that the effectiveness of knowledge remains a marginal concern in literature. They do note and cite a growing body of literature regarding the performance impact of KM on the organizations participating in inter-organizational arrangements (Frankort, 2016; Grimpe & Sofka, 2016; Herstad et al., 2014; Tsai, 2009). Another point worth calling out from the article is the importance of “absorptive” capacity of the receiving individual, organizational and inter-organizational scales of the KM effort. The nature of what constitutes “absorption” at these various scales and that interplay is not conclusive; however, the presence and significance of “moderators” can serve as connections between the KM effort and the organizations that participate and are key for absorption capabilities.

[redacted]

Figure 2.3. Inter-organizational KM framework including type, mode, and measure. Adapted from: (Milagres & Burcharth, 2018)

The rest of this chapter will evaluate the three contingency dimensions of inter-organizational KM through a discussion of type, mode, and measure found in literature within and outside of construction research and practice. This literature review provides a contextualizing and confirming function for the GT CS analysis in Chapter 06 leading to the framework development.

Table 2.3 summarizes the literature review of Section 2.1 KM Cycle and Section 2.2 Inter-organizational KM.

Table 2.3. Sections 2.1 KM Cycle and 2.2 Inter-organizational KM literature review summary

Inter-organizational KM	
Topic	Confirmation Context for Objective 04 – CS Analysis
KM Cycle	• Creating, clarifying, categorizing, codifying, communicating, contextualizing, commercializing, and continuing knowledge • Emphasis on the *Evolution of Knowledge*
Inter-organizational KM	• Antecedents: *Contextual* factors that foster or limit inter-organizational KM including supply and receiving entities include individual, organization and inter-organizational factors. *Types and needs* of knowledge in inter-organizational KM. • Process: *Modes* of KM including KM cycle, procedures, relations, and moderators. • Outcomes: *Measure* the impact of the KM through effectiveness and performance.

2.3 Types of Knowledge

2.3.1 Explicit and Tacit Knowledge

There are two broad types of knowledge: explicit and tacit. Explicit knowledge is propositional knowledge, 'knowing-why' and 'knowing-what'. Tacit knowledge is personal, 'knowing-who' and procedural, 'knowing-how' (Lundvall & Johnson, 1994; Scheffler, 1965). Explicit knowledge constitutes an estimated 10% of our knowledge repository as humans, while tacit knowledge, fostered through experience and application of explicit knowledge, makes up 90% of our total knowledge base (Figure 2.4) (Bonner, 2000; Lee & Yang, 2000).

[redacted]

Figure 2.4. Types of knowledge – explicit 'know what'and tacit 'know how'. Adapted from: (Bonner, 2000; Lee & Yang, 2000).

Explicit knowledge is representative and can be codified and communicated. It is data, records, and documents. Examples of explicit knowledge artifacts include journal publications, databases, codes, books, websites, and videos. Explicit knowledge is easily shared as words or numbers. It is information that is specifiable and can be formalized in rules and procedures (Walsh & Dewar, 1987). Explicit knowledge therefore can be stored, controlled, and transferred easily.

Tacit knowledge is difficult to transfer by means of writing or speaking. It is embedded in people, organizations, societies, and cultures (Lam, 2000). It is based on experience, thinking, competence, and commitment (Polanyi, 1966). It is intuitive. Tacit knowledge is acquired through practice and personal experience. Tacit knowledge is more important, more embedded, and more meaningful for internalizing knowledge.

Egbu and Robinson (2005), construction researchers, elaborate further on the types of knowledge. Under explicit knowledge, 'knowing-what' is an accumulation of facts that can be broken down into pieces, and 'knowing-why' is scientific knowledge that underlies technological development and product and process advancements. Regarding tacit knowledge, ‘knowing-how’, including skills or capability to do something and the reason for the formation of industrial networks to enable organizations to share and combine elements of ‘know-how’ and ‘knowing-who’, involves information about who ‘knows-what’, and who ‘knows-how to do what’.

Explicit and tacit knowledge are not mutually exclusive or divergent; rather, knowledge exists on a continuum (Collins, 2010). It is the goal of society to make knowledge more explicit, to be transferred more easily and disseminated broadly. However, it is through tacit knowledge that individuals and organizations internalize knowledge and build capacity and capability and innovate. There are subcategories of tacit knowledge that offer further clarity.

- Implicit knowledge: remembered without practice or repetition, learned by interacting with another person (Davies, 2015).
- Procedural knowledge: learned by doing after conceptualizing through each unique context (Wasonga & Murphy, 2006).
- Embodied knowledge: physical objects resulting from imbued experience (Nonaka & Takeuchi, 1995).
- Expert knowledge: depth of knowledge, niche knowledge through experience (Bradley et al., 2006).
- Distributed knowledge: held by many individuals and organizations (Venkitachalam & Busch, 2012). The OSC industry is an example of distributed knowledge whereby the knowledge required to develop a housing project is held by many different disciplines and all their knowledge is needed, collectively, to realize successful project delivery.

A key component of KM is the sharing and exchange of explicit and tacit knowledge (Ganguly et al., 2019). Tacit knowledge is fundamental to the overall quality of knowledge exchange (Goffee & Jones, 2000; Smith, 2001; Wah, 1999). Effective transfer of tacit knowledge generally requires extensive personal contact, regular interaction, and trust (Goffin & Koners, 2011). It is highly dependent on emotional intelligence of the giver and receiver of tacit knowledge (Othman & Abdullah, 2012). Researchers indicate that tacit knowledge is revealed through practice in a particular context and transmitted through social networks (Schmidt & Hunter, 1993). Therefore, tacit knowledge is exchanged through a network of individuals within and between organizations in professional communities (Goffin & Koners, 2011). It relies on experience, and without it, tacit knowledge is not able to be transferred effectively (Lam, 2000). According to Polanyi (1966), there is no objective knowledge; it is all context-specific and therefore difficult to formalize and communicate. Seviby (1997) states in reference to Polanyi's (1966) concept of knowledge,

> "True discovery cannot be accounted for by a set of articulated rules or algorithms. Knowledge is public and also to a very great extent personal (i.e., it is contributed by humans and therefore contains emotions, 'passion'). The knowledge that underlies the explicit knowledge is more fundamental; all knowledge is either tacit or rooted in tacit knowledge."

Tacit knowledge is based on experience and what Nelson and Winter (1982) refer to as "routines", or ways of doing things. March and Simmon (1958) refer to routines as "programs" and suggest, "Most programs are stored in the minds of the employees who carry them out, or in the minds of superiors, subordinates, or associates" (p. 142. Therefore, capturing and then transferring tacit knowledge requires, in most cases, direct participation and inclusion in the context in where it resides (Tyre & von Hippel, 1997). This is sometimes referred to as "stickiness" by KM researchers (Spender & Grant, 1996; Szulanski, 1996) to explain the difficulty of making tacit knowledge explicit to codify and communicate knowledge.

2.3.2 Knowledge Conversion

Deetz (1992) claims that knowledge is a critical social product accomplished in communication and is an outcome of exchange. Explicit and tacit are not separate types of knowledge but in fact are on a continuum (Nonaka & von Krogh, 2009). Therefore, it is necessary to explore the concept of knowledge conversion (Nonaka, 1994), sometimes referred to as knowledge transfer, whereby knowledge is exchanged from one type to another. This interplay is described by Nonaka through the SECI model – socialization, externalization, combination, and internalization, as outlined in Figure 2.5 and listed below:

- Explicit knowledge may be transferred to another explicit form. This transfer is called 'combination'. An example is academic archival research whereby texts are compared, synthesized and new explicit knowledge is developed.
- Explicit knowledge to tacit conversion is called 'internalization'. Knowledge is a human function; therefore, people internalize the knowledge, making it part of their subconscious activity. An example of this transfer might include reading instructions to assemble furniture and then internalizing the operations after repeated activity.
- Tacit to explicit transfer is termed 'externalization', making that which is not easily explained or documented into a written or spoken form that is easy to communicate and disseminate. This transfer is the opposite of internalization. A construction worker, for instance, may have knowledge of how to install a window and then be asked to codify this knowledge in a training manual.
- Tacit to tacit transfer is called 'socialization'. This transfer tends to be informal and is often seen in apprenticeships. It is experienced in the very act of doing.

[redacted]

Figure 2.5. Knowledge conversion scenarios and terms. Adapted from: (Nonaka, 1994).

The SECI process involves interaction and iteration through the "knowledge spiral" that can result in an innovation – product or process. In the project-based industry of construction, the SECI model has seen success in applying to multiple iterations through several projects in learning and ultimately codification of practices and standards as ways of doing (Sexton & Barrett, 2003). Knowledge is often transferred through project participants' heads in construction, which challenges the SECI model from achieving final success in integration or adoption of knowledge (Senaratne & Sexton, 2008). Therefore, the technical system and hard-management strategies that are implemented are consistently and continuously balanced with soft-personalization strategies to foster KM. This is done through creation, dissemination, and adoption of knowledge through shared learning via multiple project-based experiences (Addis et al., 2016).

This review presented the idea that most knowledge, including knowledge in construction, is tacit. KM in OSC is challenging because KM stakeholders share a common culture and implicit communication that is difficult to share. In many cases, the OSC community is not aware of the knowledge they possess and therefore unable to externalize and/or socialize the knowledge (Brown & Duguid, 1998; Nonaka & Takeuchi, 1995). Also, the way in which knowledge amongst the community is managed is intertwined with their context – social, environmental, and economic. Therefore, transferring knowledge to members that join the community or to another organization is subject to the obstacles of not being applicable to the receiving party (Nelson & Winter, 1982). Lave and March (1993) indicate that knowledge can have varying degrees of being "situated" or tacitly embedded and difficult to share, or, as Quintas et al. (1997) state, "What (knowledge) has value and meaning in one context may have little or no meaning in another context."

Table 2.4 summarizes the findings from KM type dimension literature review covered in Section 2.3 and the contextualizing knowledge referenced in objective 04 – CS analysis covered in Chapter 06.

Table 2.4. Section 2.3 Types of knowledge literature review summary.

KM Type Dimension	
Topic	Confirmation Context for Objective 04 - CS Analysis
Explicit Knowledge	• 10% of human knowledge • Representative, codified knowledge • Context independent • Knowing "why" and "what" • Data, records, files
Tacit Knowledge	• 90% of human knowledge • Embedded, implicit, procedural, embodied, expert, distributed knowledge • Context dependent • Knowing "who" and "how" • Relies on routines and threatened by "stickiness" • Experience, thinking, competence, commitment
Knowledge Conversion	• SECI Model: socialization, externalization, combination, and internalization • Knowledge conversion is socialization (tacit – tacit), externalization (tacit-explicit), and internalization (explicit – tacit). • Knowledge spiral addresses innovation

2.4 Mode Strategies

This section presents the second contingency dimension in inter-organizational KM, modes. This dimension is investigated through a socialization framework called communities of practice (CoP). The first part of this section covers the theoretical basis in literature for CoPs and associated tools of triple-helix, knowledge hub, and knowledge production. The latter half discusses specific tactics identified in the literature for enacting CoPs. The end of the section will provide a summary utility of mode contingencies for inter-organizational KM.

2.4.1 CoPs

A specific strategy of inter-organizational KM mode is a CoP. This is group participation in an activity for which the participants share understandings that what they are doing means something in their lives and those whom they serve (Lave & Wenger, 1991, p. 98). Egbu (2005) indicates that a competitive advantage for construction organizations lies in their ability to build CoPs in relationships with their clients and other stakeholders and increase their tacit and collective knowledge capital through intensive socialization. Further, the author suggests that construction organizations must take seriously their ability to shift from intra-organizational accumulation-driven KM toward more sense-making and tacit understanding to drive knowledge capital.

Likewise, Carrillo et al. (2002,) in a study at Loughborough University, showed that CoPs are the most widely used technique for knowledge sharing in construction, outside of project-based knowledge exchange. The practice of the CoP, what the CoP does, is outlined by Saint-Onge and Wallace (2012). This includes accessing existing knowledge in explicit formats and bringing it forward to the CoP; exchanging knowledge through shared experience that is primarily tacit, but may also be explicit; validating knowledge with one another's shared and individual experience, and creating new knowledge through collaborating on innovations in new products or process improvements.

Rezgui and Miles (2011) outline a process of leveraging social capital in knowledge exchange via CoPs in the construction industry. In this way, communities are developing across organizational and project specific lines that share a common concern or have similar problems. Knowledge is shared through physical or virtual means both synchronously and asynchronously, on a continual basis (Rezgui & Miles, 2011:16). The authors illustrate how CoPs foster innovation in a particular sector or interest area (i.e., sustainability, building performance, lean construction, OSC, etc.) This has given way to additional organizations whose role is to provide a CoP, such as trade associations or advocacy institutes on behalf of these interests (i.e., NIBS, American Institute of Architects, Modular Building Institute (MBI), etc.).

Li et al. (2009) explain that CoPs require that the group exist for a duration of time amongst a changing participant pool to develop its own culture and communication methods. The community learns as individuals observe and model one another. Bandura (1977) states that observing behavior allows for a more efficient way of acquiring tacit complex skills knowledge than through personal trial and error. A CoP as a learning community, therefore, must develop a high level of trust among its participants to be functional (Kling & Coutright, 2003). CoPs can be located discretely or dispersed but are linked by common interests and goals. Learning communities must be monitored for effectiveness because they are susceptible to favoring sustaining relationships over learning (Wenger et al., 2002). In this way, there is a real risk of groupthink (Turner & Pratkanis, 1998), and/or becoming dormant and dysfunctional (Lencioni, 2012). Table 2.5 lists the benefits and challenges associated with CoPs.

Table 2.5. Benefits and challenges in CoPs. Source: (Wenger, 1998).

[redacted]

CoPs borrow from education, sociology, and social theory with a focus on socialization (learning of the group) and human capital development (learning of the individual) (Li et al., 2009). Research suggests that the members of the CoP participate in self-organized groups not because of a need to socialize, although that is an added benefit, but because of a need to engage in working, learning, and innovating (Brown & Duguid, 1991; Coakes & Clarke, 2005). According to Wenger (1998), a CoP is an entity that is characterized by three interrelated dimensions – mutual engagement, joint enterprise, and a shared repertoire (Figure 2.6). These three dimensions attempt to describe the interactions of individuals within the CoP. In addition to these three dimensions, Wenger proposes a qualitative evaluation metric with 14 indicators that, when present, suggest a definition and likely success of a CoP, as shown in Table 2.6. Interestingly, most of the indicators have 'mutual engagement' and 'shared repertoire' as key dimensions, and as Li et al. (2009) point out, only two address 'joint enterprise', or the process of people working toward a common goal. There has been little success to date in validating these indicators of CoP presence and success and the results have been difficult to interpret (Carlson, 2003; Hoernig & Seaons, 2017).

[redacted]

Figure 2.6. Three interrelated dimensions of CoPs. Source: (Wenger, 1998).

Table 2.6. Wenger's indicators of CoPs, including mutual engagement, joint enterprise and shared repertoire. Source: (Wenger, 1998).

[redacted]

[redacted]

The original three CoP dimensions of mutual engagement, joint enterprise, and a shared repertoire have been updated and clarified, using the terms 'domain', 'community', and 'practice' (Wenger et al., 2002; Wenger & Snyder, 2000). The domain is a common ground of minimal competence that differentiates members from non-members. Community is the social structure that facilitates learning through tacit interactions and relationships. Practice refers to shared repertories of resources that include explicit documentation (Li et al., 2009). Wegner and colleagues claim that CoPs can optimize the creation and dissemination of knowledge when these three dimensions are present.

Li et al. (2009) suggest two additional dimensions to realize a mature CoP. The first is a leader/champion, a person well respected in the organization who is responsible for spreading the word, recruiting, and providing resources for the group. The second is a facilitator that is responsible for the day-to-day activities of the CoP. It is suggested that this person should understand the overall mission of the organization and be well connected with members (Li et al., 2009). In CoP studies, the facilitator role has been deemed the critical link: if the role is absent or if the facilitator fatigues, this most often leads to CoP failures (Bresler & Ardichvili, 2002; Lathelean & May, 2002; Pereles et al., 2002). Sometimes the leader is the facilitator, while in other cases they are separate roles (Chua, 2006; Pereles et al., 2002). This division of responsibility is based on several factors, including the size of the group, the geographical location of the members, the topic, and the overarching goals of the CoP. Table 2.7 lists the CoP dimensions of domain, community, practice, leader, and facilitator.

Table 2.7. CoP dimensions. Source: (Wenger et al., 2002)

[redacted]

Researchers claim that CoPs can either emerge spontaneously or be intentionally fostered, structured, and created to cultivate the qualities of a CoP and thereby enhance their competitiveness and effectiveness (Saint-Onge & Wallace, 2012; Wenger, 2002). Formal CoPs may include membership through fees with a central authority organization (i.e., university consortium, government laboratory, industry) (Coakes & Clarke, 2005). These types of formal CoPs might be better classified as “affinity networks” (Weber & Kaplan, 2003), including trade associations that focus on advocacy primarily and KM secondarily. Table 2.8 outlines four different types of CoPs (Coakes & Clarke, 2005; Saint-Onge & Wallace, 2012) and their associated characteristics, benefits, and problems. The CoPs range from intra-organizational (internal) CoPs, network organizational CoPs, formal network CoPs, and self-organizing CoPs.

Table 2.8. Characteristics of different types of CoPs. Source: (Coakes & Clarke, 2005).

[redacted]

[redacted]

2.4.2 Triple-Helix

Formal types of CoP networks include the triple-helix, hub, and mode 2 knowledge production frameworks. These examples were studied in the literature due to their relevance to the CSs in this thesis that were being evaluated by the researcher which used a university partnership approach. Each are presented below:

Etkowitz and Leydesdorff (1995) first theorized the triple-helix framework with the aim of fostering innovation. In the triple-helix (Figure 2.7), university, industry, and government interact as an innovation core for new ideas and solutions to economic development in the knowledge enterprise and knowledge society (Leydesdorff, 2012). The triple-helix blurs the traditional roles of the three entities: university as the source of knowledge production, industry as the primary vehicle of commercialization, and government toward regulation (Etzkowitz, 2003). This framework has also given rise to third-party organizations or partnering entities within one of the three parties such as research parks, centers, laboratories, incubators for spin off companies, hubs, networks, and CoPs (Viale & Etzkowitz, 2010). The triple-helix has been widely adopted by government agencies internationally and represents a bilateral knowledge exchange between the entities and their personnel.

[redacted]

Figure 2.7. Triple-helix of innovation is a knowledge core integrating university, industry, and government. Adapted from: (Etkowitz & Leydesdorff, 1995).

In the later part of the 20th century until today, Youtie and Shapira (2008) argue that the university is experiencing an identity change. Although the university continues to serve as a knowledge storehouse and a supplier to the economy, it is also now a knowledge hub (Figure 2.8). In this new role, it seeks to animate indigenous development, new capabilities, and innovation, especially within its region (Newlands 2003; Shapira & Youtie, 2004). In this function, the university spans industry, government, and society. It is integrated in an intelligent region and promotes indigenous development and new capabilities. Youtie and Shapira (2008) conjecture that “in an increasingly knowledge-based environment, high-performing institutions are those which have capability not only to develop, acquire and use codified knowledge, but also to effectively advance, distribute, and recombine tacit knowledge” (p. 1190).

[redacted]

Figure 2.8. Transformation of the university's role in society. Adapted from: (Gibbons et al., 1994)

Gibbons et al. (1994) explain that historically traditional knowledge creation, called mode 1, is the Newtonian model of inquiry that follows sound principles of scientific method. In this mode, the cognitive and social norms determine what counts as a significant problem and who is allowed to practice the solving of such problems (i.e., universities). Mode 1 is historically created and developed by and for the sciences. By contrast, mode 2 knowledge production is created in the context of application. While mode 1 is disciplinary and homogeneous, mode 2 is transdisciplinary and heterogeneous. Organizationally, mode 1 is hierarchical and self-preserving, while mode 2 is flexible and transient. Mode 1 employs peer review based on standards of practice. On the other hand, mode 2 is socially accountable and reflexive. It employs a temporary set of actors collaborating on a problem defined in a specific context (Gibbons et al., 1994, pp. 1-16). Mode 1 excels in explicit knowledge exchange while mode 2 thrives in tacit knowledge arenas (Gibbons et al., 1994, pp. 17, 19, 24-26, 168). Modes 1 and 2 are compared in Table 2.9.

Table 2.9. Dimensions of knowledge production and attributes of knowledge production modes. Adapted from: (Gibbons et al., 1994).

[redacted]

2.5 Mode Tactics

This subsection emphasizes tactics from KM scholars that can be used in CoP KM practice. The following tactics are reviewed below: cross-project, bi-Lateral exchange, contingent worker, knowledge broker (KB), and shared learning.

2.5.1 Cross-Project

Leseure and Brookes (2000) define cross-project KM as a subset of knowledge management that focuses on the transfer of knowledge across different projects using a variety of strategies depending on the organizational construct being considered. Kamara et al. (2005) state that cross-project KM may facilitate the reuse of the collective learning on a project by individual firms and teams involved in its delivery, provide knowledge that can be utilized during post-occupancy facilities management, and involve members of the supply chain in a collaborative effort to capture learning (Figure 2.9). The authors also point out challenges with cross-project KM, including questions of "what knowledge is reusable on other projects, how can the knowledge be captured cost-effectively and not lead to information overload, how are the nuances of context, organizational differences, human and technology challenges considered, and how can the captured knowledge be reused on the current and future projects?" (Kamara et al., 2005, pp. 109-110).

[redacted]

Figure 2.9. Cross-project learning within organizations and bi-lateral sharing between organizations via an inter-organizational community. Adapted from: (Kamara et al., 2005).

The current practice of cross-project knowledge transfer by collective learning and supply chain involvement implies that all the supply chain partners are capturing learning and knowledge. Current practice restricts this transfer to that project team proper (Kamara et al., 2005). Reliance on people, although the more effective means of tacit transfer, is also the most vulnerable with staff turnover. Project agreements can work to share knowledge. Therefore, joint ventures and vertical integration of OSC companies are an effective tactic. Furthermore, cross-project learning may also be facilitated by a university-industry research agreement to collect and measure project outcome and codify lessons learned to be shared across the project organizations and within the CoP in which they operate for new knowledge creation and clarifications.

2.5.2 Bi-lateral Exchange

Matusik and Hill (1998) provide a typological framework for assessing KM and knowledge sharing within and between organizations, as well as their contingencies, challenges, and benefits. Loebbecke et al. (2016) extend this taxonomy of knowledge within organizations to suggest how knowledge may be shared inter-organizationally. They claim that knowledge may be unilateral, shared one way to enable a new product or process (Ko et al., 2005; Oshri et al., 2015). The other way in which knowledge is shared across organizations is bilaterally, in a reciprocal exchange (Axelrod, 2000; Gouldner, 1960; Vlaar, 2008). Unilateral knowledge transfer is sequential in nature, comprising steps of identifying knowledge and then sharing in a single direction through an agreement of knowledge transfer. Bilateral, reciprocal exchange, according to the authors, is an interdependent exchange of “pooled knowledge” and creates a “more complicated work-sharing arrangement”, such as a taskforce, to control knowledge exchange (Matusik & Hill, 1998).

To manage this complicated nature of bi-lateral knowledge exchange, researchers (Dekker & van den Abbelle, 2010; Spencer, 2003) suggest adopting dynamic inter-organizational knowledge sharing through alternative means that do not include formal agreements and being more flexible, changing from unilateral to bilateral and the reverse. This allows for unintended knowledge to be transferred, for example, tacit knowledge on top of specified explicit knowledge. Although unilateral direction may be intended, bilateral results may occur. An example of this may be outsourcing a subassembly in OSC where knowledge is co-developed and a new product or service results that adds value to the OSC supply chain (Marabelli & Newell, 2012). Further, bilateral exchange may be intended but might lead to unilateral results. An example of this occurrence may be a research and development collaboration that ends in one organization providing the other with knowledge and nothing else (van de Ven, 2005).

2.5.3 Shared Learning

According to Wenger (1998, p. 237), learning in CoPs occurs through the design of 1) engagement through mutuality, competence, and continuity, 2) alignment by means of convergence, coordination, and arbitration, and 3) imagination through orientation, reflection, and exploration. Learning in CoPs may be formal (systematic collection of data) or informal (exchanging stories). Furthermore, learning may be from the members of the CoP to one another through personal experiences or with each other, by helping one another understand certain issues or knowledge topics. Figure 2.10 captures the different activities in which CoPs may engage and in which social learning takes place, adapted from Wenger (2009) and Karner et al. (2011). These are organized by:

a) FROM - learning from each other

b) WITH – learning with each other

c) FORMAL – learning through formal means

d) INFORMAL – learning from informal activities.

Arranging social learning in a CoP along intersecting axes proffers seven unique activity categories in the CoP for social learning, either focused on the members of the CoP internally (inside) or resourcing knowledge externally (outside) from the CoP. These combinations include:

1) Exchange (from / informal quadrant)

2) Productive inquiries (informal / from quadrant)

3) Building a shared understanding (with / informal quadrant)

4) Producing assets (with / informal)

5) Creating standards (with / formal quadrant)

6) Formal access to knowledge (formal / from quadrant), and

7) Visits (from / formal quadrant)

There are several social learning theories and approaches that may be applied to CoPs but are not exclusive to them (Kilvington, 2007). Social learning is a concept that recognizes that learning and knowledge sharing occurs through collective engagement with others. One such theory is experiential learning, sometimes referred to as problem-oriented learning or action learning, that is an iterative process between experience, observation, reflection, and action. Dewey (1938) argued that education is based on the interaction of an individual's external and internal conditions. The contextual situation and interaction with that context were key for Dewey, who defined knowledge as socially constructed and something that is gleaned from experience. By extension, experience is the basis to transfer knowledge to new situations and individuals (Grady, 2003). Lewin (1951) and Kolb (1984) furthered Dewey's theory to include group dynamics and action research. Lewin claims that learning is conceived as a cycle of steps based on feedback loops between concrete experience; observations; reflections; forming concepts, abstract ideas, and generalizations; and testing the implications of the concepts in new situations, only to then experience them again (Figure 2.11).

[redacted]

Figure 2.10. Learning activities used in CoPs. Adapted from: (Karner et al., 2011; Wenger et al., 2009, p. 6).

[redacted]

Figure 2.11. Experiential learning model. Adapted from: (Kolb, 1984, p. 21; Lewin, 1951)

2.5.4 Contingent Worker

Knowledge and competitive advantage are only as good as the organization's ability to integrate and apply knowledge – both private and public. This may occur through formal or informal means (Szulanski, 1995) to share knowledge in an organization or between organizations. Sometimes this is formalized through a knowledge integrator, an individual whose express job is to integrate knowledge outside of the organization for improvement (Huber, 1991). This knowledge integrator can be a permanent employee or a contingent worker that "distributes tacit knowledge and skills, or human capital, across space and time" (Egbu, 2005).

Matusik and Hill (1998) in "The Utilization of Contingent Work, Knowledge Creation, and Competitive Advantage" research the relationship of contingent workers to inter-organizational KM environments. Contingent workers are employees that may be migratory, independent contractors, consultants, technical experts, or other temporary staff that work part-time in an organization to fulfil a specific function. Employing contingent workers is a way that firms can be more flexible and adaptable to changing market conditions and control costs. Contingent workers bring public knowledge from best practices in the market and industry to inter-organizational CoPs. As workers move around they gain broad industry knowledge that is transferrable to different CoP contexts.

Private architectural knowledge is more durable in the organization and not as readily shared because it is context dependent and tacit. Contingent workers are more detached from the architectural level and therefore have not internalized the tacit knowledge to be able to share with outsiders. Contingent workers may also create or clarify knowledge in their desire to convert tacit knowledge within a company to understand what may be implied by the organization (Nonaka, 1994). Further, the contingent worker may integrate component external public or private knowledge with the knowledge of the firm, filling a gap and increasing capability.

2.5.5 Knowledge Broker

A KB is an individual that acts as a link between different groups and individuals in an organization or between organizations in a CoP, or even between CoPs that would not normally have a relationship with one another. The core part of that role is connecting people. KBs tend to have high credibility, be impartial, trustworthy, have extensive experience in the knowledge domain, research expertise, and policy level experience. With this experience, the KB has authority and presence, can effectively negotiate, communicate, network, relationship build, and know how and when to make a pitch (Jackson-Bowers et al., 2006). The KB has historically been an impartial party, such as a government official, academic, or industry consultant that does not have an implicit financial interest in the outcomes of a particular process, technology, or individual knowledge. The KB manages relationships in the CoP and between CoPs through virtual platforms, stories, and translation (Wenger et al., 2009, p. 6). In this way, KBs reflect an indigenous knowledge translator using networking effect, consensus building, and collective intelligence to build cases and facilitate the creation, sharing and use of knowledge, and as Meyer (2010) suggests, "their task is to establish and maintain links between researchers and their audience via the appropriate translation of research findings" (p. 119. KBs in CoPs may be individuals, groups, or entire organizations (Meyer, 2010).

According to Fernandez and Gould (1994), the KB's role can be as coordinator, itinerant, gatekeeper, representative, and liaison. Also, knowledge brokering involves different strategies such as informing, consulting, engaging, collaborating, and building capacity (Jacobson et al., 2005; Karner et al., 2011; Magnuszewski et al., 2010; Michaels, 2009; Newlands, 1981). The skill set for a KB is diverse as well, including interpersonal, research, critical appraisal, communication, and mediation (Dobbins et al., 2009). A summary of KB roles, strategies, and skills is reviewed in Table 2.10.

Table 2.10. KB roles, strategies and skills needed to be successful in managing CoPs. Adapted from: (Jacobson et al., 2005; Karner et al., 2011; Magnuszewski et al., 2010; Michaels, 2009)

AREA	ATTRIBUTE	DESCRIPTION
ROLES	**Coordinator**	All the actors including the KB and the source of knowledge are in the same group.
	Itinerant	Mediates between actors in the same group, but the KB is not part of the group.
	Gatekeeper	Screens external knowledge to distribute it within their own group.
	Representative	Group delegates the KB role to someone in the group.
	Liaison	Knowledge is brokered across different groups, neither of which the KB is a member of.
STRATEGIES	**Inform**	Unidirectional knowledge is transferred to disseminate content.
	Consult	Intermediary locates expertise to help solve problems and establish a connection.
	Matchmake	Brings together actors in the group to address problems for the mutual benefit of the members and group at large.
	Engage	Serves as a liaison for members responsible for addressing a problem and connecting and facilitating interactions with other members and consultants.
	Collaborate	Facilitates the coming together of the members to jointly frame and determine how they will work with one another.
	Build Capacity	Fosters the group to build knowledge and capability within the group and for the organizations that they are tied to.
SKILLS	**Personal Attributes**	Is inquisitive, enthusiastic, flexible, inspirational, imaginative, highly credible, and keenly interested in learning; able to think both at large scale and in detail.
	Evidence Gathering	Is facile at locating and researching sources (written and other media) of evidence and original research that can be brought to the CoP.
	Critical Appraisal	Evaluates knowledge quality, importance, and applicability to a particular context – should have knowledge of the sector and broader context in which it exists.
	Communication Skills	Possesses strong oral and written communication skills and ways to target diverse audiences; active listening skills.

	Mediation Skills	Assembles teams, creates and manages subcommittees, fosters collaboration amongst people and disciplines and companies that may not normally work together; reconciles misunderstandings and facilitates the identification of shared goals for mutual benefit of the CoP.

2.6 CoP Tools

KM tools include techniques and technologies used to manage inter-organizational KM. Gallupe (2001) suggests that KM technologies are IT tools that are not simply information exchange, but also "capable of handling the richness, the content and the context of information" (p. 64). Technologies in KM can enhance and enable the implementation of sub-processes in KM (Ruggles & Holtshouse, 1999). Al-Ghassani et al. (2005) distinguish techniques from technologies, calling techniques non-IT tools. This is not to say that technology is abandoned in techniques; rather, the function of IT is not front and center to the KM subprocesses and activities. Some techniques, among others, that are outlined by Al-Ghassani et al. (2005) for inter-organizational KM include brainstorming, peer review, formal and informal knowledge exchange, storytelling, apprenticeship, mentoring, and training committees and initiatives.

The selection of tools – techniques and technologies – is dependent on the needs of the CoP. Low barrier to entry solutions are often identified first, including traditions of the players, experiences from their past or the interest of the leader/facilitator or KB. The techniques, according to Al-Ghassani et al. (2005) may not be calculated but instead simply selected based on intuition. However, this quick selection allows the CoP to pivot quickly to another technique as the cost of investment is relatively low. The limitations inherent in using such KM selection of techniques include being highly susceptible to the bias of the selector due to a lack of formal structure for selection, not being matched to the subprocess need, and not being aligned with the CoP goals or purpose. The following sections review CoP tools developed by KM researchers including taxonomy, SeKLET, and CLEVER.

2.6.1 Taxonomy of Knowledge

Management researchers Matusik and Hill (1998) provide a taxonomy of knowledge that operationalizes explicit and tacit concepts in KM and their utility in characterizing knowledge in companies and organizations, as shown in Figure 2.12. The taxonomy outlines three dichotomies in relation to tacit and explicit knowledge. The first is individual knowledge, that which is individually held or is the combination of individuals' competency, information, and knowledge (Zander & Kogut, 1995). Next is collective knowledge as the organizing principles, routines, management, and practices that have organizational consensus and are widely diffused throughout the organization and commonly held by a large number of members of the organization (Lyles & Schwenk, 1992). Tacit knowledge can be held individually in skills, habits, and abstract knowledge or collectively in shared experiences (Starbuck, 1992). Collective tacit knowledge is often held by upper management through professional culture and organization routines or ways of doing things (Nonaka & Takeuchi, 1995). Explicit knowledge can also be held individually in skills that are easily documented and collectively in standard procedures and information systems (Brown & Duguid, 1991).

[redacted]

Figure 2.12. Taxonomy of knowledge for intra and inter-organizational KM. Adapted from: (Matusik & Hill, 1998).

Matusik and Hill (1998) add two additional dimensions to organizational knowledge – public versus private knowledge and architectural versus component knowledge. Public knowledge is in the public domain, not unique to any one organization in an industry such as design for manufacture and assembly (DfMA), just-in-time inventory, lean manufacturing, software applications and their use, digital workflows, and other best practices in the public domain. The authors point out that best practices and lessons learned, although in the public domain, likely started out at one point in time as private knowledge. Public knowledge is readily available and non-competitive since it is not proprietary to any one company. The authors go on to clarify however that the inability of an organization to apply public knowledge within a given project or firm can be a competitive disadvantage. Private knowledge is the opposite, being unique and specific to the organization, and is the competitive advantage in the market. It is the firm's routines, processes, documentation, trade secrets, and intellectual property (IP) and is imperfectly imitable (Barney, 1986, 1991).

Component knowledge relates to "parts" or "components" that are a "discrete aspect" of an organization's operations. This knowledge may include resources, skills and technical systems (Amit & Schoemaker, 1993; Leonard-Barton, 1992). Each of these processes is just one aspect of a firm's overall knowledge infrastructure. Component knowledge may be individual (one person responsible for a component) or collective (knowledge related to a component held by a team within the organization). Matusik and Hill (1998) discuss that component knowledge may also "contain both private and public elements" (p. 684). Private knowledge is that which is developed internally and has not been shared publicly or diffused to the broader industry. Public knowledge is that which the firm chooses to share. Both private and public component knowledge may represent a competitive strategy. On one hand, component private knowledge may be held onto as IP and be part of the trade secrets of the company. In other cases, such knowledge is integral to the identity and operation of a company and is used as a unique selling point, or a differentiator in the market. Given a head start on knowledge application in the firm, an organization can use the knowledge in advertising and customer acquisition. On the other hand, they might not be threatened by sharing knowledge and altruistically want all new entrants to an emerging and maturing market to improve and grow to compete with an incumbent industry.

Architectural knowledge is defined as holistic knowledge that is held by the organization at large. This may constitute firm wide routines and processes for coordinating various components of the organization and put them into productive use” (Henderson & Clark, 1990). Architectural knowledge, held by the entire organization, is collective knowledge and therefore, is not dependent on any singular individual to comprehend or articulate and action the knowledge. Matusik and Hill (1998) indicate that architectural knowledge is tacit by default, evolutionary in its development, and idiosyncratically tied to the unique place and time in which the firm has emerged. No two firms have the same architectural knowledge, and therefore, architectural knowledge is also private knowledge.

Both component and architectural knowledge offer potentials for competitive advantage; however, research demonstrates that it is architectural knowledge that determines an organization’s long-term competitiveness (Henderson & Cockburn, 1994; Kogut & Zander, 1992; Spender & Grant, 1996) and is more impervious to inter-organizational KM. In summary, knowledge within an organization can be public and private. Private knowledge is both architectural and component based. Although this is important for firms aiming to protect IP, it is also important to understand these dichotomies so that inter-organizational KM participants are aware of the dynamics of this knowledge taxonomy in practice.

2.6.2 SeLEKT

Given the limitation of existing methods for selecting KM tools, Al-Ghassani (2002) and researchers at Loughborough University in the UK developed a criteria-based process for tool identification in the construction knowledge space called SeLEKT (searching and locating effective knowledge tools). SeLEKT uses a three-step process: 1) identify the KM dimensions needed for knowledge transfer, 2) determine the sub-processes required to serve the dimensions, and 3) select the tool that most appropriately responds to the dimensional and sub-process needs.

Stage 1 of SeLEKT uses multiple dimensions to identify tools. These dimensions include domain, ownership, and conversion. ‘Knowledge transfer domains’ are considerations that determine whether the knowledge needed for the transfer exists internal to the participants’ knowledge base and expertise or needs to be externally sourced outside of the group. In many ways, the location of the knowledge and where it is being transferred from determines the tool – technique or technology – used in the KM enterprise. 'Knowledge ownership form' distinguishes between personal and shared - individual and collective - knowledge in the transfer, impacting what tools are selected and implemented. Ownership is closely tied to private versus public knowledge and IP sensitivities in KM (Anumba et al., 2005; Matusik & Hill, 1998). 'Individual' refers to knowledge that may be owned by an individual person or an individual company that is participating in inter-organizational KM, such as a CoP. Likewise, collective knowledge is that which is held by the KM community, whether that is at the company or inter-organizational scale. Knowledge transfer (tacit – explicit) considers what is embedded knowledge versus what is overt and codified knowledge (Nonaka et al., 1995). KM tools may be unique to tacit or explicit knowledge transfer or may be the same tools; however, depending on the conversion scenario, these tools may be applied differently.

Extant literature and CS experiences of the researcher documented in this thesis suggest that there are additional considerations when selecting tactics for KM. These include *situation, scale, expertise, importance, pace, and format* dimensions. *Situational* parameters distinguish between contextual knowledge and operational knowledge. Contextual knowledge frames a specific knowledge type. Contextual considerations may include market conditions, regulations, finance structures, and supply chain outside of the OSC industry. These situational parameters are the external forces, the circumstances which the organizations in the KM effort inherit as the context in which they operate. These are the same contextual forces in the construction industry at large. Operational knowledge is specific to the process and products of the organizational functions and value production actors themselves. In OSC, knowledge of operations includes the design, manufacture, and assembly project delivery process and associated business models, labor, skills, and innovations inside of and specific to the OSC industry. Furthermore, this dimension also considers if the knowledge is project specific or can be applied to a range of project types and scenarios (Anumba et al., 2005).

Scale criteria also impact tactical tool selection for KM. Scale knowledge may be architectural or component. Architectural knowledge is not to be confused with architectural design knowledge and associated skills. These are specific to operational knowledge (Matusik & Hill, 1998). Rather, architectural knowledge is whole system knowledge. Henderson and Clark (1990) indicate that architectural knowledge is about how the components are integrated and interrelated into a coherent whole. When instituting an inter-organizational KM strategy and working to select tools, global architectural knowledge is key. The component knowledge is then concerned with more detailed and distinct knowledge. Architectural and component innovation knowledge may be considered the 'level-of-detail' criteria that aids KM efforts to transfer knowledge that is globally or locally applicable. Some individuals or organizations involved in the KM enterprise may have architectural, component, or both types of knowledge (Smith, 2011, pp. 337-338).

Anumba et al. (2005) provide additional knowledge dimensions in KM practices. *Expertise* is closely tied to scale dimensions. It is knowledge being disciplinary specific or sourced, created or transferred from multiple disciplines. Multi-disciplinary or interdisciplinary knowledge is more challenging to manage and often requires more tacit forms of transfer through socialization methods. It also can take much longer to develop and transfer as it is not as clearly definable or explicitly transferrable. *Importance* is the difference of knowledge being auxiliary (general knowledge that is never in isolation and critical knowledge) or critical (fundamental to the effectiveness and achievement of the business goals). These dimensions are like scale parameters of architectural and component knowledge, but instead of focusing on the level of detail, importance factors define the level of significance of the knowledge to the core operations of the organizations that are participating.

Two additional considerations in knowledge dimensions includes *pace* and *format*. Pace is the rate at which the knowledge is developed and transferred. Anumba et al. (2005) indicate that 'slow' knowledge is evolutionary, fostered and shared over time through socialization efforts and continuous improvement. Conversely, 'rapid' knowledge is frequently changing and updating and therefore needs a different cadence of communication and method of transfer. The same authors also introduce format as a dimension which represents the dichotomy between knowledge that can be transferred through formal training and that which is better suited to work through human interactions. These dimensions are closely tied to explicit and tacit knowledge conversion as well.

In summary, the dimensions listed in determining CoP learning community tools (technology or technique) to be applied to inter-organization include the following:

1) Domains (internal – external)
2) Ownership (individual – collective)
3) Situation (contextual – operational)
4) Innovation (architectural – component)
5) Expertise (discipline – multi-discipline)
6) Importance (auxiliary – critical)
7) Pace (slow – rapid)
8) Format (training – interaction)
9) Conversion (tacit – explicit)

Conversion, the last domain, is the delimiting knowledge type. The other dimensions aid in determining the character of the knowledge being managed as tacit or explicit. Conversion means that the desire of the shared learning is to use the SECI-model to convert knowledge from one type to another (e.g., tacit to explicit). Fundamentally, the knowledge dimensions depend on the nature of the knowledge need in the KM effort and the strategy used by the community to manage knowledge.

Lastly, KM participants need to determine if the knowledge is being 'supply-driven' (pushed from one party to another) or if the knowledge is being 'demand-driven' (pulled from the receiving party). Scarbrough et al. (1999) indicate that supply-driven strategies are often used when the participants seek to increase the flow of knowledge within the community including by capturing, codifying, and transmitting knowledge. For demand-driven strategies, the participants pull knowledge. Supply-driven approaches are generally more technology reliant and convert using explicit means. Alternatively, demand-driven strategies use socialization and tacit means more regularly, although these are not definitive characterizations. Furthermore, there need to be at least two distinct parties (e.g., individuals, companies, or organizations) that are exchanging knowledge; however, often in CoP KM, this is multiple parties. Moreover, while one-direction transfer takes place (supply-or demand-based), bilateral transfer is more common in a shared exchange of inter-organizational knowledge. Although the tactics selection process illustrates polarity decision-making between two options in each dimensional category (e.g., domains of internal versus external), the reality is that any decision about the method or tool to be used to transfer knowledge may be on both sides of the divide (e.g., internal and external) in principle.

Table 2.11 shows the SeLEKT with added knowledge dimensions from literature and CS experiences of the researcher. These are meant to be representative. There may be additional dimensions for which a particular scenario is important. Finally, not all the dimensions outlined in this matrix are important or relevant for any knowledge transfer iteration. Inter-organizational CoP participants, together, make these dimensional determinations. The framework is a strategy meant to support tactical tool decision making.

Table 2.11. Knowledge dimensions (types) and their characteristics. Source: (Anumba et al., 2005 and literature review).

[redacted]

Stage 2 of the SeLEKT is to identify KM sub-processes that are to be used in the exchange. Sub-processes in the KM cycle are the different activities that occur in KM as outlined in section 3.1.4 of this chapter. These sub-processes may include but are not limited to knowledge generation, codification, and transfer (Ruggles, 1997), acquisition, storage, and deployment of knowledge (Wensley & Verwijk-O'Sullivan, 2000), gathering, communicating, and synthesizing knowledge (Jackson, 2005), creating, capturing, and sharing of knowledge (Laudon & Laudon, 2000), and knowledge representation, classification, and distribution (Tsui, 2002). In considering and then identifying the specific KM dimensions in Step 1, the parties then can determine what sub-processes need to be involved. The sub-processes in the SeLEKT project are listed and described here:

- Locating and accessing knowledge: search and access knowledge location and source (individual versus collective).
- Capturing knowledge: convert tacit to explicit knowledge without losing the context of the knowledge.
- Representing knowledge: present the knowledge with the aim of easing transfer.
- Sharing knowledge: communication of knowledge through written, verbal, graphical, video, face-to-face, and other means.
- Creating knowledge: combining existing knowledge to clarify or generate new knowledge through original research and development.

These KM sub-processes are likewise not comprehensive and may vary depending on the nature of the CoP and knowledge in question. Using the Table 2.11 matrix, knowledge in an example transfer scenario may be: 1) demand - pulled, 2) domain - by the KM internally, 3) ownership – collectively shared, 4) situation – contextual, 5) innovation – architectural, and 6) conversion – tacit, or short-hand coded as *pull – internal – collective – contextual – architectural – tacit*. In this sequence of knowledge transfer, the source of the knowledge in the internal CoP will need to be in an individual or smaller cohort of individuals in the CoP and ensure that it is not IP sensitive. If it is, then non-disclosure agreements or mutual trust can create a vehicle for the sharing to occur. Then the knowledge will be shared by the source or facilitated by a KB in the CoP. If the knowledge is tacit and located in individuals' minds, then it will need to be explicitly captured and/or represented. The sharing of the knowledge may be unidirectional (lateral) or it may evoke a reciprocity and bilateral sharing and create new knowledge. It may use digital technologies, face-to-face interviews, workshops, etc.

Stage 3 of the SeLEKT takes any knowledge transfer scenario, and aligns the knowledge need and dimensions to determine the sub-processes to be used and ultimately the tools (techniques and technologies) that will be employed to facilitate the transfer and exchange of knowledge. Other considerations may include the cost, user ease, accessibility, etc. There are no hard and fast rules for which tools should be used for which scenario; rather, these are fostered in the culture and practice of the KM community by the members themselves. Technological tools are more present, understandable, and seemingly tangible for CoP members to use. They are most often, as we have discussed, applied to explicit conversions driven by supply push approaches to KM. However, since tacit knowledge constitutes most transfers and much of explicit knowledge is tacitly inclined, including the contingent context and social aspects of any knowledge, investigating tactical methods to be used in tacit knowledge exchange is warranted.

Tacit knowledge is sometimes called 'organic' KM, to distinguish it from explicit or 'mechanistic' KM (Kamara et al., 2002). This includes techniques that CoPs generally employ with the different social learning activities and approaches diagrammed in Figure 2.10. Any tool that is used should take into consideration transferring both the 'content' knowledge (sometimes referred to as operational knowledge) and the 'contextual' knowledge, or the human dimensions of the KM (Anumba et al., 2005). For example, 'storytelling' is an underutilized technique (Snowden, 1999) and, as the name suggests, relies on creating a self-aware description of 'context' and 'content' of a situation for the application of knowledge.

2.6.3 CLEVER

Anumba et al. (2005), construction management researchers, developed the CLEVER KM framework as a problem-solving technique within a construction organization CoP. This tool is being considered herein as a tool for inter-organizational CoPs as well. CLEVER was developed through peer review processes in technical workshops with companies. The CLEVER framework seeks to provide processes to solve KM problems through four stages: defining the KM problem within the context, relating to the desired characteristics of the 'to be' KM solution, identifying the critical migration paths to achieve the 'to be' goal, and selecting appropriate KM processes to use on those paths. In stage one, defining the problem, the researchers suggest using a tool called a *problem definition template* in which structured questions aid in clarifying the nature of the problem, including seeking to define the type of knowledge, characteristic of knowledge, sources and users of knowledge, current processes, and restatement of the problem (Table 2.12). The researchers make a helpful distinction between characteristics of knowledge dimensions (type) and location in knowledge dimensions (source).

Table 2.12. ‘Problem definition template’: structured questions and options. Source: (Anumba et al., 2005)

[redacted]

[redacted]

In stage 2 of the CLEVER framework, the researchers propose a 'to-be' solution, highlighting the problem areas the CoP wishes to focus on and offering a sliding scale of the current situation of the knowledge, how it currently exists and the desired situation of the knowledge, and where the CoP wants the knowledge to be in the future. For each characteristic in the *problem definition template* (e.g., explicit vs. tacit, auxiliary vs. critical, discipline vs. project, etc.), the CoP members indicate the present state of the knowledge and the future desired state of the knowledge to determine the gap between them. The largest gap that emerges between the current and desired state then becomes the priority area for the CoP and the need for the greatest amount of energy and focus. In stage 3, the researchers suggest identifying critical migration paths to take knowledge from a current state to the desired state using predefined guides for each side of the knowledge characteristics. For example, the authors suggest that for 'individual' versus 'shared' knowledge migrations that may have a large gap between current and future states, the organization establishes a migration path to move from individual to shared knowledge using tacit to explicit conversions. In stage 4, appropriate KM processes are then selected. Although the researchers provide preselected processes from a standard list, these may be developed by the CoP. The goal, however, of this stage is to develop specific plans to implement the migration path as related to the KM problem. This usually involves the CoP members recognizing the 'enablers' or 'resistors' to KM.

Therefore, just as much as tools that seek to imbue a systematic process for identifying, creating, and sharing knowledge, the relational attributes of inter-organizational CoPs are critical. These are the connective tissues between organizations and specifically the members from different organizations in the CoP. Patrick Fong (2009) suggests that "contributory factors" of socialized environments for inter-organizational KM include the following: openness, motivation, time constraints, communication (thickness or quality and quantity), and trust. The act of identifying and selecting tools appropriate to KM scenarios is part and parcel of the purpose and motivations of the CoP environment. Further, tools may be adapted, developed, augmented, or abandoned when not working. They require continual assessment to ensure that the outcomes advantage the CoP generally and the members that participate. Just as the knowledge to be gained by participating in the CoP, the socialization aspect is a driver and benefit that may be called effective flow as the performance benefits for competitive advantage by the participating organizations. In this way, KM communities, learning communities, learning networks, and CoPs are socio-technical organizations to foster knowledge creation and sharing to realize innovation and improvement for the companies and industry sector the community fosters.

Table 2.13 combines the KM mode dimension from this literature review including the associated strategies, tactics, and tools from Section 2.4 – 2.6 with literature review findings and confirming context for objective 04 CS analysis in Chapter 06.

Table 2.13. Literature review summary from Sections 2.4 Mode Strategies, 2.5 Mode Tactics, and 2.6 Mode Tools.

KM Mode Dimension		
Strategies / Tactics / Tools		Confirmation Context for Objective 04 - CS Analysis
Strategies	*CoP*	• Socialized networks • Intra or Inter-organizational • Internal, network organization, formal network, self-organizing • Joint enterprise, mutual engagement, shared repertoire • Leader / champion and facilitator

	Triple Helix	• Innovation framework: University – Government - Industry
		• University integrated or led CoPs
		• HUB: integrated institution in region, spanning entity between industry, government, and society
		• Co-production: Mode 2
		    ○ Tacit knowledge focused
		    ○ Network of diverse stakeholders
		    ○ Applied research and development focused on knowledge uptake and impact

Tactics	*Cross-project*	• Shared knowledge from projects outside of projects
	Bi-Lateral Learning	• Uni-lateral versus bi-lateral

	Shared Learning	• FROM – WITH; FORMAL INFORMAL Quadrants • Activities: Exchange, Productive Inquiries, Shared Understanding, Producing Assets, Creating Standards, Formal Access to Knowledge, Visits • Experiential Learning
	Contingent Worker	• Public knowledge to private knowledge integration
	KB	• Role: coordinator, itinerant, gatekeeper, representative and liaison • Strategies: inform, consult, matchmake, engage, collaborate, build capacity • Skills: personal attributes, evidence gathering, critical appraisal, communication skills, and mediation skills
Tools	*Taxonomy of Knowledge*	• Private vs. Public • Component vs. Architectural • Individual vs. Collective • Tacit vs. Explicit – automatic, conscious, collective, objectified
	SeLEKT	• Step 1 Dimensions: Domain, Ownership, Conversion ○ Supply or Demand Driven • Step 2 Subprocesses: Locating, Capturing, Representing, Sharing Knowledge • Step 3 Tools and Techniques selection including shared learning tactics
	CLEVER	• Problem Definition Template • ‘As-Is’ to ‘To-Be’ knowledge conversion and transfer • Tool selection

2.7 Measuring KM

For inter-organizational KM to take place, the *type* of knowledge to be created or transferred needs to be defined. The *mode* of KM should be selected and then the knowledge is transferred and integrated into a receiving organization or individual. After the mode is enacted, the KM process should be assessed or *measured* to determine the KM effectiveness and impact on the involved organizations (Milagres & Burcharth, 2018). A full evaluation of KM includes a comparison of both the inputs and the outputs of KM interventions and their outcomes or impacts. A variety of performance measures could be adopted to evaluate KM alternatives.

There is no universal standard for measuring or evaluating knowledge assets and/or KM programs (Housel & Bell, 2001). Choosing an appropriate tool or method for measurement is crucial in assessing the effectiveness and efficiency of an organization's knowledge assets and KM programs. Measuring inter-organizational KM is assessing the outcomes of the KM enterprise. Milagres and Burcharth (2018) suggest that "outcomes", which is defined herein as "measures", includes two primary facets: *effectiveness* and *performance*. Effectiveness refers to evaluating how well the KM environment is working internally to the CoP and assessing the quality of the knowledge and flow of knowledge in the KM efforts. Performance determines the outcomes for the discrete and individual interests of the organizations involved in the KM effort and the industry at large.

2.7.1 Measuring Effectiveness

In a book chapter, "Performance Measurement in Knowledge Management", construction management scholars Robinson et al. (2005) provide a review of measuring KM outcomes in construction in both effectiveness and performance. Measuring the effectiveness of a KM process is the evaluation of socialization – how well the KM enterprise is working, how processes and sub-processes are being managed, how effective the members of the community are at their various roles, and how well the KB is creating value for the members and fostering trust, communication, and connection. The effectiveness of a CoP can be reviewed systematically, such as via a survey of members, to determine effectiveness.

According to Robinson and colleagues, when measuring the effectiveness or performance of a KM process, there are two distinct aspects to consider: 1) knowledge assets (stocks), what is being managed, and 2) knowledge programs or initiatives (flows) aimed at improving or increasing the value of knowledge assets. Stocks are the talents of people employed, the efficiency of the processes used, the nature of products, and customer relations. Measures for knowledge assets/stocks or intellectual capital focus on several main components – human, structural, and customer capital. Human capital is the knowledge in people's heads, acquired mainly through education, training, and experience. Structural capital is the knowledge embedded in business processes, so called non-human storehouses, including organization manuals, procedures, and database. Customer capital refers to knowledge about products, marketing channels, and customer relationships.

2.7.2 Measuring Performance

A variety of performance measurement methods have emerged to evaluate KM on the participating organizations that can be grouped into (1) metrics, (2) economics, and (3) market value approaches (Bose & Oh, 2004). *Metrics* evaluate inputs and outputs that can monitor performance of knowledge assets upon a CoP. Input “indicators” are “enablers” or actions that the CoP can take to achieve business objectives (Polley & Smith, 2007). For example, an organization may want to evaluate training days per employee, the time associated with IT system implementation, process improvement measures for quality control on a factory floor, or the number of customer inputs or variability for a particular project. Output indicators evaluate the outcomes or performances of the input actions such as defects, delays, rework, customer input time, cost, and time overruns. Metrics can be kept discrete or combined to determine the relationship/correlation between indicators and business outcomes. The goal of metrics is to improve business performance for the organization, therefore, they can be financially oriented or not, depending on the intention. One example provided by Robinson et al. (2005) is that by measuring participating rates in CoPs and defect rates, customer complaints could trigger early warning signals for corrective actions to be taken.

Robinson et al. (2005) point out several issues with the metrics approach including the following:

- Combination - The difficultly of combining different metrics into a single numeric measure to correlate with performance
- Comparison – The challenge of comparing the KM enterprise in one organization in the CoP versus another when their businesses are different
- Continuous Improvement – Metrics do not always provide adequate information about performance to enable continuous improvement

Metrics may not provide enough detailed information about the effectiveness and performance impact and therefore, inter-organizational KM efforts may need to use financial analysis to measure outcomes.

Economic measurement is financial assessment. The tools and tactics used for the strategic processes and sub-processes in KM vary in cost and benefit. This return-on-investment of this KM process can potentially be quantified at the CoP level and at the organizational level. Robinson et al. (2005) point out other financial metrics such as internal rate of return and net present value or payback period to aid in determining the effectiveness and performance of KM efforts. Economic measurement is not only financial but can also include the "valuation of knowledge assets or components" such as intellectual capital of human, structural and customer assets (Robinson et al., 2005, p. 140). Measuring capital, human, structural and customer, is notoriously difficult in method and interpretation. This is because there are a myriad of variables and contingencies to any evaluation that involves more social and human aspects of evaluation. Non-economic evaluations may include guestimates or qualitative data that may be difficult to interpret or transfer and then duplicate the outcome.

Market approaches to measuring outcomes are larger in scale. They are used to evaluate the impact that the CoP has on the industry at large, or an entire organization in which an individual may be participating in the CoP. Market value method states that the value of the company or organization is both a factor of financial capital (physical and economic assets) and intellectual capital (people). The emergence of research and development units in organizations in construction and across the knowledge enterprise is evidence of knowledge being valued differently than purely economic means. Given the importance of knowledge to continuous learning, training, innovation, and future viability of companies, existing measurement frameworks are inadequate because they are misleading (Robinson et al., 2005). As construction matures into OSC, the discrepancy between market value and financial value of any enterprise will likely continue to diverge as it has in other manufacturing industries. The recent investment into the OSC sector is evidence of the market recognition of the potential value via intellectual capital of this bourgeoning industry. Outcomes of CoPs may not be impactful for only one or a handful of the organizations involved in the KM enterprise. Further, the CoP effectiveness and performance on market factors can be evaluated through the fundamental increase in market uptake, but also through other measures such as the increase in reputation, and publications on a particular topic. The evolution of questions moving from 'why OSC' to 'what-is' and 'how-to' suggests an industry moving from selling to implementing.

Edison et al. (2013) provided a literature review of 232 innovation metrics - ways to measure innovation beyond numerical and financial approaches. The authors categorized these into five dimensions: 1) inputs to the innovation process, 2) output from the innovation process, 3) effect of the innovation output, 4) measures to access the activities in the innovation process, and 5) availability of factors that facilitate such a process. These innovation metrics can be applied to two different levels – organizational and political. Organizational is the specific company innovation and political marking the country or regional competitive advantage. Measurement of innovation at the organizational level can be performed by surveys, workshops, consultants, or internal benchmarking. Values may include revenue, research and development spending, customer perceptions, patents, etc.

Political level innovation is measured by various indices, such as the OECD Oslo Manual, Bloomberg Innovation Index, Bogota Manual (Latin America), and many others that evaluate product and process innovation as well as marketing and organizational innovation. There is a growing concern amongst scholars of the bias toward science and technology indicators of innovation versus learning by doing indicators (Barishnikova & Nevzorova, 2015). Furthermore, there is criticism for innovation indicators that rely on cost-effectiveness without considering other value-based measures of innovation as significant, suggesting that economic value is synonymous with innovation, ignoring social and environmental progress (Lanjouw & Schankerman, 1999).

Table 2.14 lists the KM measure dimension from Section 2.7 including the facets of effectiveness, performance, stocks, and flow and the contextualizing knowledge for reference in objective 04 CS analysis.

Table 2.14. Section 2.7 KM Measure Dimension literature review summary.

KM Measure Dimension	
Facets	Confirmation Context for Objective 04 - CS Analysis
EFFECTIVENESS	• Process evaluation • Role fulfilment • Trust • Communication • Socialization
PERFORMANCE	• Metrics • Economics • Market Value
STOCKS	• Human capital • Structural capital • Customer capital
FLOW	• Cycle between effectiveness and performance

2.8 Chapter 02 Summary

Chapter 02 – KM Theory reviewed KM in the extant literature with an emphasis on inter-organizational KM cycle and process. This covered: 1) identifying the type of knowledge, 2) determining the mode of method of transfer (sometimes called sub-processes) and 3) measuring the outcomes of the KM effort. The chapter then discussed each contingency dimension from key scholars in the field.

Knowledge types, including tacit and explicit knowledge, were presented with conversion scenarios using the SECI-model to convert knowledge between types and between stakeholders in KM. KM mode, the second contingency dimension, was discussed, covering the strategies, tactics, and tools. The strategies sections reviewed literature on CoP, triple-helix, knowledge hub and co-production of knowledge. The tactics section reviewed cross-project, bi-lateral exchange, shared learning, contingent worker, and KB applications. Mode tools were then reviewed (techniques and technologies) that may be employed in a CoP learning community including knowledge taxonomy, SeKLET, and CLEVER frameworks.

The last contingency dimension of KM reviewed in this chapter was measure. The two aspects of measurement, effectiveness of the KM enterprise itself (flows, quality of transfer, health of the community) and the performative value of the KM to the participating stakeholder organizations was also presented. The theories and concepts from literature presented in this chapter are contextualized in objective 04 – CS analysis as confirming and clarifying sources. The next chapter will address the second part of the literature review of SR for this thesis, a study of OSC KM and OSC knowledge characterization, needs and priorities.

CH 03 – OSC Knowledge Literature Review

This chapter is the second part of the literature review. It provides SR of OSC knowledge in two sections. First is a literature review that identifies the gap for this research – the need for an inter-organizational KM framework in OSC. This is presented through documenting the housing needs in the US and UK; the potentiality and challenges for OSC to address this need with the attenuate statistics on OSC uptake; and the role of KM to address OSC. The second section of the chapter discusses OSC knowledge characterization, categories, and priorities from the extant literature to provide triangulation to the data mining research presented in Chapter 05.

3.1 Housing Need

The State of the Nation's Housing Report 2023 indicates that in the US, nearly one in three American households is cost-burdened spending more than 30% of their income on housing (Figure 3.1). Despite a recent slowing of growth in new housing, prices for buyers have reached record highs. Escalating costs for buyers and renters, and the increasing expense of maintenance and operations, are forcing Americans out of their homes and preventing many others from finding reasonably affordable housing. While this once was a problem reserved for larger cities such as San Francisco and New York, it is now also affecting developing cities, suburbs, and small towns that are rapidly growing and gentrifying (JCHS, 2023).

[redacted]

Figure 3.1. Moderately and severely cost burdened households that spend 30%-50%+ of their income on housing. Source: (JCHS, 2023)

Goddard (2021) reports that only 6,500 social homes were built in England in 2020, despite the 1.1 million people waiting for social housing. Shelter (2022) shares that the housing crisis in the United Kingdom (UK), the fifth wealthiest country in the world, affects one in three adults, equating to 17.5 million people. Josh Ryan-Collins (2018), British economist, indicates that the treatment of housing as a financial asset during the 1990s and 2000's, in response to low interest rates, rather than a place to live, has encouraged an international real estate investor market that has been detrimental to housing affordability. Given the fact that countries such as the US and UK are ranking among the most affordable for housing indicates how dire the housing situation has become worldwide. Bloomberg Global City Housing Affordability Index (2017) suggests that the average housing cost as a percentage of net monthly income is reaching an untenable situation in emerging economies in which lower average incomes makes housing relatively less affordable.

In a McKinsey Global Institute report, Woetzel et al. (2014) claim that that there are several strategies that can optimize the cost of housing by as much as 50% including: unlocking land supply through regulatory reform toward more inclusionary land-use policies and reducing the complexity and cost of entitlements (-23%), lowering finance costs for both buyers and developers (-7%), improving operations and maintenance of the housing stock (-2%), and reducing construction costs (-16%). Ivory Innovations (2020), a housing affordability think-and-do-tank, and The Housing Lab (2020), associated with the Terner Center for Housing Studies at University California, Berkeley corroborate that policy and regulatory reform, finance and advocacy revision, and design and construction research and innovation diffusion are pathways to achieving greater housing access and affordability (Figure 3.2).

[redacted]

Figure 3.2. Levers to reduce the cost of housing including 12-16% reduction from use of OSC. Source: (Woetzel et al., 2014)

3.2 Housing and OSC

OSC, a design and construction innovation, is one of the practices that has the potential to deliver more affordable and accessible single and multi-family housing at scale (Barbosa et al., 2017; Bertram et al., 2019). In the US, the Department of Housing and Urban Development (HUD) has likewise identified OSC as a strategy to delivering more affordable housing (HUD, 2020). A report from The Construction Industry Council's Off-site Housing Review (Miles & Whitehouse, 2013) and The Lyons Review (Lyons, 2014) claims that OSC can be used to increase the supply of affordable housing in the UK as well.

The terms ‘off-site fabrication’, ‘factory-built’, ‘prefabrication’, ‘pre-assembly’, ‘modularization’, and ‘offsite manufacturing’ have been frequently used interchangeably with OSC (Gibb, 1999; Hairstans, 2015; Staats, 1976). However, these designations are manufacturing-specific, representing a step in the OSC project delivery value chain – that of technical production. Taken holistically, OSC for housing is the entire process to develop, finance, design, plan, permit, manufacture, inspect, transport, and assemble components and subassemblies that have been prefabricated offsite, or literally remote to the jobsite in a conditioned environment (Smith & Quale, 2017, p. 264). Industrialized construction is a term used internationally (Lessing et al., 2005, 2015) to describe applying manufacturing-based principles and production methods including advancements in digitalization, automation, lean construction planning and management, data, and materials science to both onsite and offsite conditions (Barbosa et al., 2017). In the UK, OSC and industrialized construction have become synonymous with Modern Methods of Construction (MMC) – or the application of modern planning and process principles in construction (Davies, 2018). As Burwood and Jess (2005) point out, “while all OSC is MMC, not all MMC is OSC”. For this thesis, OSC describes an industrialized construction approach to entire project delivery for single- and multi-family housing using the offsite manufacture (OSM) of sub-assemblies.

OSC leverages the factory environment to create value added ‘subassemblies’, to take a term from product manufacturing, of various degrees of prefabrication ranging from 1D (kit of parts), to 2D (panelized), to 3D (volumetric), to complete structures (manufactured homes) (Smith et al., 2022). Modularization (Schuh, 2017) is an approach to OSC that uses the principles of DfMA (Boothroyd, 1994) and predefined product platforms to allow for project reconfigurability and adaptability through a set of standards, interchangeable and continually improvable subassembly elements (2D or 3D) (Gao et al., 2020; Harland et al., 2020; Lu et al., 2021). The subassemblies may serve different building system functions including structure, enclosure, finishes, mechanical/electrical/plumbing (MEP), etc. An important but often overlooked terminological distinction with significant impact on OSC refers to whether a factory-built component is an enclosed section or open before it leaves the factory. Enclosed subassemblies are often inspected in a factory before assembled onsite, while open structural components can be inspected onsite. Enclosed subassemblies are inspected in the factory because the manufacturing of the element hides inspection-related systems within, making site inspection of structure, thermal, electrical, or other systems not visible. The subassemblies that are enclosed can be 2D panels (Figure 3.3), 3D volumetric modules, and 3D service pods. The ICC/MBI 1200 standards provide more context and definitions of offsite industry accepted terminology in the US (ICC, 2021).

Figure 3.3. Closed panel turnkey manufacturer-builder Bensonwood / Unity Homes in New Hampshire, USA.

OSC is different from traditional site construction and thereby impacts project finance, entitlements, contracts and procurement, design, supply chain, construction estimating, scheduling, labor, warranty, operations, and maintenance (Smith, 2010). Off-site fabrication, synonymous with OSC, is “part of the broad spectrum of innovative contemporary techniques available to clients, developers and project managers seeking greater cost-effectiveness in construction” (Gibb, 1999, p. xiii). OSC is innovation - a relatively new process and product that necessitates knowledge outside of the conventional wisdom in traditional construction practice (Davenport, 1993; Goulding & Arif, 2013).

OSC is growing internationally. In a McKinsey and Co. report, Bertram et al. (2019) report on global OSC housing as a percentage of total of new housing starts per annum in the following countries respectively: Scandinavia (Finland, Norway, and Sweden) is 45%, Japan 15%, Germany 10%, China 6%, Australia 5%, UK 5%, and US 3% (Figure 3.4). A literature review of OSC by Sutrisna et al.(2020) suggests similar findings in market share including Sweden (85%), Japan (20%), Germany (15%), US (7%), UK (6%), and Australia (6%). In the US, OSC is not tracked as a general category by the government, mortgage companies, code permissions, or otherwise. However, the MBI, the trade association for volumetric modular manufacturers, reports that ~5% of the total construction industry spending in the US for 2020 was volumetric, up from 2.5% in 2015 (Smith & Rupnik, 2018). Their membership of approximately 250 manufacturer members produced each, on average, around 290 “permanent” and “relocatable” modules for commercial use in 2019. Amongst housing typologies, MBI (2021) data is focused on multi-family commercial. In 2019 the MBI members report manufacturing 2,041 units with the average of 85 volumes produced per development project.

[redacted]

Figure 3.4. Percentage of OSC housing share by country. Adapted from: (Bertram et al., 2019).

Volumetric modular statistics for single-family detached housing are not recorded in the US. Data service, 360i (2019), reports that the panelized market (open and closed) is both estimated and projected to be 4.11% of the total housing construction industry by expenditure between 2018-2026. The Freedonia Group (2021) reports on the projected growth of OSC subassemblies in US housing between 2019-2024 as follows: manufactured (2.1%), volumetric modular (5.2%), precut timber kits (2.9%), and panelized (2.0%). In 2020, Freedonia indicated that in the US closed panels constituted 14% of the total OSC panel market compared with 86% open panel.

Although definitive percentages of construction type (steel, wood, concrete) used in OSC in the US and Canada are not tracked, most of housing construction generally, up to 90% in fact, is light wood frame and has been for decades (Cavanagh, 1997). “Stick frame” from 1-5 floors is the ubiquitous “unconscious system” (Cavanagh, 2016) by which workforce knowledge, procurement practices, scheduling and costing in housing production and delivery are all based, but it is unknown how the ongoing supply chain disruptions and fluctuating lumber prices will affect light wood frame demand in the US. Despite these material and construction type questions, the total OSC demand in the US is projected to grow by 6.4% between 2019-2024 (Freedonia, 2020). According to Builtworld Insights 2019, of the total OSC spending in the US, 12% is attributed to single family and 48% to multi-family, with the remaining 40% in other building types such as hospitality, healthcare, retail or other.

Grandview Research 2019 reports global modular construction market will grow by 6.4% between 2021-2028, with most growth in residential multi-family housing. In Sweden, it is estimated that 45-50% of all housing is OSC using primarily light wood frame panelized and volumetric solutions (Lidelow, 2017). In Japan approximately 15% of all housing is OSC with a mix of light gauge steel and light wood frame volumetric solutions (Buntrock, 2017; JPCSMA, 2022). In single-family construction and low-rise multi-family, that percentage is likely much higher (Smith & Rupnik, 2018). Helena Lidelow (2017) indicates that approximately 90% of all single-family new housing in Sweden today is built with light wood frame panelized construction. Although OSC is growing in both the US and UK, these countries are significantly behind Japan and Scandinavia in uptake, maturity, and supply chain integration (Smith & Rupnik, 2018). An exception to this is Scotland, which like Sweden, has a proliferation of light wood frame open and closed panel manufacturers (Figure 3.5) that have matured since 1970 to now constituting nearly 75% of housing (Timbertrends, 2013) and is beginning to experience a growing volumetric modular industry using similar techniques and automated machinery from Scandinavia (Smith et al., 2013).

[redacted]

Figure 3.5: CCG Offsite Manufacture in Glasgow, UK is an example of a closed panel manufacturer in Scotland. Source: (Edinburgh Napier University, Centre for Offsite Construction and Innovative Structures, 2014).

OSC was first applied to housing in the US around the turn of the last century (20th C) and exported abroad during the interwar period (Bergdoll & Christensen, 2008; Rupnik, 2015). During the immediate postwar period, growth of OSC in European and Asian countries increased through government sponsored programs designed to meet the massive worldwide housing crisis (Bruce, 1945; Kelly, 1951; Rupnik, 2015). These programs ensured a steady demand for the fledgling offsite industries in those countries, lowering the risk for the significant capital investment required for any manufacturing industry. The general stagnation of population growth as well as the energy crisis (which directly impacted the transportation cost of highly prefabricated concrete systems) led to a significant decline of the use of OSC in much of Europe and Asia. Two important exceptions to this decline are Sweden in Europe and Japan in Asia; two countries whose initial public investments in growing OSC were followed by a series of industry led and sponsored standardization initiatives that have maintained and even further increased OSC's market penetration up to the present day (Rupnik & Smith, 2018; Smith, 2009). A new massive worldwide housing crisis, combined with the climate and labor crisis, has in turn led to a renewal of interest for OSC globally (Woetzel et al*.,* 2014).

There is an increase in the use of OSC today (Bertram et al., 2019; McGraw-Hill, 2011, 2020; MBI, 2020) fueled by the availability of affordable mass marketing through social media channels, online webinars, the rapid pace of digital publishing, and international knowledge transfer at a scale not achievable in the past. Furthermore, investor interest in OSC has been promulgated by international management consultant McKinsey (Barbosa et al., 2017; Bertram et al., 2019), who have claimed in their reports that a dramatic increase in productivity is possible by virtue of industrialization and OSC. Some of these investments have been ill informed, not contextually dependent, and too reliant on technology alone (i.e., significant investment in automation without an assessment of value or the Katerra effect) (Davis, 2021) (Figure 3.6). The growing affordable housing gap, lack of available labor workforce, supply chain and trade difficulties, and changing climate all point to the need to reconsider how we build better, delivering housing via industrialized means and OSC.

Figure 3.6. Investment capital into North American OSC companies in the past decade. Source: (Author tracked investments into OSC for past decade)

3.3 OSC Opportunities and Challenges

Productivity has been identified as a barrier to advancement and innovation in the construction sector (CII, 1996). For example, several UK Government initiatives have raised concern over construction productivity (Barker, 2006; Eagan, 1998; Latham, 1994). Likewise, the US continues to lag in construction productivity, despite being the largest construction expenditure country in the world at $1.36T in 2020, exceeding pre-recession spending (US

Census, 2020). Productivity in US construction has declined by 10% from 1964 – 2004 (Figure 3.7) while all other non-farm production industries have increased in productivity by 100% (Eastman & Sacks, 2008). McKinsey charted construction productivity from 1995 – 2015 in the US and marked a declined of over one percent productivity compared with the general economic productivity that increased by 1.76% (Barbosa et al., 2017).

[redacted]

Figure 3.7. US construction industry productivity 1995 – 2015. Adapted from: (Barbosa et al., 2017).

Likewise, the UK has stagnated in construction productivity from 2000 to 2021 (ONS, 2021). Construction productivity is affected by both internal and external factors (Olomolaiye et al., 1998), including labor force balance and motivation, degree of mechanization, continuity, and complexity of work, required quality of finished work, method of construction, type of contract, the number and quality of managers, and weather impacts. Moreover, construction workforce skills levels have consistently been cited as a key factor influencing levels of construction productivity (Lavender, 1996; Naoum, 2001). Since 2009, construction has rebounded from the recession; however, the workforce numbers and skills needed to meet the new demand are not available, potentially leading to even greater productivity declines (Goodman, 2021). One of the answers to these systemic challenges of productivity and labor shortage in construction is OSC (Goodrum et al., 2009; NRC, 2009).

Citing a McKinsey 2017 report (Barbosa et al., 2017) titled *Reinventing Construction: a route to higher productivity*, the Economist (2017) writes, "Construction holds the dubious honour of having the lowest productivity gains of any industry". Supply chain pricing and the challenges of regulatory compliance (two cited root causes of construction difficulties) are only partially responsible. There are two primary culprits to productivity in construction, according to the McKinsey study: 1) the construction industry has become less capital intensive and relied on workers over industrialization strategies and 2) the industry has failed to consolidate with the average construction industry company constituting ten employees or less. This has resulted in an industry that curbs investment in favor of riding through economic volatility that disproportionally affects construction in comparison to other industries by remaining more flexible and agile as small companies. One might argue if construction, therefore, can be considered an industry or is more appropriately referred to as a sector, as it has failed to industrialize. McKinsey suggests that to overcome the productivity barriers in construction and become an industry, the sector needs to apply a "manufacturing-style" approach, or in other words rely on industrialized means, including onsite and OSC improvements to production of housing to realize a potential 1000% productivity gain based on the precedent of the modern agricultural industry transformation between 1820 – 1975 (Barbosa et al., 2017).

OSC has demonstrated improvements to vertical construction project productivity and performance in cost, schedule, and fewer change orders (McGraw-Hill, 2011; Smith et al., 2018; Smith & Rice, 2015), increases in worker safety (ILO, 2005; US BLS, 2009), potential for training and skills (Nuttpowell, 1985), and reductions in ecological impact of building construction (Quale et al., 2012). Furthermore, Neale et al. as early as 1993 documented the benefits of effective use of OSC principles to workforce and laborer. Conversely, OSC also has associative challenges directly related to OSC operations and project and delivery and external contextual obstacles. These include regulatory barriers, financing gap concerns, material supply chain disruptions, design to manufacture software incompatibility and workflow obstacles, factory pipeline inconsistencies, cultural and social barriers, and transportation complications (Smith et al., 2022). While labor is unavailable across the construction sector, OSC workforce challenges also persist, such as union roadblocks, layoffs due to inconsistent factory volume, recruitment, training, and the lack of capacity and capability of OSMs and suppliers (Cowles & Warner, 2013; McGraw-Hill, 2011, 2020; Smith, 2015, 2018; Smith & Rupnik, 2018).

3.4 Knowledge in Construction

Given the potential for OSC to increase productivity for construction generally, companies willing to invest in OSC are embracing innovation to differentiate themselves in that market (Baregheh et al., 2009). Innovation, when diffused across the construction sector can foster and increase competition (Rogers, 1962) as it more directly responds to end-user needs to solve personal, organizational, and inter-organization problems (Von Hippel, 1988). The management of OSC innovation is the management of knowledge – knowledge input and knowledge output (Quintas, 2005). Like any innovative method or practice that is evolving and maturing in construction, OSC for housing is fraught with challenges and opportunities, trade-offs, and unrealized potentials. Further, although OSC is being researched, developed, and implemented in various geographies and cultures, it continues to be a regional practice. This is because construction in large measure and multi-national global companies notwithstanding is by necessity regionally specific – material, labor, and climate (McIntyre & Strischek, 2005; Rhodes, 2015). The lack of KM culture and infrastructure - development and sharing and feedback loops - has made knowledge diffusion challenging for construction, including OSC (Quintas, 2005). Several reasons have been documented explaining why knowledge innovation is not fostered and shared in construction and by extension OSC including limitations on capacity and capability, regulatory context, competition, and lack of data culture. These obstacles to innovation are outlined in Table 3.1.

Table 3.1. Obstacles to construction innovation. Source: (literature review)

OBSTACLE	DESCRIPTION
GEOGRAPHICALLY DISPERSED	Construction is site specific, requiring unique topographical, environmental and market differences that range from the regulatory context, to supply chain, availability of workforce, and manufacturing capacity. Multi-national AECO organizations practice construction differently across country borders, even within one organization (Liu et al., 2020). Some innovation aspects in OSC are transferrable, while others are entirely contextually contingent.
REGULATORY CONTEXT	The regulatory compliance process for new products and materials is time consuming and expensive, making any investment into innovation a concern

	for company IP protection, even when the material or process improvement is not particularly innovative or protectable (Aon, 2018). The industry has complex standards and oversight bodies at the local, regional, and national scale, making innovation diffusion challenging.
LIMITATION ON CAPACITY AND CAPABILITY	Construction is dominated by small/medium enterprises with the average AECO organization being 10 persons or less and having little capacity for innovation – research and development investment, process improvement, investment in skills building and integration of digitalization and automation (McIntyre & Strischek, 2005; Rhodes, 2015). These small/medium enterprises have unique cultures and approaches that are not harmonized across the sector. OSC organizations tend to be start-ups or migrations across the supply chain working to offer additional value downstream requiring new skills and knowledge.
COMPETITION/LITIGATION	Construction in the western culture is litigious and an exercise in risk mitigation managed by financing and insurance organization just as much or more than the stakeholders that design, manufacture, and construct. Innovation, OSC included, is seen as inherently risky and therefore more expensive and limits trust and open access to knowledge and information (Merton, 2013).
DATA CULTURE	There is no significant data culture that is often seen in other manufacturing industries to measure for improvement and to claim performance (Fox & Skitmore, 2007). Furthermore, there is not a knowledge sharing platform in construction. Even if OSC actors wanted to share knowledge, there is no infrastructure or model for doing so.
PROJECT-ORIENTED	Actors in construction are concurrently working on several projects with different roles and responsibilities, scopes, and timelines. This makes knowledge sharing across project boundaries challenging as individuals are the primary vehicle for knowledge transfer and innovation diffusion. Construction, OSC included, is bespoke, making each project iteration a one-off prototype. Generalizing knowledge gained from one project to a broader industry knowledge base without the appropriate contextual frame may oversimplify or be absorbed by others sans lessons learned and situational relevance.
FRAGMENTED	There are various and diverse disciplines with unique cultures, methods, knowledge sets, and standards that converge on construction projects. The stakeholders and supply chains that support construction are highly fragmented and disassociated due to the uniqueness of each project

	iteration, geographic context, development practices, and labor and workforce pool and union coordination.
WORKFORCE	Labor in construction, the trades and craftsmen, are mutable and inconsistent project to project. Also, labor in construction is intense and demands up-skilling as new products and processes, systems and approaches are introduced. In a small/medium enterprise dominated industry, there is a significant lack of investment in people and process improvement.
PERMANENT	The product of construction, a building, is intended to last for several decades and in some cases centuries. Although the product is relatively easily maintainable, serviceable, and reusable throughout its lifecycle, something unique to construction production, this also means that in general the product is not transportable and in many cases is challenged to be recycled in the circular material supply chain.
PARTNERSHIPS	Business relationships in construction are temporary, short-term, intense, and focused on completing the singular project iteration. There is a lack of investment in long-term relationships and a significant dearth of interest in joint ventures due to this iterative nature. The volatility of the economy disproportionately affects construction organizations and therefore firms continuously hedge risk and are not forecasting consistently, including not investing in improvements, workforce, and strategic partnerships.

The knowledge needed to address the peculiarities of construction outlined in the previous table are unique from other market sectors. To understand the nature of construction knowledge, and by extension, OSC knowledge, Rezgui & Miles (2011) classify construction knowledge into four areas as follows:

1. Domain Knowledge: Administrative information, standards and regulations, codes of practice, technical rules, and product/material sources. This is fragmented and maintained by different institutions but made available to all through web portals and databases.
2. Organizational Knowledge: Company specific corporate records, information/communication technology systems, and in the heads of employees and skills of the individuals. Business relations with other partners, clients, and stakeholders.

3. Project Knowledge: Useable knowledge from individuals and the companies they represent combined for the sake of the project (domain and organizational). Often recorded for the project proper and not brought forward to future projects systematically.
4. Individual Knowledge: Bringing forward all three above acquired by individuals. This is usually tacit in form and unavailable from a codified source.

Despite the interest and effort put into KM by construction organizations, the practice of KM in construction is in its infancy (Graham & Thomas, 2008). Among the reasons for limitations are explained by Rezgui (2001) in the categories of time, intent, data, learnings, transitions, standards, and strategy. Each are reviewed below:

- Time: Valuable construction knowledge is acquired over long periods of time through many projects and rests in the minds of experts working in the domain.
- Intent: Generally, knowledge is contextual; however, intent on decisions in projects is not recorded adequately, so the knowledge may be applied again, but without the context to determine the appropriateness for a new situation.
- Data: the people collecting, and documenting knowledge are typically not the ones that will be using it. Different disciplines interpret data and knowledge differently and the data is often not managed well during the project generally, rather captured after it is complete. At that point, project stakeholders have moved on and new projects have already started.
- Learnings: Project lessons learned are not organized well and are buried in detail, making it difficult to compile and transfer knowledge to another project.
- Transitions: Knowledge is generated by individuals who often move from one company to another for employment, making it difficult to keep and transfer knowledge within an organization.
- Standards: There is a lack of standards for information technology processes and data management; not just the drawing and specifications, but all the data, emails, etc. generated for a project can be forgotten as a new project begins.
- Strategy: KM is relatively new to the construction sector, but not to manufacturing, which is an opportunity for OSC.

The construction industry is a knowledge-based industry. According to Egbu and Robinson (2005),

> "The industry can be viewed as a 'stock of expertise'. These stocks of expertise come from the flows in complex input-output systems. Knowledge flows in through hiring, training, and purchase of capital goods, while some knowledge gets 'manufactured internally'. Knowledge flows out through staff departures and imitated routines".

Construction knowledge, and OSC included, is developed in the process of construction between project teams, shared for the project proper, but rarely developed, maintained, and shared outside of discrete construction organizations and companies and these project teams. There is a need for inter-organizational KM outside of the domain of a singular project or an individual project. The aim of this project is to develop a non-project-based framework for inter-organizational KM in OSC for housing.

There are three aspects of knowledge to manage in the construction context: products or project types, processes, and people (Davenport, 2000). Products are characteristic of the services or goods being produced (Hansen et al., 1999). These end products can be devised into three distinct types: standard construction, traditional construction, and innovative construction (Bennet, 1991). Innovative projects are needed to satisfy unusual client or situational needs for which traditional or standard construction will not suffice (Bennett, 2000). Process factors are the technical and management systems required for project delivery. These can require both explicit (representative or codified) and tacit (embedded) knowledge to deliver projects. Innovative construction requires highly flexible management procedures characterized by higher utilization of tacit knowledge to manage complex design and construction processes. People factors relate to the skills and abilities of the team members.

Although standard projects can rely on basic knowledge and skills, innovative construction demands problem-solving and creative people that are facile with tacit knowledge. Team stability from project to project is key to inter-organizational learning, innovation, and development of skills and knowledge with experienced teams (Bennett, 2000; Egan, 1998). The knowledge of a construction organization or a CoP is a function of the procedures put in place to capture knowledge about processes, products, and people because it relies primarily upon people and not technology to gather, translate, and apply knowledge (Davenport, 2000; Egbu & Robinson, 2005). Technology is important, but second to people, as an enabler for KM process in any construction project or construction organization. Knowledge does not exist outside of an agent (a knower), and it is shaped by users' needs as well as their knowledge (Alvai & Leidner, 2001; Fahey & Prusak, 1998; Tuomi, 1999).

A central issue for tacit and explicit knowledge in construction, including OSC, is that personal interpretation of knowledge, to fit a specific project-based context, complicates KM practices. This makes knowledge useful in one context and sometimes useless in another (Nonaka, 1994), or worse, ill applied in a new context. Construction traditionally is tacit based (Addis et al., 2016; Rezgui & Miles, 2011). It is often characterized as a "social" sector, where knowledge is tied to people and communities – implying that explicit, codified knowledge and codification strategies may be less suited for construction (Bresnen et al., 2005; Lindgren, 2018, 2020). That issue is not stopping the construction sector, however, as there is an increase in the use of explicit knowledge by companies to improve performance (Cowan et al., 2000). But there is little in the literature to suggest ways in which construction companies can integrate and transfer tacit knowledge outside of naturalistic methods in project teams and from project-to-project migrations via people (i.e., cross-project KM).

Firestone and McElroy (2003) classify KM in construction as an evolution of three generations. The first stage of KM in construction focuses on intra-organizational knowledge sharing. This generally has referred to the use of information/communication tools for KM, codification of best practices and lessons learned within a discrete organization. This stage also includes distributing information to support decision making within the organization (Snowden, 2002). It is focused on "supply-side" KM through knowledge sharing (McElroy, 1999). This may be considered a push-based mode of KM. Second generation KM in construction is focused on human and cultural factors. It emphasizes inter-organizational learning, tacit and explicit knowledge conversions (Snowden, 2002), and "demand-side" knowledge creation and sharing (McElroy, 1999). Second generation is a pull-based mode of KM. The third generation of KM in construction is the dynamic capability development through ubiquitous, open access knowledge creation and exchange. Some product and process innovations in construction (i.e. information technology) have gone through the first and second generation and are now being used to foster value-based approaches to construction, including social justice and environmental equity.

OSC is arguably in the first generation of construction KM evolution, with much sharing occurring within organizations and project teams. It is just beginning to be addressed in the second generation with an emphasis on inter-organizational KM. Rezgui and Miles (2011) state, “practitioners have started realizing that to succeed in sharing tacit knowledge, it is necessary to share knowledge through know-how involving face-to-face or virtual interactions between knowledge transmitters and receivers”.

Liu and Elhag (2007) conducted a questionnaire survey on KM in construction for the UK and China based on tacit knowledge transfer ‘know-how’. This study was built upon previous tacit KM studies (Bresnen et al., 2003; Brown and Duguid, 2002). A total of 103 responses were captured, indicating that the stronger the reciprocal exchange context and social relationships within them, the higher the quality of ‘know-how’ was transferred. This was true for intra-organizational and inter-organizational exchange alike. However, the authors did conclude the quality of ‘know-how’ transferred between individuals in the same organization is higher than the quality of ‘know-how’ transferred between project individuals from different organizations. They found that the degree of reciprocity is negatively correlated to the presence or absence of inter-organizational competition, real or perceived, and can impact future reciprocity (Schrader, 1991). However, this is diminished when social relationships are strong between two individuals from competing organizations, following on precedent studies outside of construction (Bouty, 2000; Melin, 2000; Hansen et al., 1999). As such, inter-organizational KM in construction is directly related to both social and economic aspects of projects, competition, and individuals. The authors conclude that a key aspect of fostering inter-organizational KM behaviors amongst individuals is through modeling and encouragement by management via formal (business alignments) and/or informal (social) structures.

Summarizing Section 3.4, construction in large measure, is regionally specific with unique material supply chains, labor skills, and trades that are linked to local building conventions, and climatic demands that impact project delivery and technical criteria of development and building (McIntyre & Strischek, 2005; Rhodes, 2015). Most knowledge regarding construction is tacit or implicit, embedded within people and organizations (Bigliardi, 2014; Chimay et al, 2007). Therefore, OSC practice knowledge, built from experience, is held by individuals and organizations within these discrete regions that have delivered projects and the lessons of which have yet to be unpacked. This regional character of construction presents a barrier to knowledge sharing and advancement and innovation in the construction sector (Barker, 2004; CII, 1996; Latham, 1994). This research seeks to address the gap in OSC KM through inter-organizational exchange outside of project-based paradigms using a socialization framework. This can provide a structure for individual and company/organizational stakeholders to engage and foster KM at a more rapid pace to exchange explicit and more especially tacit, impacted knowledge, to foster OSC improved uptake and innovation.

3.5 Knowledge in OSC

OSC involves working within two areas – manufacturing and construction – where knowledge of both is required to be successful (Hjort et al., 2014). Although individual domain knowledge of both is important, the intersection of manufacturing and construction knowledge as they interface and integrate is more important for successful outcomes. OSC, to reach its full potential, applies the principles of manufacturing to construction to both onsite and offsite conditions (Mao et al., 2015; Smith, 2011). A manufacturing-style approach to design and construction practice suggests several unique technical and process changes that are specific to the operations of OSC (Hjort et al., 2014).

For architecture and engineering, the principles of design are much more aligned with product design and industrial design (Aitchison, 2017) than architectural design, using a DfMA or modularization and product platform approach (Lessing & Brege, 2015, 2018; Rupnik et al., 2022). For construction, the principles of assembly, just in time delivery, and single source contracting may be important. And for manufacturing, the fabrication of large subassemblies is more like ship building than car manufacturing due to the uniqueness of the output and mix of machines and human labor (Kieran & Timberlake, 2004). Further, the supply chain and procurement approaches are more integrated and co-dependent in OSC (Tatum, 1987).

OSC requires the ability to integrate this unique knowledge into an established construction context with its associated delivery models, finance structures, culture, labor practices, insurance and bonding, management practices, etc. This involves changes in the way that construction is practiced that impacts, according to Goulding and Arif (2013), people (stakeholders), process (operationally how things are done) and technology (building and digital tools and techniques used to deliver OSC). OSC has the potential to facilitate a shift of the construction industry to a “knowledge-based” industry (Nadim & Goulding, 2011; O’Neill & Organ, 2016), less reliant on “bricks and blocks” and more on technology and communication.

Early OSC literature from Tatum et al. (1987) suggests that workflow and project delivery in conventional construction and OSC differ (Figure 3.8). Conventional construction aligns the phases of planning, design, procurement, manufacturing, and site assembly sequentially and the delineations of which stakeholders are involved is more discrete and fragmented. Alternatively, OSC concurrently schedules workflow phases of planning, design, and procurement with considerable overlap. Manufacturing, the subassembly fabrication stage of OSC, is much more significant, requiring effort of project stakeholders in planning, design, procurement, and site assembly to center efforts around the value creation of the manufacturing phase. Furthermore, in OSC, the authors suggest that design and procurement is inextricably linked to manufacturing, much more like product and industrial design. Also, planning, often associated with early stages of delivery, is connected to site assembly as a continuous production flow.

[redacted]

Figure 3.8. Workflow related to conventional construction versus OSC, illustrating the overlaps of knowledge needed and relationships between knowledge domains of design, manufacturing, and construction. Adapted from: (Tatum et al., 1987).

Considering Tatum et al. (1987) and findings from the extant literature on OSC knowledge and skills in project workflow (Gibb, 1999, p. 22; Kamara et al., 2005; Smith, 2010), Table 3.2 was developed to compare construction knowledge to OSC knowledge for each project delivery phase.

Table 3.2. Knowledge and stakeholders associated with project delivery phases of planning, design, procurement, manufacturing, and site assembly.

PROJECT STAGE	CONSTRUCTION KNOWLEDGE	CONSTRUCTION STAKEHOLDERS	OSC SPECIFIC KNOWLEDGE	OSC STAKEHOLDERS
PLANNING	• Do we need a project? • What is the purpose of the facility? • What project delivery method will be used?	• Development managers/owner • Property consultant • Project manager • Planning authority • Financial consultant	• Does OSC aid in meeting the cost, time, labor site, and programmatic goals for the project? • What project delivery method	***Same as conventional construction PLUS*** • OSC consultant or OSM feasibility for feasibility evaluation

	• Where is the project going to be built? • Who are the firms to do the work? • Who will support our goals?	• Lending institution • Insurance bonding agent	will facilitate early decision making and collaboration? • Is the site accessible, are transportation paths open, and is craning possible? • What firms can manage an OSC process, and can we pre-qualify them?	• Transportation company • General contractor (GC) / construction manager (CM) planning assist
DESIGN	• What are the site responses for design? • How do the regulations apply? • What are the size, shape and materials and methods used in the project? • How much will it cost? • What is the schedule?	• Architects and design team • Engineers • Facility managers • Cost estimators • Project managers • Code officials	***Overlap of planning and design phase work in OSC*** • What approvals and inspections are needed for enclosed construction offsite? • What product platform is being used? • What are the manufacturers standards for subassemblies and integration? • How will the project be manufactured, transported and site assembled (DfMA)?	***Same as conventional construction PLUS*** • OSM manufacturer • GC design assistant • CM • Site subcontractors • Owner/developer

			• What design aspects need to be locked and when? • What is the LOD prior to manufacture? • What drawing and specification conventions define site and factory scope delineations?	
PROCUREMENT	• Where can we obtain materials, products and components? • How and when do we need them on site?	• GC • CM • Materials and equipment suppliers • Architects and design team • Engineers • Lending institution • Insurance and bonding	***Overlap of design and procurement phase work in OSC*** • How is site work and factory workforce sequenced and coordinated? • Who needs to communicate with whom and when? • How and when do subassemblies and materials need to be onsite?	***Same as conventional construction PLUS*** • OSM manufacturer • Site subcontractors • Owner/developer
MANUFACTURE	***Overlap of procurement and manufacture phase*** • How are design changes reduced and orders placed?	• Material suppliers • GC • Architects and design team • Engineers	• What sub-assembly prototypes need to be manufactured and approved? • How and when are subassemblies	***Same as conventional construction PLUS*** • OSM manufacturers • Owner/developer • CM • Code official

	• What shop drawings need to be reviewed and who will review them? • What change orders on materials need to take place?		inspected in the factory by regulators? • How is design and procurement work coordinated with manufacturing? • How are the DfMA subassemblies executed, and feedback loops ensured? • How are subassemblies sequenced in order of installation just in time? • How are site and scope delineations reinforced and communicated? • How are subassemblies transported, stored and staged?	
SITE ASSEMBLY	***Overlap of manufacture and assembly phase*** • What inspections need to take place onsite?	• CM • GC • Sub-contractors • Sub trades • Inspectors • Architects and design team • Engineers	• What sequence are subassemblies arriving? • How will subassemblies be installed? • How will subassemblies	***Same as conventional construction PLUS*** • OSM manufacturer • Owner/developer

	• How can we organize labor to perform the project efficiently? • How can site storage and handling be minimized? • How can change orders be identified and processed efficiently? • How can we ensure quality and safety? • What close-out commissioning needs to take place?		connect to site work? • What labor will perform site assembly? • How will the building be buttoned up?	

Similarly, Ginigaddara et al. (2019, 2021) studied the unique skills that are needed to manage OSC processes and projects. This was accomplished through a literature review and workshop that engaged industry participants to identify OSC skills needs. The authors organized the findings into three categories: vocational skills, professional skills, and skills common to both vocational and professional roles. The results indicated that although vocational skills are generally considered 'hard' trade skills (Daly, 2009) and professional skills are often associated with 'soft' management and administration skills (Nadim & Goulding, 2010), in OSC, the two areas converged more than in conventional construction. Industry respondents in the study indicate that the most "critical skills" for both professional and vocational workers in OSC were interpersonal, followed by knowledge of OSC and then digital design skills. This confirmed the findings from the literature review by the team in which "knowledge management" and "knowledge" (generally) was of highest importance for both vocational and professional workers in OSC.

Gan et al. (2018) indicate that stakeholder collaboration is key to aggregating knowledge, material, technology and other resources highly dispersed across various stakeholder groups to address the barriers to OSC adoption. The researchers point out that there are numerous studies that identify the barriers and rank them on their impact for adoption and diffusion of innovation accordingly. The authors linked 13 identified barriers with 15 stakeholders in China to provide a unique perspective on stakeholder collaboration in OSC using a two-mode social network analysis. The findings suggest that government and developers are the most influential stakeholders, and knowledge and expertise amongst these stakeholder groups is the most significant barrier to OSC adoption. The authors suggest that government and developers actively lead in fostering “collaborative networks” with designers, manufacturers, and contractors in developing an “information exchange platform” to form a “shared repertoire” (Wegner, 1998) to increase stakeholder collaboration in OSC. It is unclear if the findings of this research are relevant in the context of more mature OSC contexts such as the UK and US, and even more evolved contexts of Japan and Sweden. However, the results do suggest that there is a direct relationship between OSC barriers and stakeholder groups (disciplines) that warrants further study, and that CoPs and exchange platforms are important for knowledge share to increase adoption and uptake of OSC in the context of this study.

Section 3.5 addressed the general differences of construction versus OSC knowledge. A characteristic of OSC knowledge is the integration of two domains, manufacturing and construction. Furthermore, the literature suggests that designers are required to have knowledge and skills similar to product design and builders to have supply chain integration knowledge. Furthermore, OSC project delivery is different because pre-planning is more critical than in traditional construction, designs must be locked early on, and a DfMA approach is employed to consider how the design will be manufactured, fabricated, transported, set, and finished onsite.

3.6 OSC Knowledge Categories

This section of the chapter is an assessment and categorization of OSC knowledge. The review includes literature from 1) books – sole, co-authored, and edited volumes and 2) industry reports. Books and reports are codified publications intended for a generalist audience, written by scholars and expert practitioners. Therefore, these texts are of interest because they are artifacts that infer decisions by authors to organize OSC knowledge in a particular way. In the following sections, the two types of literature – books and reports - are reviewed, observations recorded, and then a frequency analysis is provided to determine the most common OSC categories that emerge from these sources.

3.6.1 Popular Versus Specialist Books

Matthew Aitchison and co-authors (2018) in *Prefab Housing and the Future of Building: Product to Process* explain the foundations of literature in OSC housing. They point to the difference, separation, and chasm between “popular works and specialist works” of literature. Popular content in OSC has an aspirational, mysterious, marketing orientation that suppresses the realities, complexities, and problems, while overselling the benefits and potentials, beauty, and novelty of OSC that can be summarized in the lay term “prefab”. The authors cite specialist and scholarly “landmark studies” including Kelly (1951), Bemis and Burchard (1936), Bernhardt (1969), Herbert (1978, 1984), Davies (2005), Bergdoll (2008), Fetters (2006), and Smith (2010). Popular (coffee table) text examples include Koones (2016), Serrats (2012), Friedman (2021), and Arieff and Burkhart (2002).

Aitchison et al. (2018, p. 32), postulate that the reason for the gap between popular and specialist texts in OSC is because of several factors: 1) limited formal education of built-environment disciplines in OSC; 2) growing divide between academy and industry; 3) reductive and superficial approach to popular articles; and 4) the idea that OSC fulfills a crucial role in the public imagination. Gilbert Herbert (1984) refers to this as the “dream of the factory-made house”. OSC presents an imagined “silver bullet” or “holy grail” for those in the construction sector and those outside, it “represents a kind of science fiction”.

Alison Arieff (Arieff & Burkhart, 2002), one of the populist authors, was also the editor at Dwell Magazine at the time this publication was released and the Dwell prefabricated housing competition was held that spurred a resurgent interest in OSC public awareness in the early 2000’s. The magazine continues to play a significant role in evangelizing OSC as “prefab” to lifestyle media consumers in the US.

A related category of literature oriented at practicing architects contains monograph books that demonstrate examples of OSC housing, details, systems and stories of manufacture and assembly that are richly illustrated. These books include the following examples: Meuser (2020), Bayliss and Bergin (2020), Hogan-O'Neill (2021), Wallance (2021), Staib et al. (2008), among others. There are also manufacturing specific books for OSC including Mullens (2011) and Albern (1997), aimed at engineers. OSC and manufacturing specific books are less common, and most of this information is highly technical and appears in peer-reviewed journals regarding factory optimization, application of information technology, and OSM quantification research.

Aitchison's authored and edited text itself is a balance of practical and theoretical lessons, presented by leading OSC academicians. The book covers not only the foundations of OSC housing literature, but also the historical changes in OSC housing from 1950 wherein there was a clear polarization between "utilitarian and conceptual" OSC, to the present in which the OSC industry has evolved into more diverse market offerings as multi-family housing has increased in the broader construction sector. The book covers the barriers to uptake and success, as other texts aim to address, but also a unique chapter on the "total system" of OSC housing through an analysis of OSC as "innovation" (Lindgren, 2020; Rogers, 1962), "knowledge production" (Gibbons et al., 1994), "wicked problems" (Rittel & Webber, 1974), "design thinking" (Brown, 2008; Martin & Martin, 2009), and "problem solving" (Wang & Chiew, 2010).

In "Building Offsite: an introduction", a Royal British Architects endorsed continuing professional development primer on OSC, Hairstans (2014), professor at Edinburgh Napier University, organizes OSC knowledge into the following sections: system categories (i.e., panel, modular, components, etc.) and levels of enhancement, terms and definitions, advantages, barriers, design, information technology, technical performance, environmental performance, site management, and case examples. The primer is centered on Scottish OSM Timber Systems. A longer and more comprehensive version of this pamphlet is *Off-site and Industrialised Timber Construction*, also by Hairstans, first published in 2010 with a new edition in 2019.

The US corollary, *Design for Modular Construction: An Introduction for Architects AIA Guide to Modular Construction* (Wilson, 2019), follows a similar pattern to Hairstans, aimed at architects. The introductory text covers contextual market drivers, system categories, manufacturing process, benefits, barriers, project delivery phases (pre-design, design, post-design, and site assembly) and how OSC is unique at each phase. *High-Rise Modular Construction* is a guide that is similar in scope, purpose, and length and was written by a team from ARUP Group, a full service engineering built environment firm, with contributions from experts in modular construction (Deormann et al., 2020) covering a brief history, market data, drivers and benefits, project delivery (planning, design, construction), and regulatory frameworks focused on North America (US and Canada) in particular. This text provides an expanded section on navigating the regulatory process of the Canadian Standards Association and the International Code Council (US), pointing to new standards developed by the organizations for the US and Canadian OSC markets to overcome the unique challenges of North American permitting and inspection processes that are managed at the local municipal level. These digital publications are broad overviews of concepts and definitions and meant to be an introductory primer pointing to more detailed sources. The *AIA Guide* and *High-Rise Modular Construction* were developed in a consensus process involving subject matter experts across the OSC supply chain.

Arguably the trailblazing practical and applied guide of 21st century OSC is Alastair Gibb's seminal work, *Off-site Fabrication: prefabrication, pre-assembly, and modularization* (1999). Written from a UK construction management perspective, this reference provides insights into techniques, project delivery, productivity, and safety, arranged in easily consumable bullet points, tables, and simple black and white illustrations on OSC broadly and not specific to housing. Likewise, Lawson et al. (2014), a trio of academic professors in the UK, present a thorough *Design in Modular Construction* book on UK volumetric modular. The focus is on steel and concrete commercial applications of modular, and a wide array of building types. The volume is heavy on technical criteria for modular construction – structure, enclosure, and service systems. It covers factory production and site construction issues of volumetric modular, in addition to the economics and sustainability of OSC. Offsite built examples are sprinkled throughout.

The MBI, modular trade association, commissioned a textbook titled *Introduction to Modular Construction*. Chris Piper (2015), lead author and construction management academic in the US, organized the manual in two parts. The first part, principles and participants, covers the process, pros and cons, stakeholders, and safety programs in modular construction. The second part addresses the phases of project delivery, including design, pre-construction, and construction when using modular. The textbook identifies people as a key component to OSC knowledge.

In addition to popular and specialist literature on OSC housing, edited volumes that compile researched and scholarly works on OSC topics have materialized. The author and John Quale, professor at the University of New Mexico, edited and wrote *Offsite Architecture: constructing the future* (2017) that assembles contributions from leading thinkers, scholars, and practitioners internationally to address theories and practical findings that identify and communicate opportunities and challenges, successes, and failures of OSC. Although the edited volume covers OSC broadly, it emphasizes OSC housing across two parts – theory and practice – with a final section on international OSC including Sweden, Japan, and Scotland as contexts. Similarly, Goulding and Rahimian's (2020) edited book *Offsite Production and Manufacturing for Innovative Construction: people, process, and technology* collects leading experts in the field of OSC to provide original research inclusive of housing. At the end of each contribution are helpful "key learning points" as insights that connect the discrete contributions. The edited volume addresses the following knowledge areas: OSC drivers, inhibitors, accelerators, disruptors, design, manufacture, site assembly, virtual reality, information/communication technology and automation, organizational learning, stakeholders, contracts, and innovation diffusion. The last chapter by Lindgren (2018, 2020) provides significant insights and points to primary literature sources referenced in Chapter 02 of this thesis on KM theory.

3.6.2 Industry Reports

Another format of OSC literature is industry reports that are both general and specific. The goal of industry reports is to capture the current state of practice in OSC, as well as the barriers and opportunities of such to communicate to both OSC experts and the architecture, engineering, construction owner (AECO) industry that is new to OSC. There is a third audience that these reports speak to, that of investors outside and inside of the construction supply chain that are seeking to disrupt and find solutions to productivity challenges and capitalize accordingly. The reports aim at generalist knowledge, not specific to any one discipline in OSC supply chain or knowledge background and are international in focus, aimed at addressing all OSC building types. The reports, however, are focused on more mature economies that already have an established industrial supply chain for construction.

The UK has developed a series of reports that are aimed at identifying and suggesting ways to overcome the documented lack of productivity to improve efficiency. The Latham Report (1994), titled *Constructing the Team*, was commissioned by the UK government in partnership with industry to review the procurement and contractual arrangements in the UK construction sector that are limiting growth and progress systemically. Latham criticized the construction sector as being adversarial, ineffective, fragmented, not delivering, and lacking respect for workforce. The 53 recommendations from the report were intended to change industry practice and replace the wasteful and confrontational construction culture to one of cooperation, trust, and mutual improvement.

The Eagan Report (1998), officially titled *Rethinking Construction*, following Latham and supported by a host of industry organizations, has been highly influential in developed economies around OSC topics. The report was an assessment of the UK construction sector and identified five key drivers of change: committed leadership, focus on the customer, integrated processes and teams, a quality driver agenda, and commitment to people. Furthermore, Eagan advocated for an integrated process to construction delivery consisting of product development, project implementation, partnering the supply chain, and production of components. The latter stages, supply chain and production, point directly to OSC.

In 2016, Mark Farmer, CEO of a Cast Consultancy, raised the challenge to the construction industry to "Modernise or Die" in a report focused on UK construction labor titled *The Farmer Review of the UK Construction Labour Model*. The review highlights the construction industry's dysfunctional training platform, lack of innovation and collaboration, and dearth of R&D activities and culture. Farmer points to this negligence of the sector as part of the cause of rising inflation that is a result of and caused by labor shortages and the decline of housing affordability. He offers ten recommendations for immediate action that are specific to UK organizations, and a few are OSC specific. Farmer suggests that the Construction Industry Training Board reorganize its grant funding for skills and training toward a future modernized industry. Another recommendation is that industry and government invest in R&D and innovation by changing commissioning trends from traditional to pre-manufactured approaches. Further, there is a suggestion that government promote the use of pre-manufactured solutions in the housing sector. Fundamental to this report and a shift from previous reports that called for productivity improvements, Farmer implores government and industry to face the labor shortage head on by using OSC methods, among others. Since the release of the report, there have been many funding schemes, pilot projects, research organizations, and universities in the UK that have oriented their efforts toward solving the productivity, cost overruns, and lack of labor supply through studying and applying industrialization of onsite and offsite operations of development.

In the US, similar industry-based consultancy reports have come forth. In 2013, FMI Corporation, a management consulting company, performed a survey to identify the barriers to adopting OSC and the extent to which OSC has contributed to a return on investment – value creation – for project-based construction economics. The survey was distributed to building construction trade companies in the US including GCs, CMs, MEP subcontractors, and heating/ventilation/air conditioning (HVAC) subcontractors, etc. through email. The survey captured comments on "challenges" and "hurdles" that users must overcome when utilizing OSC. The most frequent comments were grouped into the following categories in order of priority: 1) the need for early collaboration and engagement of stakeholders; 2) perceptions/stigmas; 3) permitting issues (regulatory); 4) design-bid-build contracts; 5) design and construction culture; and 6) labor unions (Cowles & Warner, 2013).

Also in the US, in 2011, the SmartMarket Report team at McGraw-Hill Dodge Data, a construction industry data and publishing organization, produced a report, titled

Prefabrication and Modularization: Increasing Productivity in the Construction Industry, to provide industry views on prefabrication and modularization and their impact on the construction sector. The report is a result of an online survey of 809 respondents from across the AECO professions. The survey quantifies the impact of OSC on project schedules, cost, safety, quality, and waste reduction. The study also involved 15 in-depth qualitative interviews with owners and developers. The study asked about barriers to OSC from two discrete groups -users and non-users. The results of the report indicate the primary reason for not using OSC is that architects do not design them into the project and architects claim that they are getting resistance from owners.

A follow-up longitudinal report was issued by the SmartMarket team titled *Prefabrication and Modular Construction 2020* and demonstrates OSC industry is maturing in the US. The survey portion of the report of AECO professionals determined to separate the respondents into experienced and less-experienced stakeholders (versus experienced and no-experience from 2011) to identify perceptions versus actual experience of OSC performances. Furthermore, the 2020 survey distinguishes general prefabrication (components and kits, MEP racks, etc.) from permanent modular construction or volumetric modular that is growing rapidly in the US, illustrating an evolving and maturing industry. The obstacles to increased use of general prefabrication include project delivery limiting effective planning, products not designed for OSC, project type not being amendable to OSC, availability of fabricators near the site, and availability of trained workforce for installation. For volumetric modular, respondents indicated the following obstacles: owner is not interested in modular, availability of modular manufacturers, project type not applicable, delivery method prevents effective planning; all scored above 50% of respondents. A key finding from the report is that information technology "enhances improvements" of performance (cost control and schedule reduction) when implemented in OSC projects. Some challenges noted by the report indicate that for owners/developers using OSC, there is a lack of accurate cost estimating from GCs and OSM suppliers, the finance sector is not knowledgeable, and there is evidence of poor designer knowledge in DfMA.

Fannie Mae is a US federal and national secondary mortgage capital lender for housing. In 2020 the organization partnered with the National Institute of Building Sciences (NIBS) Offsite Construction Council (OSCC) members to produce a report, the *Multifamily Modular Construction Toolkit*. The report references the NIBS surveys and many publications by the NIBS OSCC and the author on legal, finance, how to, barriers, opportunities, and futures. The audience for the report was the general stakeholders in construction, with an emphasis on Fannie Mae's constituents, lending institutions and developers of multifamily housing. The report identifies challenges with OSC in the US including increased coordination between stakeholders, greater upfront capital draws for design assist, design time and factory deposit and set up, regulatory overlaps between the authority having jurisdiction (AHJ), or regulatory agency, and the state enclosed modular program, and technical limitations such as floor-to-floor heights, transportation restrictions, limited spans, lack of transparency in costing, and limitations on future adaptive reuse of OSC structures (Smith, 2016).

The report targets how OSC is different procedurally than conventional construction for developers and lenders. The list of differences includes the need for considerably more pre-design planning, including the developer being more engaged and hands-on early in the process to pre-qualify manufacturers, assess site feasibility for crane locations and picking access, determine if the transportation route from factory to site is viable, ensure that insurance and bonding will accommodate OSC, and determine scope delineations for the design to manufacture to assemble handoffs. Furthermore, the report points out the need to determine early on AHJ understanding and acceptance of OSC and the relationship between the AHJ and the state if there is an enclosed modular code (35 of the 50 states have an enclosed construction code) (MBI, 2022). It goes on to instruct developers and lenders about when to use OSC for greatest potential success including parameters such as projects that have the need for shorter schedules, are repetitious, need a higher degree of control, stakeholder experiences with OSC, difficult remote or dense urban sites, limited available skilled labor and lack of supply chain access to affordable material.

In a 2017 report by Barbosa et al., McKinsey and Company turned to construction as a new domain for business opportunity through the report, *Reinventing Construction: a route to higher productivit*y. The authors of the report point out the productivity challenges in construction broadly with only 1% growth over the past 20 years, compared with 2.8% in the world economy and 3.6% in manufacturing globally, identifying industry wide causes to the lack of efficiency. Ten root causes are listed by McKinsey including the following: 1) increasing project complexity, 2) extensive regulation, 3) informality and potential corruption distort the market, 4) opaque and fragmented industry, 5) contractual structures and incentives misalignment, 6) bespoke and suboptimal owner requirements, 7) design process investment inadequate, 8) poor project management and execution, 9) insufficient skilled labor across the board, and 10) underinvestment in digitization, innovation, and capital. The authors also outline seven areas to boost sector productivity by 50-60%: reshape regulation, rewire contracts, rethink design, improve procurement and supply chain, improve onsite execution, infuse technology and innovation, and reskill workers. These seven areas identified by McKinsey are repeated in many of the knowledge area needs in this chapter of the thesis.

The 2017 report led to a follow on by McKinsey (Bertram et al., 2019) titled, *Modular construction: From projects to products,* in which the authors identify a “manufacturing-style” approach to both onsite and offsite activities to improve construction productivity dramatically. The report offers the industry much needed clarity on terminology and concepts in the OSC sector including means and methods of units, panels, and volumes. The report normalizes the benefits for a broad audience of investors, builders, owners, and OSC stakeholders as well. The report is positive indicating the potential benefits of OSC across the value chain of construction; however, it does outline how the supply chain may need to change to move to manufacturing oriented construction, including suggestions for investors, material suppliers, the public sector, architecture, and engineering firms, and all those across the supply chain. Although the claims, concepts, and futures outlined by McKinsey in this report are not new to OSC scholars and practitioners, the authors present these concepts in business language that has captured the interest and imagination of investors inside and outside of the current construction industry, positioning construction as potentially able to be disrupted via technology, as has occurred in many other industries (Smith & Rupnik, 2020).

3.6.3 OSC Knowledge Categories Summary

This section reviews observations from the books and reports on OSC that are written as overviews of OSC knowledge. The aim of these texts is to categorize knowledge into digestible format for readers to understand the scope, scale, and contingencies of OSC. Common themes noted from these literature sources include the distinction between popular and scholarly literature, contextual versus operational knowledge, project delivery or project-based organizations of OSC knowledge, and a focus on 'why' (explicit) OSC instead of 'how' (tacit).

Popular literature is written for the public (e.g., lifestyle pieces) and the general or traditional AECO industry through popular press journalism (e.g., professional magazines and blogs). Specialist/scholarly texts are peer reviewed and seek to create or clarify knowledge. Another set of defining categories discovered in this literature review of OSC knowledge types is historical versus contemporary texts and theoretical versus applied sources. Historical texts represent the first wave of OSC from the late 19th century to the post-war OSC boom in the middle of the 20th century. Distinct from first wave, OSC is 21st century OSC with the accompanying information technology, modern management techniques, and progressive contracting. Although the lessons from the past are important for future practice, second wave OSC is the emphasis of this thesis to progress OSC today. This thesis focuses on contemporary knowledge concerns. Lindgren (2020) points out that knowledge creation and exchange is central to innovation development and innovation diffusion, including OSC. Both generalist and specialist knowledge are needed to solve problems in an overall efficient manner.

Another theme that emerges from the OSC knowledge analysis is contextual knowledge versus operational knowledge. In this distinction, contextual knowledge is that in which OSC exists including the regulatory, economic, social, cultural, and labor situation. Conversely, operational knowledge is that which is specific to develop, design, manufacture, construct, and maintain OSC: the skills needed to deliver and manage OSC effectively and efficiently. There are knowledge and skills that are inter-organizational in nature. However, many types of knowledge are specific to the condition in which they emerge – a discrete company or geographic location. OSC in the UK is different than OSC in the US because of the contextual forces, and OSC in the US and UK are significantly different than OSC in China, for example, due to availability of labor and material, supply chain alignments, and procurement practices (Liu et al., 2020). These forces have shaped the construction industry in these contexts, and the OSC market and industry in these countries as well, making generalizable knowledge difficult to codify in any construction knowledge domain, but especially in OSC.

An additional observation from the generalist books and reports on OSC knowledge is that construction relies on a project-based work method, following traditional project delivery stages and conventional stakeholders – illustrating how OSC is different for these parties. This is unique from other business sectors such as manufacturing that has more fluent and non-disrupted processes (Naar et al., 2016). OSC requires a long-term commitment between parties and closer control and coordination to reach a higher level of industrialization (Lessing et al., 2015) which differs from traditional construction that has a short-term project-based perspective (Barlow, 2000). Construction also lacks a long-term planning approach (Miozzo & Ivory, 2000) and is fragmented with adversarial relationships (Annan, 2012). The investment in long-term partnership and long-term planning, long-range commitments toward innovation are not warranted in the cyclical and episodic construction practice. However, OSC presents a new opportunity for continuous process improvement, and enabling learning across a series of projects with consistent stakeholders (Lessing et al., 2015). Lindgren (2020) claims that “inter-organisational focus with changes across the construction process may create greater benefits” (p. 490 - 514. He continues, “Continuity of production processes offers improved opportunities for effective collaboration, compared to traditional fragmented construction processes.”

The literature frequency analysis indicates that more than 50% of the OSC books and reports address the following knowledge areas in order of most frequent to least (Table 3.3):

- Construction culture changes in OSC
- Barriers and challenges in OSC
- Stakeholder roles in OSC
- Housing solutions in OSC

- Market and organizational drivers for OSC
- Cost and schedule performance of OSC
- Manufacturing principles in OSC
- Benefits of OSC
- Supply chain alignments in OSC

The books and reports analyzed seek to answer ‘why’ and ‘what’ of OSC and not necessarily ‘how’. The literature explains the high-level benefits (cost and schedule), challenges, opportunities, drivers, and cultural difficulties of moving from conventional construction to OSC, but does not offer solutions, processes, and methods for delivering OSC. At the bottom of the list of reference topics by frequency of occurrence in the OSC books and reports is ‘how’ to accomplish OSC – technologies, processes, procedures, details, etc. This may be because OSC is still relatively new and because other literature sources, such as peer reviewed journal articles, cover more technical criteria. However, this is also because ‘how-to’ knowledge is tacit, and difficult to codify in publications. It is ideally transferred through socialization modes, between project and in-between project learning via inter-organizational exchange.

Table 3.3. Frequency analysis of categories of OSC knowledge in the literature.

OSC KNOWLEDGE CATEGORY	Books																				Industry Reports								Totals
	Aitchison et al., 2017	Kelly, 1951	Bemis & Burchard, 1936	Bernhardt, 1969	Smith, 2011	Herbert, 1978, 1984	Davies, 2005	Bergdoll, 2008	Fetters, 2006	Arieff & Burkhart, 2002	Hogan-O'Neill, 2021	Wallance, 2021	Hairstans, 2019	Wilson, 2019	Deormann, Finzel, Barret, 2020	Gibb, 1999	Lawson, Ogden & Goodier, 201	Piper, 2015	Smith & Quale, 2017	Goulding & Rahimian, 2020	Latham, 1994	Eagan, 1998	Farmer, 2016	FMI, 2013	McGraw-Hil, 2011, 2020	Fannie-Mae, 2020	Barbosa et al., 2017	Bertram et al., 2019	
Culture	1	1	1	1	1	1	1	1	1	1		1	1	1		1	1		1	1	1	1	1	1	1		1	1	24
Barriers/Challenges	1		1	1	1						1	1	1	1		1	1	1	1	1	1	1	1		1	1	1	1	20
Stakeholders			1	1	1								1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	18
Housing	1	1	1	1	1						1		1			1	1	1	1		1	1	1		1	1	1	1	18
Drivers			1	1	1				1		1	1	1	1			1	1	1	1					1	1	1	1	16
Cost / Schedule				1	1								1	1	1	1	1	1	1	1			1	1	1	1	1	1	16
Manufacturing principles	1	1	1	1	1								1	1		1	1	1	1	1		1	1		1			1	16
Benefits	1		1		1						1	1	1	1		1	1	1	1	1					1	1	1	1	16
Supply Chain	1	1	1	1								1	1			1	1		1	1	1	1	1		1		1	1	16
Design (DfMA)	1				1					1	1	1	1	1		1	1		1	1			1		1			1	14
Productivity		1		1												1	1	1		1	1	1	1		1	1	1	1	13
History of OSC	1				1	1	1	1	1	1	1	1			1	1			1										12
OSM subassemblies	1	1			1						1	1	1	1		1	1		1									1	11
Sustainability					1								1			1	1		1		1	1	1		1			1	10
Regulatory process				1										1	1		1	1	1					1	1	1		1	10
Market statistics		1	1	1											1				1		1	1	1		1			1	10
Site Assembly				1	1						1		1			1	1	1	1	1								1	10
Safety				1												1	1	1		1	1	1	1		1			1	10
Workforce																1		1		1	1	1	1	1	1		1	1	10
Commercial					1						1					1	1	1	1	1					1		1	1	10
Case studies	1	1		1	1								1			1	1		1	1					1				10
Fragmentation																1	1			1	1	1	1		1		1	1	9
Project delivery phases					1								1	1		1	1	1			1	1			1				9
Theory	1		1									1				1			1	1							1	1	8
Financing				1	1													1	1						1	1		1	7
Contracts					1											1	1	1						1	1			1	7
Customer centric																			1	1		1	1				1	1	6
Site industrialization				1					1												1	1	1				1		6
Product platforms	1										1		1						1	1								1	6
ICT/BIM					1						1		1				1			1					1				6
Technical criteria				1	1						1		1			1	1												6
Business Models	1	1																		1							1	1	5
Details					1						1					1	1												4

3.7 OSC Knowledge Priorities

Section 3.6 reviewed the categories and types of knowledge in OSC found in books and reports organized by scholars and practitioners to communicate with a general audience about the scope of OSC knowledge. Building upon this overview of OSC knowledge categories, this section aims to identify the knowledge needs and priorities of OSC through analyzing barriers and opportunities in the OSC knowledge domain. The barriers and challenges to OSC target the obstacles to increasing industry uptake and adoption, progress of innovation, and advancement. Despite the many documented and researched benefits to OSC covered in this chapter, OSC uptake is slow. The perceived versus actual benefits of OSC continue to evade researchers and practitioners with the gap being technical, social, and political (Nadim & Goulding, 2010). Barriers are also a key indicator of knowledge gaps, knowledge needs, and the areas that research can aid in overcoming and finding solutions to address these roadblocks to successful OSC decisions and implementation. Literature sources that identify key research needs are found in peer reviewed articles and research roadmap projects.

This literature review of OSC barriers and research needs was performed through a key word search using Google Scholar search engine, and the University of Utah and Washington State University physical and digital library archive. The key word "offsite construction" and hyphenated "off-site construction" was searched in combination with "barriers", then "challenges", "obstacles", "adoption", "uptake", and finally "research needs". In all these combinations, "offsite construction" was replaced by the word "prefabrication", then "industrialized construction" and then "offsite manufacture". The most frequent journal articles that resulted in these searches were gathered. Together, these references were analyzed, and the author noted the reoccurrence of several articles that were summarized by key authors who performed their own literature review of OSC barriers. Therefore, these gateway articles were assimilated with the most relevant "barrier", "challenges" and "obstacles" articles to form the basis of the literature review in determining OSC knowledge needs from the available literature. During the review, it was noted that there are a few research roadmap reports that result from the "offsite construction" and "research needs" combination that are particularly relevant to identifying knowledge gaps in OSC. In the following sections, research needs are analyzed from these journal publications and research roadmap efforts and then summarized as knowledge needs results using a frequency analysis.

3.7.1 Journal Publications

This section identifies the key barriers to OSC by assessing peer-reviewed journal publications that use a systematic approach to knowledge gaps analysis and finding commonalities and frequency of barriers identified. Some themes that emerge in reviewing the articles and studies on OSC barriers are cross referenced to one another and therefore reveal common themes and knowledge needs.

Hosseini et al. (2018) performed a systematic literature review of 501 journal articles to critically evaluate the state of OSC research. The authors, through a bibliometric study, use a keyword analysis and a co-citation analysis via software. The paper points to the fact that most OSC research publications are focused on 'product' aspects of OSC such as specific OSC technologies, materials, and systems, and that research in OSC is primarily conducted in isolation as singular authors. The paper outlines the need for research in OSC operations, process, management, and strategic considerations for identifying a factory, which influence decision making processes when using OSC. A limitation to the study is that all things OSC are grouped into this analysis, and therefore it is clear that precast dominates all categories by a 2:1 ratio in the keyword analysis. In the co-citation assessment to find "patterns" of topical focus, precast likewise dominates. Of the nine citation cluster foci identified, precast concrete system, free-form concrete panel, and temporary precast facility are included. Despite this imbalance, 67% of all the studies belong to no cluster, meaning the OSC research landscape is fragmented. There is a need for researchers to "collaborate and enhance dialogue, debate and cross-fermentation of ideas and initiatives," due to the "lack of focus, exchange of ideas and debate among investigators" (p. 244) in OSC.

Akmam et al. (2018) reviewed literature to seek factors that influence the decision-making process when using offsite strategies in the housing sector. The authors determined that these factors can be categorized into three areas: contextual, structural, and behavioral. The contextual factors include the macro-economic conditions, maturity of technology development and adoption, government involvement, sustainability value, and stakeholder participation. The structural factors include project conditions, procurement methods, management approach, communication process, and decision-making style. The behavioral factors include experience, awareness, and attitude, and “bounded rationality” whereby individuals have limited ability to make decisions due to their cognitive ability, time constraints, and imperfect information (Akmam, 2018). Gusmao et al. (2020) review the decision factors affecting the use of OSC in the US multi-family housing market. The authors organize their literature review of 45 journal articles and industry reports from 2000 to 2019 into three primary areas of social, environmental, and economic findings to compare to the sustainability triad. The analysis resulted in 28 factors affecting decisions on the adoption of OSC that reiterate extant literature on the subject and reinforce Zakaria et al.’s findings from 2018.

In Li et al. (2014), the authors reviewed 100 studies related to the management of OSC and found the following common research areas: industry prospect, development and application, performance evaluation, environment for technology application, design, production, transport, and assembly strategies. The authors point out the propensity for OSC researchers to seek to identify the opportunities and challenges, benefits, and barriers, to applying OSC and performing evaluations of industry development. This includes internal strengths and weaknesses of management ability, technology ability, financial ability, organization, and operations. For external opportunities and threats, the authors point to social and political context, economic context, market opportunity, and competition mechanisms.

Jin et al. (2018) discuss the status of OSC literature relative to Li et al. (2014) and propose that the future research in OSC should focus on process improvement, technology applications, and performance evaluation. Other authors have outlined process barriers to OSC including transportation parameters that dictate OSC subassembly formation and dictate decision up and downstream (Tatum et al., 1987), the impact of delivery method on OSC success (Salama et al., 2018), and the need for clear market and business strategy and approaches that align (Lessing & Brege, 2017) with a product platform with standardized products that are configured into different building outcomes. This approach relies on customer feedback and continuous improvement strategy for the OSM subassemblies and macro building design.

A research paper by Salama et al. (2021) in the *International Journal of Industrialized Construction*, titled “Overview of the Characteristics of the Modular Industry and Barriers to its Increased Market Share in Canada”, provides a comprehensive analysis of knowledge categories and knowledge needs in OSC in North America. The authors used precedent studies and surveys conducted in the past decade by MBI (US), BuildOffsite (UK), McGraw-Hill (2011), FMI (Cowles & Warner, 2013) and studies from NIBS (Smith, 2014, 2018) in Section 4.3 of this chapter. The authors then conducted their own survey with the purpose of verifying the findings from the precedent surveys to categorize OSC. The survey by the authors of this article also identified barriers that limit market uptake. The findings indicate the following five barriers and proposed solutions from respondents:

1) Negative Stigma for OSC: Solutions include workshops with industry, government, and universities involved to share knowledge and to have trade associations target the AECO with continuing education and universities to offer OSC specific courses.
2) Lack of Published Precedents: Document built examples sponsored by government and academic research that highlights data on performance of the built OSC projects and lessons learned to be disseminated.
3) Standards and Regulations: These continue to be a barrier, especially in North America, and respondents indicate working with code officials to foster education through trade associations.
4) Procurement Practices: OSC changes the perception of relationships between project stakeholders and requires more coordination and planning with design freezes earlier in the project development timeline requiring more study into supply chain optimization strategies in other industries as they may be applied to OSC.
5) Project Finance: Ownership of the assets in OSC is seen as confusing and a risk factor by respondents and a solution is to have a clearer definition of scopes and payment schedules as a standard for the industry developed through research as well as finance vehicles and lending practices for OSC specifically.

Razkenari et al. (2020) performed a thorough review of US practices in OSC through a survey in connection with a symposium held at the University of Florida on OSC. Respondents were diverse in background and disciplines with the average experience in construction at 23 years and 87% having more than 10 years of experience. The majority of those surveyed indicated less than 50% of their experience in OSC and one-third of respondents have more than 70% of their professional experience in OSC practice. The challenges in OSC practice were assessed in the survey, pointing to knowledge needs. The most significant barrier from the survey was lack of contractor experience, followed by inflexible design changes, lack of familiarity, and higher initial cost. Less significant challenges included logistics of on-site handling, assembly issues onsite, aesthetical limitations and longer design phase time. The barriers from the survey were not statistically significant. However, they provided insights into qualitative knowledge needs, including respondents' difficulty with regulatory requirements, focus on first costs, industry culture, high initial capital investment for factories, and difficulty achieving economies of scale. Some of the solutions to these barriers and challenges include improving DfMA, improving demand and production balance (volume throughput in factory), information technology integration, regulatory changes, and production optimization in the factory.

Razkenari et al.'s (2020) survey reaffirms precedent studies that seek to identify the barriers to OSC from 2007 forward. The authors list the studies in a table with the key barrier overlaps between studies, including a study by the author of this thesis (Cowles and Warner, 2013; McGraw-Hill, 2011; Pan et al., 2007; Smith et al., 2015; Tam et al., 2007). Some findings from this analysis of barrier studies include inflexibility of design changes and the need for early design decisions. Furthermore, there is a consistent lack of familiarity, experience, and knowledge of stakeholders involved in OSC processes, and this is linked to the ongoing problems of construction cultural barriers that resist change. Regulatory barriers in the US context persist, as indicated in the survey, for modular and enclosed construction. Initial higher construction costs and capital investment for factories pose a challenge to widespread adoption as well.

An article by Gan et al. (2018) was discussed previously in this chapter. The 13 barriers from the researchers were identified by searching key words for "barriers" in relation to "offsite construction" and related terms. The articles retrieved were analyzed based on the Technology-Organization-Environment (TOE) framework used in studies of construction innovation (Nadim & Goulding, 2011; Tornatzky & Fleischer, 1990). The 13 barriers were grouped in the following three perspective: *technological* barriers, *organizational* barriers, and *environmental* social and market barriers. Technological barriers refer to cost, logistic, quality, and aesthetic performance. Organizational barriers are management, process, knowledge, and business models of OSC. Finally, social and market barriers, according to the authors, are contextual and external environment barriers that hinder OSC.

Similarly, Carnemolla (2019) in part 3 of the study "Scoping potential of virtual reality and offsite manufacturing" identifies OSC barriers by analyzing relevant literature in OSC from eight theme regions as "only indicative of general obstacles" to OSC globally. The literature sources include Europe (Nadim & Goulding, 2010); UK (Goodier & Gibb, 2007); Australia (Blismas & Wakefield, 2009); China (Mao et al., 2013); Malaysia (Azman et al., 2012); Pakistan (Ansari et al., 2016); Sweden (Larsson & Simionsson, 2012); and Nigeria (Rahimian et al., 2017). The eight themed barrier topics that emerged from this literature search include: 1) process/program; 2) cost/value; 3) worker health and safety; 4) skills and knowledge; 5) logistics/site operation; 6) sustainability; 7) regulatory; and 8) industry/market culture.

3.7.2 Research Roadmaps

The editors of the volume, *Offsite Production and Manufacturing for Innovative Construction: people, process and technology*, Goulding and Rahimian (2020), discussed in in section 4.2.2, provide a lead article, "Offsite manufacturing: Envisioning a future agenda" as a summary and extension of Goulding's work with Mohammad Arif, from a CIB Task Group and Working Commission W121 on OSC. The International Council for Research and Innovation in Building Construction (CIB), established in 1953 with United Nations' assistance, is "a world-wide network of construction experts that cooperate and exchange knowledge to improve the quality and impact of research and innovation activities in the sector." Goulding and Arif co-authored a participatory publication titled *Research Roadmap for Offsite Construction* (2013).

This report emphasizes the need for additional OSC research to provide knowledge in design, construction, and manufacturing with specific emphasis on information/communication technology integrated solutions, socio-economic drivers, value streams, and skill development to support OSC. This report pointed to three primary types of knowledge needed in OSC practice called “drivers” including: people, process, and technology (Davenport, 1993). These three types of knowledge are mapped across three AECO delivery modes in OSC of design, manufacture, and construct to offer a framework by which to understand OSC knowledge and prioritize research. The roadmap identified priorities in mature markets and priorities in developing markets as separate. Table 3.4 outlines the drivers, core AECO areas and priorities for a five- and ten-year strategy in research from this report for mature markets including the UK and US.

Table 3.4. Drivers for OSC are people, process, and technology from the CIB W121 Research Roadmap with priorities. Adapted from: (Goulding & Arif, 2013).

[redacted]

[redacted]

Noticeably absent from this roadmap is the full end to end OSC delivery consideration, including pre-design planning development and finance as well as post-construction facilities management and maintenance. Therefore, the report focuses on operations of OSC, and not the contextual drivers and barriers. The decision to utilize OSC is in many ways outside of the realm of designers, manufactures, and CMs. Furthermore, many of the barriers to OSC are attributed to the context in which it emerges; regulatory, available labor, material supply, as well long-term maintenance, and durability. OSC is fundamentally concerned with value creation (Mostafa et al., 2016; Pan & Goodier, 2012; Razekenari et al., 2020), and not all projects or building types can benefit from OSC (Ginigaddara et al., 2019; Jang et al., 2021). This also varies depending on the geographic context in which the project exists (Lui et al., 2020). This roadmap is valuable in identifying the breadth of operational knowledge and priorities for people, process, and technologies within the AECO and manufacturing industry proper to OSC practice but does not identify the knowledge areas or priorities needed for contextual stakeholders, external factors, and those who decide to use or not use OSC.

The Construction Leadership Council is a UK-based and UK-oriented industry convening organization that focuses on developing solutions to meet 2025 challenges. The council works with government and industry to promote industry initiatives to "reduce cost, reduce programme, reduce carbon emissions and reduce trade gaps" (CLC, 2022). The council assembles "Workstream Workshops" around topics relevant to achieve these goals. In 2016, the council convened a workshop of over 40 experts in government, academia, and across the value chain of construction, in partnership, organization and support from Saint Gobain, UK Department for Business Innovation and Skills, and the University of Cambridge, to develop a "Roadmap for Modular Methods of Construction" (Oughton, 2016). The purpose of the workshop was to "help develop a strategic roadmap of barriers to the take-up and commercialization of MMC and develop solutions to help increase the percentage of new buildings built using, substantially, MMC". The aim was to "improve productivity, capacity and the use of innovation in the housing sector by removing barriers to progress and helping the industry to move the new methods from development through to actual commercial use and thereby increase housing supply".

The participants proposed four primary findings, prioritized categories that need to be addressed to meet 2025 challenges, including: 1) External Drivers that will shape MMC adoption; 2) Issues within the construction Value-Chain related to MMC; 3) Key Barriers to MMC adoption; 4) Innovations and Technologies (products, process and information technology) applicable to overcome these barriers; 5) Other Enablers necessary for success to overcome the identified barriers. The report indicates that external drivers and value-chain create the conditions of the key barriers. The outcomes also suggest that Innovations and technology and other enablers are solutions for overcoming the 'key barriers'. This process places the key barriers at the center of the knowledge needs argument, suggesting that if the barriers were to be overcome, OSC would increase in uptake. Under each of these knowledge-need categories are 'headlines', and then under each headline, associated 'details', tactical actions that the industry can take between 2016 to 2026 and beyond. The workshop participants then prioritized the details under the headline as most significant or highest concern to be addressed or implemented with a timetable that illustrates how the details relate to one another and address barriers. Table 3.5 outlines the workshop findings of detailed barriers to OSC.

Table 3.5. OSC barriers to adoption from Roadmap for MMC. Adapted from: (Oughton, 2016).

OSC BARRIER TO ADOPTION	DESCRIPTION OF BARRIER
Barrier A – Stakeholder Knowledge and Collaboration	Need strategic partnerships within supply chain > Lack of collaboration
Barrier B – Public Perception and Demand	No demand > passive consumers unaware of MMC including poor perception of prefabrication
Barrier C – Manufacturer Capital	Investment needed in MMC suppliers – volume surety and volatility
Barrier D – Finance and Insurance	Lending, valuation, and insurance – concerns over product durability and equity retention
Barrier E – Supply Chain	Immature supply chain (need auto model: component > subassembly > building assembly)
Barrier F – Risk Culture	Risk-averse culture
Barrier G – Contracts and Procurement	Fragmented procurement and need for new models
Barrier H – Business Models	Business case for change – ability to demonstrate benefits
Barrier I – Construction Performance	Need better, safer, cleaner, faster building at the same cost
Barrier J - Standards	Requires economies of scale (lack of standards)
Barrier K – Operational Performance	Lack of performance data and running costs for OSM housing

The most significant barrier identified by the workshop participants through consensus is barrier 'A' – the lack of collaboration in the supply chain and the need for supply chain partnerships. The description of this barrier in the report points to several KM issues and potential solutions including:

- The need to understand stakeholder drivers as the participants recognize that different supply chain partners do not understand the key motivations and drivers for decision making.
- Look at more sophisticated industries for models of knowledge transfer.
- Collaborative knowledge sharing is unique based on individual companies and project engagements. There is a need for standard “templates” or set approach to knowledge exchange.
- The need for a common platform for sharing build project lessons learned between stakeholders in the OSC sector, not only a project basis, but across the industry.

In 2015, the UK Commission for Employment and Skills identified low productivity as a challenge in the UK construction sector to be addressed and in 2015 launched the UK Futures Program to encourage R&D approach to skills and development application in the workplace. Coinciding with recommendations from the Farmer Report (2016), five projects under the ‘Addressing the skills and deficiencies in the OSC sector’ were selected, including project 4, Offsite HUB Scotland, a university and industry collaborative project led by Edinburgh Napier University, Center for Offsite Construction, and Innovative Structures. During this project, three “tiers” of knowledge needs were assessed and developed by industry, university, and government partners. The first was company specific knowledge content as training for operators – the daily OSC practitioners at two leading and partnering OSM industry companies, CCG OSM and Stewart Milne Timber Systems. The second type of educational information developed was OSC generic training materials. The third was scaling and internationalization of Scottish OSC knowledge. The structure and CoP description and findings from this project are part of the PR02 CS in Chapter 06 and codified in “Offsite HUB (Scotland): establishing a collaborative regional framework for knowledge exchange in the UK” (Hairstans & Smith, 2017).

For the second tier, generic materials of knowledge needs, over a period of six months a core group of Offsite HUB members including seven OSC companies from industry were interviewed based on a questionnaire developed by the Centre for Offsite Construction and Innovative Structures with input from Scottish government and this thesis author in the US for international applicability. Qualitative interviews were conducted covering key topics: technical, skills/culture, branding/marketing, business models and strategies, and internationalization. On completion of the survey, each industry partner was sent a copy for review and comment as well as a request to reflect on each of the topics discussed. The finalized interview information was then aggregated to capture the overarching qualitative sentiment of the group via generic statements and the surveyed ratings of key topics averaged to rank them by importance. A core meeting was then held to discuss the generic statements in an open forum and to develop a consensus of approach and allocate a series of prioritized actions going forward. The results of the qualitative OSC knowledge needs assessment are included in Table 3.6.

Table 3.6. Offsite Hub (Scotland) OSC knowledge needs. Adapted from: (Hairstans & Smith, 2017).

OFFSITE HUB (SCOTLAND) GENERIC OSC KNOWLEDGE NEEDS	
RANK 1 - SKILLS	Improved skills pathways for operators. Specific skills were identified including: • Project management • DfMA • Onsite assembly • Maintenance and repair • Digital information and manufacturing technology • Building performance The training needs to be focused, quick, more accessible, understandable, and transferable to inform demand side (i.e., client or end user).
RANK 2 – BRANDING and MARKETING	There is a need for improved client and end user understanding of the OSM offering that sells its higher value and level of finish to improve margin. This is a challenge given individual company versus industry wide communication needs and considering the diversity of knowledge of the various audiences.
RANK 3 – BUSINESS MODELS AND STRATEGIES	Development, finance, procurement, payment schedules are all established to service onsite conventional construction. New strategies are needed in OSC. A secure project pipeline is needed to allow investment and scaling to take place in OSM companies.
RANK 4 - TECHNICAL	The value proposition of OSC is not clearly defined given traditional construction business models and procurement methods. As a result, there is a

	need to devise a feedback loop capable of demonstrating the benefits of the OSC offering relative to key market drivers of Quality, Speed, Performance (acoustics, thermal, indoor air quality, etc.) with respect to whole life cost and not just build cost.
RANK 5 - INTERNATIONALIZATION	There is limited scope for international OSM product export. However, there is the potential to export expertise, IP, and knowledge exchange with staff transfer, internships, and learning journeys identified as ways of building international collaboration.

After the knowledge needs analysis, generic materials were developed in collaboration with the partner companies, BuildOffsite trade association, Homes for Scotland, and the Scottish Government. The content was combined with sections selected from the company-specific content and then was delivered in a series of events hosted by Architectural Design Scotland and the Construction Scotland Innovation Centre that were filmed and hosted on the respective organizations' websites for dissemination. The knowledge areas identified include "what", "why", and "how" of OSC, including built project content from the industry partners to further explain these principles in practice. The specific knowledge needs categories to address the priority rank 1 area of operation skills include the following: project management, DfMA, onsite assembly, logistics, maintenance and repair, computer-controlled manufacturing, information technology and building performance. Learners may take a novice, advanced beginner, competent, proficient, or expert route through the operational skills pathway.

In 2020, these resources were further developed by Construction Scotland Innovation Center and Edinburgh Napier University with partners Ministry of Building Education, Construction Wales Innovation Center, City of Glasgow College, and Class of Your Own into a set of training modules that are delivered face-to-face and virtually, synchronously and on-demand, covering a range of OSC topics under the banner "Offsite Ready". The program is a comprehensive suite of flexible training content for industry broadly, construction workforce specifically, and formal higher education. Project leads are Dr. Mila Duncheva and Caitrona Jordan (2020). The project, funded by the Construction Industry Training Board, includes seven modules: fundamentals, digital design, estimating, logistics, OSM, onsite assembly, and management/integration. Each module contains an accompanying PDF booklet (whitepaper), a slide deck, an infographic as a summary of the knowledge areas, and testimonial and summary videos. The modules are organized by core competency (knowledge area) including the following: A) digital skills, information management, and communication; B) procurement, tendering, and contracts; C) health and safety; D) management and planning; E) factory operations; and F) site operations. These core knowledge competencies are targeted at specific roles including the skilled worker, supervisor, and/or manager.

3.7.3 OSC Knowledge Needs Summary

This section presented literature from peer reviewed journal publications and research needs reports to determine the knowledge needs in OSC. Findings from the literature include the following: First, the literature review of journal articles reinforced the preceding categories' literature review by illustrating that knowledge needs fall along project delivery stages. Further, the barriers and challenges to OSC uptake are the very drivers that create the need for OSC (regulatory, productivity, workforce, supply chain). There is also a lack of consistency in the various researchers' focus on OSC topics and needs, evidence that more dialogue and discussion amongst OSC scholars is critical to establishing and fostering a stronger core knowledge base in the discipline. This illustrates and confirms the need to form an academic CoP or knowledge hub.

Through frequency analysis, the journal publications and reports indicate that the following knowledge needs occur in 50% or more of the sources in the following order of priority:

- On-site management of OSC assembly
- Process improvement of OSC delivery
- Quantifying construction performance (cost and schedule) of OSC
- Knowledge and skills of OSC stakeholders

The findings from this literature review of OSC knowledge needs further confirms the generalist literature review of books and reports, that there is a lack of 'how-to' knowledge in OSC practice. Three of the four topics listed above, on-site assembly, delivery, and skills, are tacit knowledge topics. ‘Quantifying performance’ is focused on the need for evidence that OSC performs to increase uptake.

The articles and reports categorized knowledge needs in different ways. Zakaria et al. (2018) organized knowledge needs as follows:

> 1) Contextual: external factors that shape OSC practice such as regulatory, finance, market, supply chain
> 2) Structural: operations directly related to carrying out OSC practices including stakeholder roles)
> 3) Behavioral: cultural and interpersonal obstacles that stem from conventional fragmented construction practice.

Similarly, Gan et al. (2018) follow the TOE framework (Toransky & Fliescher, 1990) in organizing OSC knowledge needs into technical (means, methods, and systems), organizational (operations and management), and environmental (social and contextual) (Figure 3.9). Goulding and Arif (2013) indicate that knowledge in OSC is related to people, process, and technology across the dimensions of project stages of design, manufacture, and construction. The TOE structure focuses on the role of people as knowledge vehicles in OSC and the literature has clearly indicated that the role of the stakeholder (discipline and vocational vs. professional orientation) determines the knowledge needs depending on the knowledge type – contextual, structural, behavioral, technological, organizational, environmental, personal, and/or procedural.

[redacted]

Figure 3.9. TOE framework of technology, organization, and environmental knowledge needs to increase OSC adoption. Adapted from: (Tornasky & Fliescher, 1990).

Although all these approaches to categorizing knowledge are useful, for the purpose of this research on knowledge needs in OSC, the TOE framework is used. TOE is a theoretical tool that explains technology adoption in an organization or diffusion in an industry as a function of and influenced by the technological context, organizational context, and environmental context. TOE focuses on organizational or inter-organizational level analysis and not individual behaviors within organizations or CoPs. In Table 3.7, the TOE framework is mapped to each topical need demonstrating the type of knowledge assigned to each topic – technological, organizational, or environmental. This analysis indicates that three topical needs to overcome barriers are technological-focused, 28 are organizationally-oriented, and 11 relate to the environmental context. This reaffirms the need for 'how-to' knowledge responding to the need for organizational, procedural, and structural knowledge improvements to realize greater uptake and diffusion of OSC. Furthermore, environmental factors likewise are a significant contributor. Both environmental and organizational factors outweigh the importance of fostering technological context. Technology, digital and manufacturing, is available but the organizations and the environmental conditions are the obstacles not allowing OSC to evolve.

Table 3.7. Frequency analysis of OSC knowledge needs from literature with TOE framework.

Technology Organization Environment (Tornatzky & Fleischer, 1990)	OSC KNOWLEDGE NEEDS	Journal Publications								Research Roadmaps				TOTALS
		Hosseini et al., 2018	Zakaria et al., 2018	Li et al., 2014	Jin et al, 2018	Salma, Moselhi & Al-Hussein, 2021	Razkenari et al., 2020	Gan, Chang & Wen, 2018	Carnemolla, 2020	Goulding & Arif, 2013	Oughton, 2016	Hairstans & Smith, 2018	Duncheva & Jordan, 2020	
O	Site management	1	1	1			1	1	1	1		1	1	9
O	Process improvement	1	1	1	1			1		1		1		7
O	Construction Performance			1	1		1	1	1	1	1			7
O	Knowledge & skills						1	1	1	1	1	1		6
E	Project and Industry Data		1	1	1	1			1					5
T	Technology development		1	1	1							1	1	5
E	Culture			1		1		1	1					4
E	Finance & Insurance			1		1					1	1		4
E	Sustainability		1						1	1		1		4
O	Supply chain		1			1				1	1			4
O	Procurement		1			1					1		1	4
O	Business models				1			1			1	1		4
T/O	Design (DfMA)				1		1			1		1		4
E	Regulatory factors		1			1			1					3
E	Factory capital			1			1				1			3
O	Factory management	1										1	1	3
O	Expierence		1				1					1		3
O	Stakeholders		1							1	1			3
O	Decision factors	1	1							1				3
O	Communiciations		1									1	1	3
O	Health and Safety								1	1			1	3
T/O	ICT/BIM									1		1	1	3
E	Project Delivery				1						1			2
E	Standards					1					1			2
E	Aesthetic limitations						1	1						2
O	Logistics							1	1					2
O	Operational performance										1	1		2
O	Collaboration		1								1			2
O	Risk analysis									1	1			2
E	Transportation				1									1
E	Lifecycle analysis									1				1
O	Case studies (need)					1								1
O	Programmatic requirements								1					1
O	Early engagement	1												1
O	Planning												1	1
O	Product platform				1									1
O	Economies of scale						1							1
O	Partnerships											1		1
O	OSM subassemblies									1				1
O	Quality							1						1
OE	Multi-family housing		1											1
OE	Commerical	1												1

3.8 Chapter 03 Summary

Chapter 02 and 03 comprise the SR literature review of this thesis. Chapter 02 researched KM theory, strategies, tactics, and tools. Chapter 03, this chapter, presented a literature review of OSC knowledge. The chapter reviewed the housing need globally, with the potential for OSC to meet this demand. Furthermore, the literature covered the role of KM in construction and OSC specifically to augment innovation diffusion and foster an increase in OSC uptake. The review addressed OSC knowledge by characterizing, categorizing, and then prioritizing the knowledge as found in the extant literature. Journal articles provided information on the character of construction knowledge and then the specificity of OSC knowledge. To characterize OSC knowledge, the researcher reviewed popular and specialist books and texts, as well as research reports that set a precedent for how OSC knowledge is categorized in the field. A literature review of journal publications and research roadmaps was reviewed to determine the OSC knowledge needs and priorities.

The SR from Chapter 03 OSC Knowledge are verified and clarified in Chapter 05 – Data Mining in which PR is presented by way of research projects that yielded OSC topical research needs. The results of Chapter 03 are compared with the findings from the PR projects reported in Chapter 05 for conclusions on knowledge needs in OSC. Both parts of the literature review, SR01 in Chapter 02 – KM Theory and SR02 covered in Chapter 03 – OSC Knowledge provide a contextualizing function for Chapter 06 – Case Study Analysis of four KM CoPs and the development of the theoretical framework, TM3, in Chapter 07.

CH 04 – Research Methodology

This chapter explains the research methodology in four sections. Section 4.1 covers the overarching research methodology for this work, which is constructivist GT. It reviews the motivations, research aim, and objectives of this research. Section 4.2 is an overview of philosophical approaches including a discussion of ontological (being) and epistemological (knowing) paradigms and epistemic positioning of the researcher from a constructivist lens. Section 4.3 reviews qualitative and quantitative methods that use inductive and deductive reasoning and how they serve the philosophical approach. Section 4.4 covers research tactics including surveys, archival analysis (literature review), CS analysis, and ethnographic approaches. As an ethnographic approach, constructivist GT is emphasized as a tactic to address inductive qualitative research and the focus of this work, theory building. Section 4.5 presents the research design structured through the five research objectives. The section includes specific methods that were employed for each phase of the research and justification for why these methods were selected and how they were applied.

4.1 Research Aim, Objectives, Methodology

The motivation for this research was to increase housing affordability globally through OSC uptake and adoption and to do so by fostering OSC knowledge sharing. The research aim was to overcome the lack of knowledge sharing in OSC housing by developing a non-project-based framework for inter-organizational KM. To develop the framework, this research had five objectives listed below and illustrated in Figure 4.1:

- Objective 01 – Identify the research aim and gap identification fostered through professional experiences of the researcher and a preliminary literature review into the barriers to OSC adoption.
- Objective 02 – Perform a literature review of SR sources organized into two parts. SR01 – KM Theory was a literature review of inter-organizational KM discourse. SR02 – OSC Knowledge reviewed literature on how OSC can address housing needs in the US and UK and how KM can support the uptake and adoption of OSC. This part of the

literature review covered the extant literature on OSC knowledge categories and knowledge priorities.

- Objective 03 – Mine data from four PR projects conducted by the researcher as follows: PR01 - OSC industry surveys, PR02 - OSC performance studies, PR03 -OSC strategic growth plan, and PR04 - OSC housing research roadmap. This objective was to verify the knowledge needs and priorities in SR02 – OSC Knowledge from Objective 02.
- Objective 04 – Analyze four KM research socialization CS contexts using GT tactics of theoretical sampling, constant data comparisons, and theoretical saturation. The CSs were contextualized in the PR and SR sources from Objective 02 and 03.
- Objective 05 – Develop a theorical framework called TM3 for inter-organizational KM in OSC for housing that was reviewed by the participants in the CSs and peer researchers. This objective included developing a plan for next steps in testing and validation of the framework.

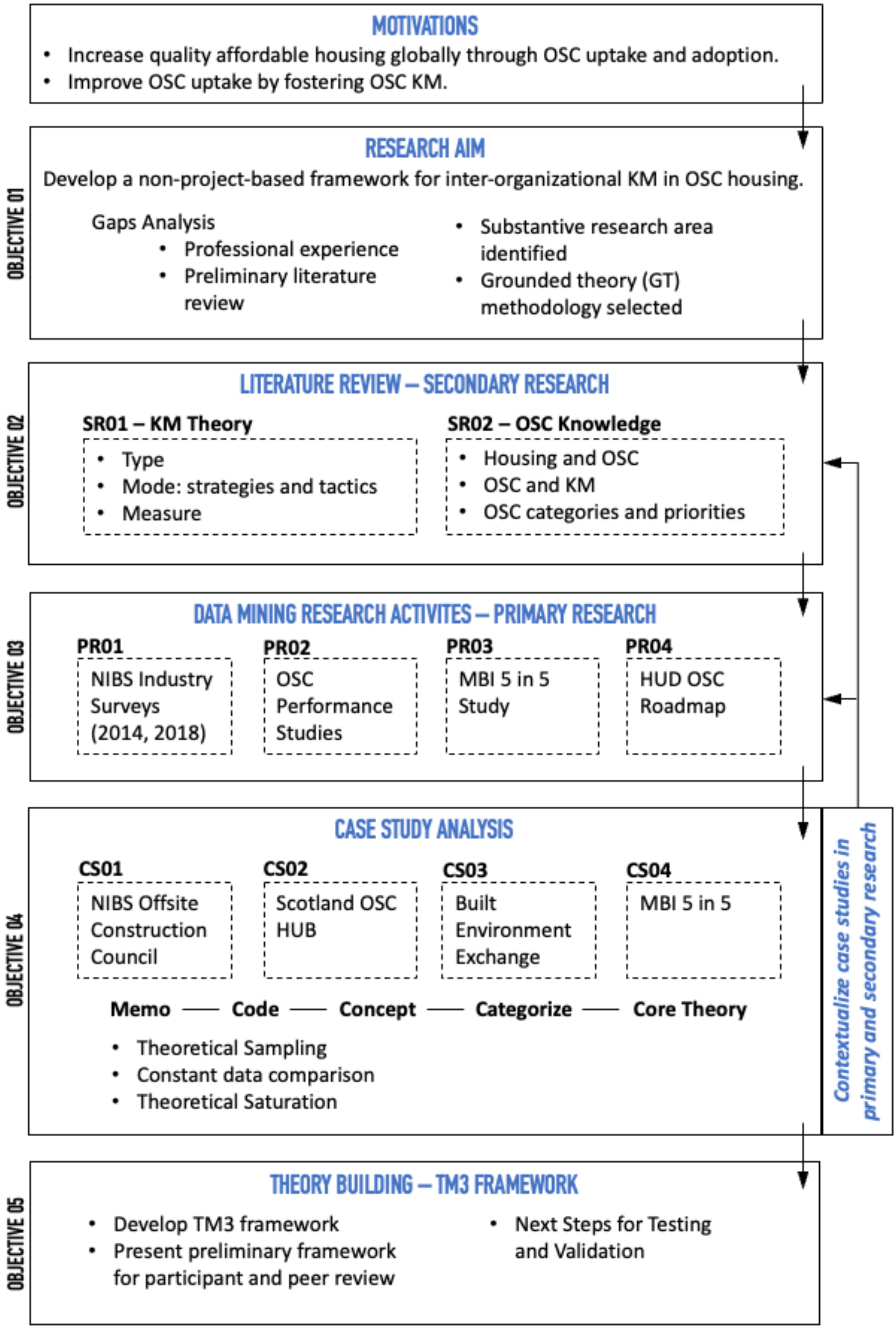

Figure 4.1. Constructivist GT research methodology flow chart. Source: (Author).

Constructivist GT was selected as the research methodology because the aim of the research was to establish a theoretical framework, the researcher had experience using qualitative methods, and the researcher was participating in ongoing KM CoP CSs (Charmaz, 2006; Glaser & Strauss, 1964; 2017). Justification for this research methodology, with the accompanying philosophical paradigm and position of the researcher is outlined in the following sections.

4.2 Research Philosophy

There are two primary areas of research philosophy – ontology and epistemology. Fellows and Liu (2015) indicate that ontology is the study of being and reality, and that the two polarities of being are realism and non-realism. While realism is concerned with truth-conditions or situations that create truth, irrealism holds that truth is understood by reference to contextual conditions (Fryer, 2022). Epistemology is the study of knowledge, or how one knows. It is concerned with the origins, nature, methods, and limits of human knowledge. In epistemology, there are also two primary positions - objectivism and subjectivism. Grayling (2003) points out that an objectivist position posits that there are no significant barriers to producing knowledge and that through observation and measurement, we can discover knowledge. Subjectivists are skeptical that we can observe the world from a position of neutrality and objectivity because most questions are contextually contingent and it is difficult to isolate variables (Fellows & Liu, 2015).

Given these two research philosophical paradigms of ontology and epistemology, four combinations that define philosophical “positioning” (Blaikie, 2010) are possible, as outlined in Figure 4.2. These include position combinations of:

1) Positivist (Realism / Objectivism)
2) Constructivist (Irrealism / Subjectivism)
3) Critical Realist (Realism / Subjectivism)
4) Confused (Irrealism / Objectivism).

Combination number four, “Confused”, is negligible because objective knowledge cannot be developed from something that does not exist. As such, positivism, constructivism and critical realism are the three fundamental philosophical positions from which researchers investigate (Blaikie, 2010).

[redacted]

Figure 4.2. Philosophical positions of positivism, constructivism, and critical realism. Adapted from: (Blaikie, 2010).

Positivism, often referred to as rationalism, takes a realism / objectivism perspective. This position claims that the world is made up of universal laws and that we produce knowledge in an objective way (Larrain, 1979). Although correlation may be present, positivism risks the presumption that correlation implies causation. This misrepresents how knowledge is produced and ignores the need to reflect during the evolution of research processes (Geels, 2022).

At the other end of the spectrum, constructivism, sometimes called empiricism, idealism, or interpretivism, is an irrealism / subjectivism position that sees knowledge production as fallible and theory dependent (Blaikie, 2010). Constructivists acknowledge the challenge of pursuing universal laws for questions involving society beyond the physical world. In social science research, constructivists use methods involving discourse, meaning, and the experiences of people to produce data and results (Schwandt, 1994). Constructivism is an important part of ethical research because it honors reciprocity, engagement, and human interaction as a key component of the construction of reality (Amineh & Asl, 2015). However, extreme constructivists run the danger of taking a limited view of the world by focusing on experience and context only. It can be too idealistic and reaches, sometimes unnecessarily, for interpretation (Moses & Knutsen, 2019).

This research took a constructivist approach and used theory-dependent positioning. The researcher believed in causes and aimed to have the research be applied to overcome barriers to OSC knowledge sharing. The research approach was solutions-focused and the research design and outcomes were informed by phenomenology (the study of consciousness and the objects of direct experience) and hermeneutics (knowledge reliant on interpretation) (Denzin & Lincoln, 2005). Table 4.1 highlights the constructivist philosophical approach used in this research – an ontological paradigm of multiple constructed realities and an epistemological knowledge being co-constructed with research participants (Mugeraer, 1995).

Table 4.1. Philosophical paradigms as they relate to positioning. Adapted from: (Guba & Lincoln, 1994; Mugerauer, 1995).

[redacted]

4.3 Research Methods

Cresswell and Plano Clark (2007, p. 23), research methods scholars, outline two broad methods of reasoning - induction and deduction. Research that is based on a positivist position are explored deductively. Deductive research methods work from the top down, from theory to hypotheses to data, to prove or contradict a theory. Deduction begins with general and ends with specific, while induction moves from specific to general. This research used inductive research methods that engaged in a constructivist position, working from the bottom up, using participants' views to build broader themes and generate theory through interconnecting themes.

The primary difference between induction and deduction is how the researcher views the nature of reality and therefore the relationship of the researcher to the participants. In quantitative research, the researcher separates themselves from the participant, while in qualitative research, the researcher is engaged to some degree and this relationship is important to understanding the observable event (Onwuebuzie & Leech, 2005, p. 271). In qualitative methods, sometimes referred to as naturalistic or participatory methods, the researcher becomes the instrument for data collection (Soiferman, 2010). This thesis research used qualitative methods, moving from specific observations to broader generalizations and theories consistent with inductive reasoning. Tentative hypotheses were generated and explored that led to further general conclusions and theories (Creswell, 2005). Table 4.2 lists quantitative and qualitative methods, their philosophical paradigms, and highlights the position of the researcher in relation to the event or participants that was used for this research thesis.

Table 4.2. Philosophical paradigms as they relate to qualitative and quantitative research methods and inductive and deductive processes. Adapted from: (Creswell, 1994).

[redacted]

Creswell and Plano Clark (2007) explain that in quantitative research, literature review plays a primary role in justifying and identifying the purpose of the study and data is collected numerically to be statistically analyzed. Conversely, in qualitative research, a literature review is used to provide evidence for the purpose of the study and to identify the underlying problem that will be addressed by the research. Also, qualitative methods use words, images, interviews, and recordings of participants collected in context by the researcher. The data is interpreted and organized into themes, concepts, and categories to draw conclusions.

The researcher used three factors in determining the methods of research appropriate for this work including:

1) Match the approach to the research problem: selected qualitative methods for deep understanding (Dainty, 2008, p. 2).
2) Fit the approach to the audience and intention: considered the audience who will read and use the findings (OSC researchers and industry) of the study and wanted to present a more nuanced approach to KM in OSC.
3) Relate the approach to the researcher's experiences: the researcher had precedent experiences and training in qualitative methods (Soiferman, 2010).

To the last point regarding the researcher's experiences, the efficiency of familiarity of a method was balanced with the appropriateness of the method for the research problem. All researchers have bias toward methods that have yielded positive results in the past, produced knowledge, made an impact on the field, and fostered their scholarly reputation (Podsakoff et al., 2012). To reduce the impartiality of bias, the researcher took caution to remain conscious and conscientious while employing qualitative methods in the research.

Edmondson and McManus (2007) indicate that methods of research are directly related to the maturity of research in the discipline. Another reason that qualitative methods were selected for this research is that construction inquiry is a relatively "nascent" or "intermediate" field requiring more nuance in the approach and results (Fellows and Liu, 2015). Qualitative methods and their associated tactics are the most common approaches in humanities and social science research and by extension construction research that seeks to employ an approach that investigates people, human interactions, human behaviors, and organizational contexts (Denzin & Lincoln, 2005).

4.4 Research Tactics

Research tactics, or styles, are operational tools that are used to address a qualitative or quantitative method. Yin (1994) considers five common tactics employed in research: surveys, experiments, archival analysis, histories, and CSs. Bell et al. (1993) suggests additional tactics of ethnography and action research. The tactics used in research may serve qualitative or quantitative methods through a positivist, constructivist, or somewhere-in-between paradigm. No one tactic belongs to a particular position or method, and therefore, tactics are used as vehicles to put the research into action to collect data through the most effective means given the nature of the problem or question (Bachiochi & Weiner, 2004).

Triangulation uses two or more qualitative and/or quantitative methods to study a topic. O'Donoghue and Punch (2003) suggest that together the methods can lead to a greater understanding of causation, taking the advantages of both or eliminating the disadvantages of one method, providing a multi-dimensional view of the subject. Denzin (2010) indicates that triangulation may be used for entire studies to investigate a problem from several perspectives or may be used for individual parts of a study such as a mix of survey and ethnographic tactics and that triangulation occurs in four main ways: multiple sources and types of data, more than one researcher, different paradigms, and divergent methodological approaches for data collection and analysis. Related to triangulation, "bridging" involves linking two or more research tactics to make them more mutually informative or complimentary while maintaining the distinct contributions and integrity of each independent approach (Turner et al., 2017). The triangulated research tactics used in this work are reviewed in Table 4.3 below with their associated positioning and research methods.

Table 4.3. Research tactics used in this project with the associated descriptions, philosophical positions, and research methods.

RESEARCH TACTIC	DESCRIPTION	POSITIONING	RESEARCH METHOD
Archival analysis	Searching and extracting data from original archives; often called literature review or SR	Positivist and Constructivist	Quantitative and Qualitative
CS	Analysis of data extracted from real-life contexts	Constructivist	Quantitative and Qualitative
Ethnographic	Participatory research of the researcher; GT and action research are types	Constructivist	Qualitative

- *Archival Analysis*, sometimes called literature review, uses reports, articles, books, videos, and other archived resources to provide SR data in each research topic. Xiao and Watson (2019) explain that literature review involves a critical analysis of archived products through study, comparison, and Scientometrics, a subfield of Informetrics that is the measuring and analyzing of scholarly literature. The researcher uses a systematic and structured approach to archival analysis. This included key word search through publication indices and search engines to identify and categorize documents based on reading and determining relevance, number of citations, and ranking of the journal for reputation. Beginning with the general theory on which the research is based, leading texts provided a strong basis for explanations of the topic with citations to other key texts on related and more detailed topics. Citation indexes provided tracing links between publications, especially journal papers. This initial archival search created a map of subtopics related to the general theory that were then searched individually as well. Literature review was used in the SR portion of this research covered in Chapter 02 and Chapter 03.

- *CS analysis* uses live projects and contexts in which the researcher can observe phenomena and record data. Robert Yin (1994) defines CS method as "an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between the phenomenon and context are not clearly evident, and in which multiple sources of evidence are used" (p. 23). The purpose of CSs can be explanatory, descriptive, and/or exploratory (Yin, 1994), meaning that CS research is neither positivist or constructivist, deductive or inductive, quantitative, or qualitative, but can be used to serve any of these positions. However, CS research is particularly useful for qualitative research, as in the work of this thesis, because it serves as the test bed for events or situations for data gathering within contexts (Zainal, 2007).

Groat and Wang (2013) provide a useful characterization of CS research as having one or more of the following: 1) a focus on either single or multiple cases studied in their real-life context; 2) the capacity to explain causal links; 3) the importance of theory development in the research design phase; 4) a reliance on multiple sources of evidence, with data converging in a triangular fashion; and 5) the power to generalize to theory. Yin (2009) reiterates that CS tactic strength is its capacity to generalize to a theory, much the way a single experiment can be generalized to theory, which can in turn be tested through other experiments. Therefore, although sometimes appropriate for quantitative methods, CS analysis is more commonly used when addressing qualitative problems for inductive approaches to research. The cases under observation may be a business case, litigation case, construction project case, or other organization of people, processes or products that warrant investigation to create knowledge (Zainal, 2007), such as CoPs investigated in this research. The analysis of the case may take place in the cross-section with data collected at one point in time or through a longitudinal study in which the data is collected repeatedly over time (Yin, 1994).

The CS method has been criticized for lack of robustness as a tactic. This can be overcome by having multiple CSs, depending on the research aim, so that conclusions can lead to more generalizations (Meyer, 2001). Another way to overcome the challenges of data reliability and research transferability is by triangulating CS with other methods and tactics (Love, 2002). However, the results from a CS “stems on theory rather than on populations” (Yin, 1994). Confirmed by Tellis (1997), the design of CS in this research included eliciting implicit and explicit data from participants, linking the CS to the research aim, and operationalizing the CS to derive theoretical a framework that will be further tested in the future. This research used an explanatory CS tactic that examined data closely both at the surface and in depth to explain phenomena in the data. Based on the data, the research then formed a theorical framework and the researcher set to test this theory (Zainal, 2007).

- *Ethnographic tactics* are when the researcher becomes part of the group under study and observes participant behaviors. A common qualitative approach used in anthropology and social sciences, ethnographic tactics are also used in business research for reflection on patterns and trends. This research used a subset of ethnographic research called action research, in which the researcher participated to identify, promote, and evaluate problems and potential solutions. Lewin (1946) indicated that action research actively and intentionally endeavors to change a social system with knowledge being leveraged to effect the change. A related ethnographic tactic that has emerged in the last 50 years as a more codified action research approach is GT, the tactic employed for this research scope.

- *GT* is a constructivist social science research approach (Denzin & Lincoln, 2000). In GT, ideas and concepts "emerge" from the data rather than beginning from a hypothesis. This approach is useful for research that seeks insight into existing theory but has no or little current research available (Aspers & Corte, 2019). The methodology searches for logic and relationships through coding and taking notes and memos, recognition of phenomena and occurrences, and consistently comparing learnings through descriptions, integration of thoughts and findings, and theory building throughout (Strauss & Corbin, 1990). The GT method does not commence with a theory, rather the theory evolves during the research process and is produced from the continuous interplay between data analysis, data collection and resulting theory (Corbin & Strauss, 2015). This emerging, evolving theory leads to further data collection and analysis, further developing the theoretical constructs as GT seeks to make sense of data collected to determine meaning and significance (Parker & Roffey, 1997). GT method and the associated ontological and epistemological philosophical paradigm, positioning, and characteristics used in this research are outlined in Table 4.4.

Table 4.4. GT Method. Source: (Corbin & Strauss, 2015).

[redacted]

GT, from a constructivist paradigm, is a qualitative method that differs from quantitative research. GT claims credibility, applicability, transferability, dependability, and confirmability of research outcomes instead of positivist criteria of validity, reliability, generalizability, and objectivity (Corbin & Strauss, 2015). Researchers in GT cannot apply the same criteria as in quantitative research as the quality of findings and validity of findings are not synonymous (Allan, 2003). Credibility is a term preferred over truth as it indicates that the findings are trustworthy and believable in that they reflect participants', researchers', and readers' experiences, but at the same time explain only possible plausible interpretations from the data (Cullen & Brennan, 2021).

GT approach summarized from several constructivist scholars (Corbin & Strauss, 2015; Cullen & Brennan, 2021; Glaser & Strauss, 1964; Goulding, 2009; Graham & Thomas, 2008; Suddaby, 2006) can be described in seven stages:

- Stage 1 – Research problem: Start with a broad substantive area, a specific research problem or a research question. This may involve preliminary review of literature or drawing on professional experience to select the problem.
- Stage 2 – Initial field research: Begin by entering the field to observe phenomena and simultaneously collect and analyze data. This analytical process involves the use of coding strategies. Coding is the process of identifying topical themes in GT. Data is collected through experiences. The data is generated by notes, voice notes, video, oral stories, and especially memos. The researcher employs open coding whereby data is reviewed several times, breaking down the qualitative data into excerpts and summaries of themes, then concepts, categories, and core theories.
- Stage 3 – Conceptual development: Researchers systematically develop concepts in terms of their properties and dimensions, then validate interpretations by comparing against incoming data. Validation is not a testing of a hypothesis but assessing interpretations both with participant and against emerging data as the research progresses. The circular process of data collection and constant comparison continues until the research reaches the point of "theoretical saturation", that is, the point in the research when all the concepts are adequately defined and explained.
- Stage 4 – Category development: The researcher clusters concepts into descriptive categories and re-evaluates the concepts for interrelationships. This process, known as axial coding, compares categories to each experience to look for similarities and differences. Defined summaries are then compared with the extant literature to gage emerging theory confirmation or differentiation. The higher-order categories emerge as key theories.
- Stage 5 – Theoretical integration: The researcher lifts the analysis to a more abstract level to theory development by creating a theoretical framework from the higher-order categories. At this juncture, one can share with participants or colleagues for feedback. The research at this stage reflects on the framework, identifying gaps in the theory, and is refined as required. The researcher writes a descriptive story to provide a theoretical explanation, with integrative diagrams.
- Stage 6 – Contextualize in literature and prior research: Contextualize the theoretical framework in SR and/or PR by identifying similarities and differences between new theory and prior work. Use the literature review and PR to provide vocabulary and

test emerging theory against other scholars' works to build upon extant knowledge. This highlights contributions of the new framework to demonstrate its significance and impact.

- Stage 7 – Present theoretical framework: Present the theoretical framework in final form. GT, as an inductive method provides a fresh understanding about patterned relationships between social actors and how these relationships and interactions actively construct reality.

Corbin and Strauss (2015) and Cullen and Brennan (2021) further explain GT Stage 3. Memos are written records of analysis that depict relationships between analytical concepts in the GT approach. The researcher records their thought processes around identification of concepts in this memo format. Memo writing is continuous throughout the analytical process in GT. The memos lead to evolving concepts by alternating data collection with analysis or "theoretical sampling" (researchers sample concepts in data, not people). Through the longitudinal study, the researcher continuously compares new data to existing for similarities and differences. During this coding analysis, the researcher applies theoretical sensitivity to collect data they uncover, so that the meaning of nuances in what they see can be fully understood. The researcher oscillates between the stages continuously in a linear line (Figure 4.3).

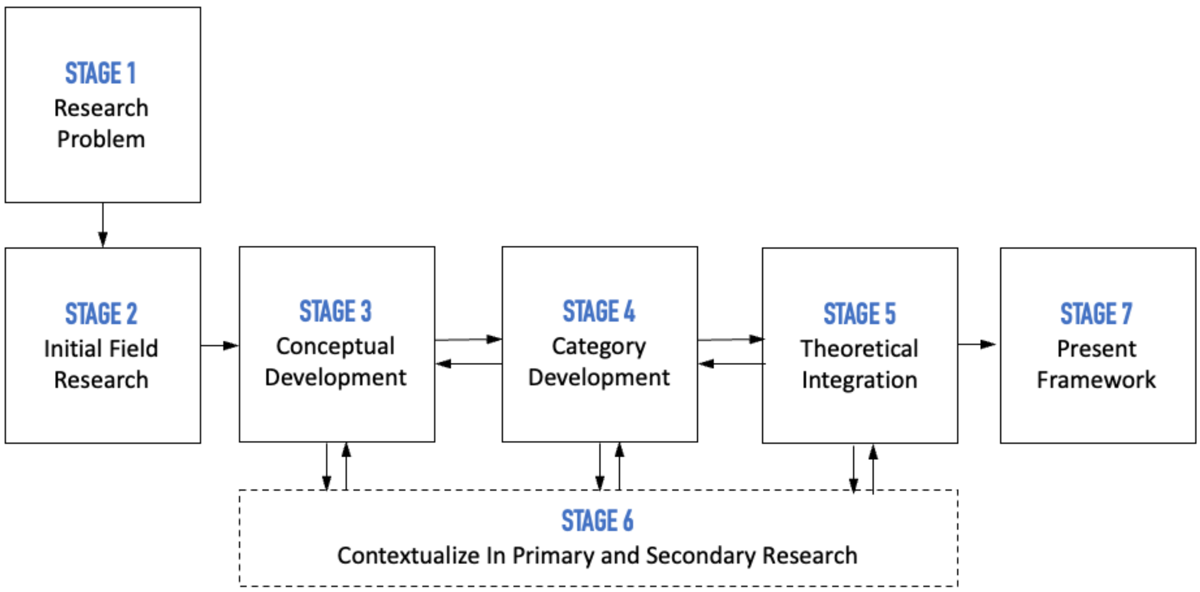

Figure 4.3. GT stages. Source: (Cullen & Brennan, 2021; Goulding, 2006)

Stage 2 discussed coding as a tactic for identifying themes, concepts, and categories. Coding places data into classifications and then creates hierarchies from the classes. Initial sorting of themes includes CCP (Pettigrew, 1985). The categories are assigned properties and dimensions. Coding requires constant comparison where categories are continually compared to one another to create sub-themes and properties. Strauss and Corbin (1990) outline several coding processes in GT that progressively and interpretively refine the data (Figure 4.4) including open coding, axial coding, and selective coding. Open coding, or substantive coding, is conceptualizing on the first level of abstraction. Written data from field notes or transcripts are conceptualized line by line. The researcher goes back and forth while comparing data, constantly modifying, and sharpening the growing theories. Axial coding is a "set of procedures whereby data are put back together in new ways after open coding, by making connections between categories" (Strauss & Corbin, 1990). Selective coding is conducted after the researcher has found the core variable or what is thought to be a tentative core theory (Rahmani & Leifels, 2008). The core theory explains the behavior of the participants in addressing their main concern (Thornberg & Charmaz, 2014). The tentative core theory is not right or wrong; it simply fits with the data and as such is appropriate (Hallberg, 2009). After the core theory is chosen, the research selectively samples new data with the core theory in mind, a process called theoretical sampling (Breckenridge & Jones, 2009). Selective coding is conducted by reviewing memos that have already been coded in an earlier stage of the research and by coding newly gathered data (Rahmani & Leifels, 2018). The constructivist GT methodology used in this research with the associated memoing and coding stages is explained in the next section.

[redacted]

Figure 4.4. Coding process in GT methodology. Source: (Strauss & Corbin, 1990).

4.5 Research Design

This section covers the research design and structure that was employed for this project. Returning to the aim, the intent was to develop a non-project-based framework for inter-organizational KM in OSC for housing. Since the development of the framework was theory building, the overarching approach was to derive the theoretical framework from and with engagement of participants. Therefore, the research employed a constructivist position or lens, seeing ontological being as existing between realism and irrealism and "ways of knowing" as more subjective than objective on the epistemological spectrum.

As this was a study of organizations and their sharing of OSC knowledge within non-project based contexts, the research used qualitative methods of multiple CS analysis and applied a constructivist GT methodology. The CS analysis was contextualized through SR and PR. The SR used archival sources through literature review to conceptualize, categorize, and then theorize the qualitative data gathered in the CS analysis and foster a vocabulary that could be applied to the CS analysis. Data mining of PR from research studies verified the SR in the literature review to further contextualize the CS analysis and theory building from the GT approach. The GT approach, leveraging CS method, resulted in the development of a theoretical framework, a hypothesis, called TM3, to be used in non-project based inter-organizational KM for OSC.

To develop this framework, this research project had five objectives: research aim, literature review, data mining, CS analysis and framework development, as illustrated in the methodology flow chart in Figure 4.5. The research design for each of the objectives is reviewed below with the associated research methods and tactics that were employed from Section 4.3 and 4.4 of this chapter. Justification for why these methods and tactics were selected and how they were applied to this research design is also included.

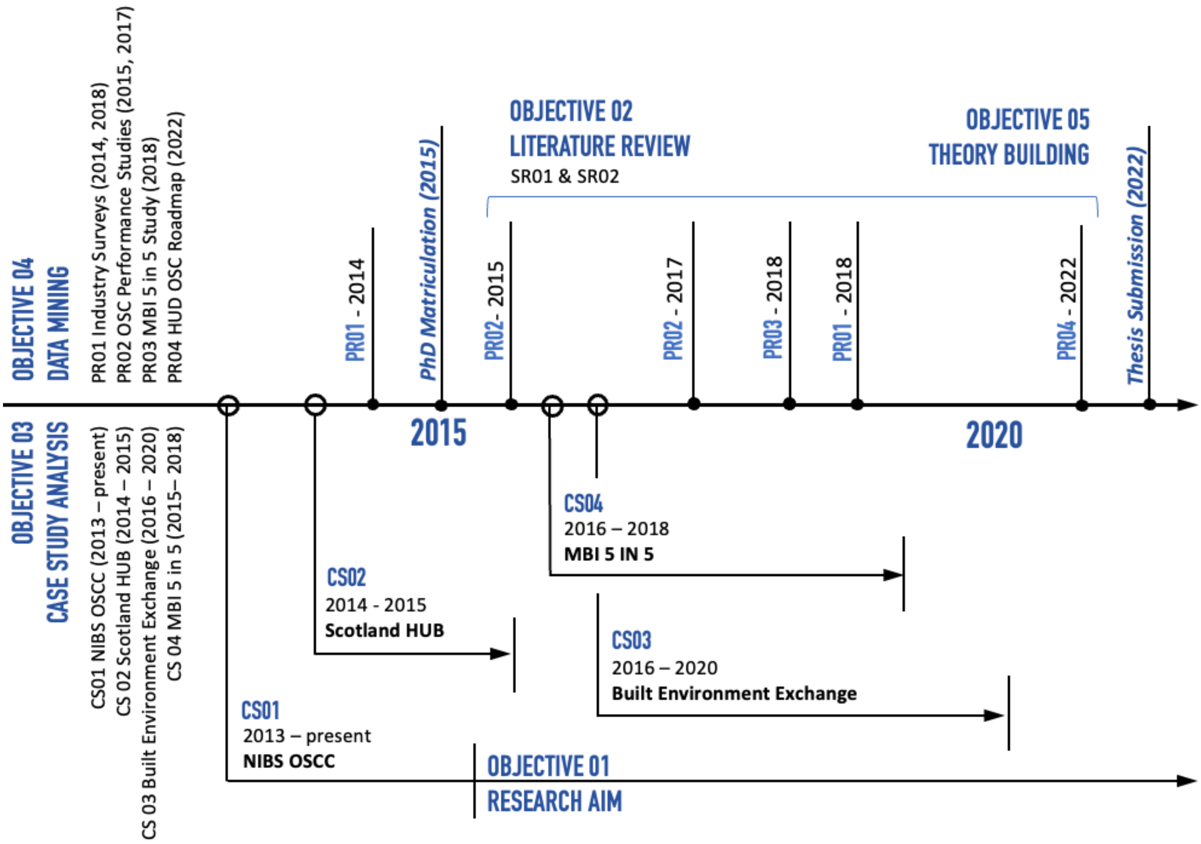

Figure 4.5. Timeline of the period of study, and corresponding research objectives, and SR and PR activities.

Objective 01 - Research Aim: The research aim was not established from the outset of the research. The researcher was performing research activities in CS01 – NIBS OSCC including surveys, interviews, and workshops with co-investigators and industry partners at the beginning of the period of study. Noting the lack of OSC uptake and adoption documented in literature and the surveys, the researcher identified the need for increased levels of knowledge sharing between OSC stakeholders. This was confirmed in extant literature upon preliminary review and with the research collaborators to build theoretical sensitivity to KM as a subject (Glasser, 1978). In studying innovation in other industries (Christensen et al., 2004; Christensen et al., 2006), the researcher identified KM as a theory and practice applicable to inter-organizational exchange and desired to support the advancement of the OSC industry by fostering KM practice in the field through applied research.

Upon initial review, there was a dearth of SR sources that addressed KM in OSC and construction more generally. Therefore, the research aim was identified, to develop a KM framework for OSC. Since the research was concerned with framework development, a theory building effort, GT methodology was employed. This methodology was selected based on prior experience of the researcher in qualitative methods and finding that preliminary research on KM involved CS analysis with participation of the researcher in the research context. In identifying the research aim and methodology, several research questions were developed including:

- What is KM?
- Why is KM needed in OSC?
- What are the OSC knowledge categories and needs to be used in KM?
- How can knowledge be exchanged in OSC?

Objective 02 – Literature Review: SR was performed for this project to establish the extant literature in two parts. SR01 – KM Theory was a literature review of KM scholarship of the strategies, tactics, and tools of inter-organizational KM. SR02 – OSC Knowledge included a literature search of the housing crisis and need for affordability and access of housing in both the US and UK. The literature review also covered the potential for OSC to address this need. Further, this part of the literature review synthesized literature on how KM can support the uptake and adoption of OSC and the gap of knowledge, the need for tools that can be used to manage inter-organizational KM in OSC. This extant literature on OSC knowledge categories and knowledge priorities was also conducted. Following GT approach (Glaser, 1978), the literature review was used to provide "theoretical sensitivity" in attuning the researcher to the KM theory and OSC knowledge and confirming / reinforcing the categories that emerged for the main contextual vehicle, or test bed for the research, the CS analysis.

The two parts of the literature review provided a boundary for the search, so it was manageable given time and resource constraints. The literature review was performed using methods outlined by Jesson et al. (2011). Keywords and phrases were listed associated with each of the four reviews and then searched for in Google Scholar. In the first part of the literature review, SR 01 – KM Theory, the researcher found peer reviewed journal publications and peer reviewed chapters in books as the sources for information. In SR02 – OSC Knowledge, Section 3.1 Housing Need and Section 3.2 Housing and OSC the researcher found that popular press sources and research reports provided SR on determining the market conditions of housing and OSC. In Section 3.3 OSC Opportunities and Challenges, Section 3.4 Knowledge in Construction, and Section 3.5 Knowledge in OSC, journal articles provided the literature sources to determine how OSC is a unique knowledge domain and characterization. Section 3.6 OSC Knowledge Categories discovered information in popular and specialist books and industry reports, and Section 3.7 OSC Knowledge Priorities qualified the needs in OSC through journal articles and research roadmaps literature review.

The initial literature search in Google Scholar was organized in Zotero software to determine literature relevancy to the categories. These sources were evaluated for applicability to the aim and objectives of the research, the number of citations, and the reputation of the journal in which they were published. The sources were then organized in MS Excel by category, date, author, title, and memo notes on relevancy to the aim and objectives of the research. From this initial sort, themes, debates, and gaps were identified with the leading scholars noted from the reoccurrence of the authors article appearing during the search and the repeated citations in papers to these scholars. A second round of literature search was then performed in Google Scholar of these leading scholars to identify additional sources of their works on the relevant topics. The themes from this second round were added to the MS Excel file. In some cases, more detailed keywords were identified from the larger category and another search was performed using the same process. This ultimately led to a final categorization that became the structure for literature review Chapters 02 and 03.

The literature review occurred throughout the research period of study duration. SR02 Sections 3.1 – 3.5 regarding the housing need, OSC as a potential solution and the role of KM in OSC uptake were performed at the beginning of the research to identify the aim and objectives. SR01 remaining Sections 3.6 and 3.7 categories and priorities and SR01 KM Theory were performed concurrently with the CS analysis for contextualization. In GT Methodology, the goal was not to use literature for deductive determinations, rather, to support the qualitative process of confirmability reinforcement in the inductive development of theory. For SR02 Sections 3.6 and 3.7 categories and priorities, a frequency analysis was performed to determine the number of occurrences of key words and concepts around OSC knowledge needs – a key objective from this research was to identify the OSC knowledge types associated with KM. The SR sources in SR01 KM Theory literature review aided in contextualizing the CSs (vocabulary forming, category confirming, and gap identification) leading to developing the TM3 framework.

Objective 03 – Data Mining: This objective involved mining data from four PR projects conducted by the researcher. PR01 – OSC Industry Surveys cataloged two industry-based quantitative surveys conducted in 2014 and 2018, respectively. This longitudinal survey analysis, with first and second surveys separated by four years, documented the US knowledge needs in OSC specifically. PR02 – OSC Performance Studies evaluated two parallel research studies (one on volumetric modular construction and the other on mass timber construction) that documented construction performance attributed to OSC and the contingent qualitative contextual factors by which OSC may be successfully realized. PR03 – MBI 5 in 5 Study codified strategic growth research that identified four barriers to OSC volumetric modular growth in North America consisting of a survey, SWOT analysis, international precedents, and a strategic growth plan. Lastly, PR04 – HUD Research Roadmap was a qualitative methods approach to consensus research to perform a barriers analysis and research roadmap for OSC in housing in the US resulting in six key knowledge need areas.

These PR projects resulted in raw data, synthesized reports, and peer reviewed publications. The data mining was conducted in two steps. First, the publications that resulted from the PR (reports and peer reviewed journals publications and conference publications) were reviewed through the lens of identifying knowledge needs and priorities in OSC for housing. Notes were recorded as the publications were analyzed using coding of key concepts and categories. Second, the raw data was evaluated. For PR01 – OSC Industry Surveys, this included mining the CSV files that were produced by SurveyMonkey from the industry surveys that were conducted. For PR02 – OSC Performance Studies, this included mining the qualitative data from the interviews that were conducted on volumetric modular and mass timber CSs, logged in MS Word. Data was mined from PR03 – MBI 5 in 5 study by searching the raw CSV file from a manufacturer survey, MS Excel spreadsheet used to code the SWOT workshop, and the MS Word documentation of the field notes from international visits to Japan and Sweden. Lastly, from PR04 – HUD Research Roadmap, the memos taken in MS PowerPoint in real time during the series of consensus workshops with OSC industry stakeholders were reviewed again to identify OSC knowledge needs.

Each PR project data mining was triangulated to each other and together with the SR02 – OSC Knowledge literature review to confirm and identify conflicts. This was performed by keeping an MS Excel spreadsheet with unique tabs dedicated to each PR project whereby the key knowledge needs were logged as the two steps in this data mining objective were conducted. This was then analyzed for statistical frequency and compared with the frequency analysis outlined for SR02. The data from these PR activities, with the SR02 literature review, provided contextualization for GT methodology discussed in Objective 04 – CS Analysis, toward theory building and TM3 framework development process. Further, the research of identifying OSC knowledge needs and priorities through data mining of concurrent PR projects compared to the SR02 literature review constituted a discrete knowledge discovery.

Objective 04 – CS Analysis: The vehicle for this research was the live CSs that provided the context for a participatory longitudinal study. GT and the associated tactics were applied to four KM research socialization CS contexts as illustrated in Figure 4.6. The CSs were CoPs, formal networks, created by the author and co-investigators and industry partners, for the purpose of a particular project or ongoing socialized knowledge exchange in OSC. The researcher actively participated in the four KM research groups (CS01 – CS04) over several years, observed the phenomena of the groups and conducted the research. The steps taken in this CS analysis used a constructivist GT approach referencing the following scholars: Charmaz (2006), Corbin and Strauss (2015), Cullen and Brennan (2021), Goulding (2006), and Hunter et al (2005) as follows:

> Step 1 – Events: The data and analysis of the CSs occurred as the researcher and respective stakeholders participated in the activities and engagements of the CoP.

Each discrete activity (i.e., workshop, meeting, webinar, project) of the CoP was considered an “event”. Gathering data from events was considered through three parameters of the CCP. CCP is a strategic framework for managing change within and between organizations (Pettigrew, 1985; Scott, 2004). The CCP framework was selected because it provided an approach that addressed the fundamental questions for any information gathering effort – ‘who’, ‘what’, ‘where’, ‘when’, ‘why’, and ‘how’. The CCP was an initial filter for classifying data inputs that were observed by the researcher.

Step 2 – Memoing: Data associated with each event from CSs was documented using handwritten notes, bullet points, narratives, sketches, and diagrams in medium sized journal notebooks. Each CS had a separate notebook(s). Each event was entered into the respective notebook, dated at the top of the entry. Notes related to the happenings and observations of the event were recorded on the right side of the page of the notebook spread, while KM notes were recorded on the left side organized by CCP parameter – context, content, and process.

Context memos were recorded for ‘why’ the event was occurring in the larger scope of the CoP, ‘who’ - the parties involved, their interests, and motivations for engaging in the event, ‘when’ the event was occurring and the schedule of the event or event(s), and ‘where’ the event was occurring. The memos likewise recorded the content parameters to note ‘what’ the event was, its character, make up, and structure. Lastly, the researcher wrote memos regarding process parameters, the most extensive data recorded of the parameters, to answer ‘how’ the event worked, the interactions, exchange of information and communication, logistics, outcomes, and future impact of the events in the aggregate.

Memos were recorded during the event and then reviewed and further clarified by additional memos afterward for emerging themes. Memoing in this initial stage used an open coding approach. During memoing, data was tagged (coded) with keywords, properties, and dimensions, and entered into a spreadsheet using MS Excel. A unique tab was created for each CS sample and associated events. As additional memo data was gathered from subsequent events, it was added to the spreadsheet.

Step 4 – Concepts: The researcher developed concepts from the coded data for each CS using frequency analysis of themes in MS Excel. The new and existing data was compared for relationships of concepts within a CS through axial coding. The researcher continued to collect and analyze data concurrently until theoretical saturation was reached for the respective CS.

Step 5 – Categories: The concepts from each of the CSs were then combined to form categories. This was accomplished through another frequency analysis of concepts across all the CSs and thereby categories emerged. The categories and associated concepts were mapped in a relational diagram (nodes and relations) first through sketching and then in graphic software, including Adobe Illustrator and MS PowerPoint. The categories were evaluated for their relations and interrelations through descriptive categories to search for similarities and differences (axial coding).

Step 6 – Contextualize: The emerging concepts and categories were confirmed and contextualized in the SR literature review (Objective 02) and PR data mining (Objective 03). The SR and PR sources were referenced for vocabulary and terminology consistent with KM theory, as well as category harmonization and differentiation to identify the unique intellectual contributions of this research.

Step 7 – Core Theories: The process of constant comparisons and simultaneous data collection and analysis continued through selective coding, contextualized by the literature and research work in Objectives 02 and 03, until abstract core theories emerged. These core theories formed the contingent dimensions of the TM3 – a theoretical framework for inter-organizational KM in OSC.

Figure 4.6 illustrates the steps employed in the CS analysis.

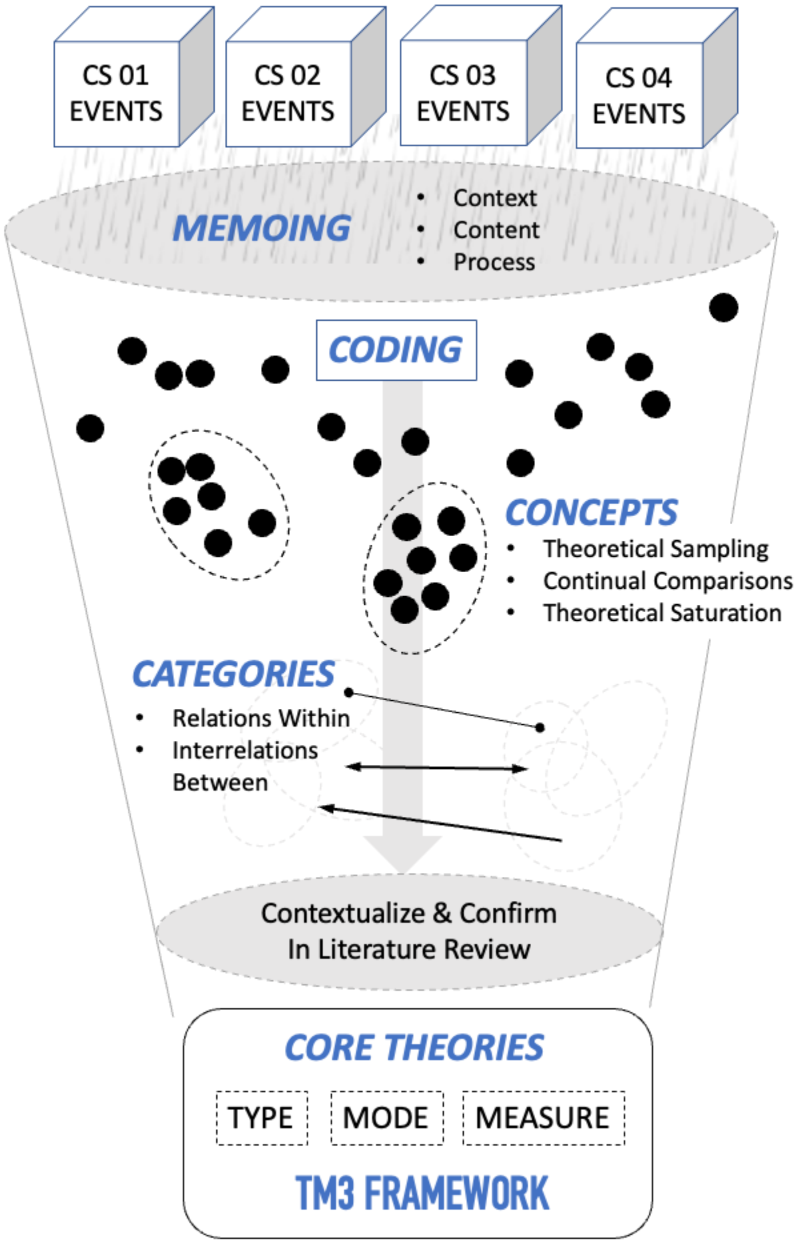

Figure 4.6. CS analysis process using constructivist GT that employs CS events through memoing, coding, concepts, and categories, leading to core theories and the TM3 framework.

Objective 05 – Theoretical Framework: Once the core theories and categories were formed constituting the contingent dimensions of the TM3 framework, sub-concepts, and sub-categories formed under the three framework dimensions. The contingent dimensions were diagrammed in a notebook and then transferred Adobe Illustrator and MS PowerPoint. The illustrations consisting of the contingent dimensions (type, mode, measure) and sub-processes were socialized amongst CoP participants for feedback and then reviewed with research peers for clarity. The TM3 framework was refined thereafter.

The TM3 framework constitutes a substantive theory, a new hypothesis. As such, the next step in the research will be to identify the extent of limitations of the theory and to test it for credibility, applicability, transferability, dependability, and confirmability in future KM in construction socialization contexts.

Ch 05 – Data Mining

Data mining is the process of turning raw data into useful information. It identifies patterns, trends, and insight from separate research activities, reassessed and analyzed through a specific purpose and lens (Corbin, 2007). *Objective 03 – Data Mining* involved mining data from four PR projects conducted by the researcher. PR01 – OSC Industry Surveys covered two cataloged industry-based quantitative surveys conducted in 2014 and 2018 respectively. PR02 – OSC Performance Studies evaluated two parallel research studies that documented construction performance attributed to OSC. PR03 – MBI 5 in 5 Study codified strategic growth research that identified four barriers to OSC volumetric modular growth in North America. Lastly, PR04 – HUD Research Roadmap was a qualitative methods approach to consensus research that identified six barriers to OSC uptake in the US.

This objective was focused on identifying the knowledge needs and priorities in OSC. Four research projects conducted by the researcher were analyzed using two steps. First the research publications that resulted from the projects were read again through the lens of OSC knowledge needs and data was coded. Then, the raw data from the research activities was evaluated. The data from the PR projects was compared and then triangulated with the SR02 OSC Knowledge literature review in Chapter 03. Moreover, the identification of knowledge priorities provides the context for reference in the CS analysis and theoretical framework development in Chapter 06 and Chapter 07. Although the function of the data mining of research activities presented herein is operative for identifying knowledge needs in the TM3 framework, the identification of knowledge priorities through literature review and primary data sources, is a discrete unique research outcome that has applicability beyond this work alone.

5.1 PR01 – OSC Industry Surveys

In 2013, the NIBS OSCC was established with a threefold mission of industry research, education, and outreach. In 2014, the council set out to gain an understanding of how the construction sector, the AECO, in the US was viewing and using OSC techniques by conducting a survey of the building industry. The survey tactic follows a quantitative deductive process from a post-positivist position. The survey was conducted through a questionnaire protocol co-developed with the NIBS OSCC using closed-ended questions. The researcher was the principal survey author. The survey queried the systems of OSC in the US, including components, panels, and volumetric modules to MEP racks and headwalls, mass timber, and enclosure. In the fall of 2014, the NIBS OSCC, led by the author, conducted the survey with the following purposes: 1) identify the opportunities and challenges associated with the use of OSC processes and technologies in the US; 2) determine, as a baseline, the current state of practice; and 3) investigate what NIBS OSCC could do to support and advance the state of knowledge and uptake of OSC in the industry as its next strategic step of the council.

This survey was developed in SurveyMonkey was distributed through the NIBS communication network and *Building Design and Construction Magazine* and *Engineering News Record*, two noted professional journals in the US. The OSCC members also distributed the survey through their personal contacts. There were 312 anonymous respondents to the survey with the following demographic distribution: construction management/general contracting (46.7%), engineering (38.3%), trade contracting (27.3%), architecture (15.0%), and owners/developers (8.3%). Most respondents had utilized OSM components to some degree in the prior year. Specific to housing, 24% of respondents indicated OSC multi-family use and 8.0% for single-family (Question 14).

The primary benefit to OSC, according to this survey, was a reduction of overall project schedule. Also, respondents indicated that while not the lowest cost solution, OSC is cost effective and reduces defects through increased quality. Regarding barriers and challenges to implementing OSC, respondents identified transportation difficulties in managing the cost and logistics associated with how far the OSM factory is from the jobsite. The need for clear programmatic requirements was also noted as a challenge as well as the difficulty of using OSC for certain building types such as long-span. A key finding from the survey is that the lack of industry knowledge is a perennial barrier to OSC uptake as well as overcoming the challenge of organized union labor that hinders OSC workforce (Question 5 and 6). The survey also pointed to the lack of supply chain integration for OSM, and GCs are having trouble managing OSC and handling OSM element assembly onsite.

A significant finding from this survey was who makes decisions regarding OSC use (Question 4). The respondents (57.1%) indicated that the CMs or GCs are most often the ones deciding to use OSC. This is followed by architects and engineers (51.5%), then owner/developers (27.9%), and others. This finding indicates that additional education is needed for current decision makers (CMs, GCs, and design consultants) for increased OSC uptake and that our field must make a concerted effort to educate owners/developers on the use of OSC for increased uptake.

Questions 10 and 11 of the survey specifically targeted knowledge needs in OSC. Question 10 asked what the NIBS OSCC can provide to AECO stakeholders to benefit companies implementing OSC practices. The results indicated that the knowledge areas most needed include 1) design standards, details, and specifications for OSC, 2) built CS examples, and 3) industry data on construction performance (cost, schedule, worker safety). Furthermore, Question 11 asks what aspects of OSC information and data are needed. The respondents identified the following knowledge needs at more than a 50% response rate: design, engineering, and specification (68.1%), commercial construction examples (59.3%), and accelerated construction schedule methods (59%). Not as critical to the respondents, but still knowledge needs, include installation logistics (44.1%), project management and delivery best practices (43.7%), materials, products, and systems (42.7%), lean manufacturing (41.7%), transportation logistics (38.6%), regulatory codes (37.3%), and labor skills and training (27.8). Other knowledge needs received lower than a 25% response rate.

The most significant barrier to OSC that respondents claimed through this survey (Question 2) is design and construction culture including late design changes, lack of collaboration, and project delivery and procurement methods that promote an adversarial climate. The council, following the survey, developed an “Off-site Construction Implementation Guide” for the building industry and a series of webinars on OSC topics from the survey that need to be addressed for increased OSC uptake in the areas of design parameters, standards, details and specification, contracts, software use, phasing of construction, trade coordination, procurement methods, and transportation and installation logistics. The survey results, codified in the “Report of the Results of the 2014 Off-site Construction Industry Survey”, are included in Appendix A.

The researcher compared the 2014 NIBS industry survey with the “Prefabrication and Modularization: increasing Productivity in the Construction Industry” (2011), McGraw-Hill SmartMarket Report, a survey of 806 AECO professionals on the state, opportunities, and challenges of OSC and the FMI, “Prefabrication and Modularization in Construction Survey Results” (Cowles and Warner, 2013), aimed at identifying the barriers to adoption of OSC. This evaluation was published in a chapter titled “Offsite Construction Industry Meta-Analysis” (Rice and Smith, 2017). Comparing the outcomes of all three industry surveys, the following findings were shown to be relevant for research needs in OSC by identifying the overlapping barriers. The McGraw-Hill study identified the following challenges to OSC from most significant to least: lack of DfMA, owners not knowledgeable or unwilling to engage OSC, project not amendable to OSC, lack of supply of available manufacturers or available trained workforce, and unfamiliarity with the OSC process. The FMI study outcomes claim additional challenges that need to be overcome for OSC success including need for early engagement of stakeholders, overcoming perceptions and stigmas, permits and inspection, progressive contracts, design and construction culture, and labor unions.

Four years later, in January of 2018, the OSCC conducted an identical follow-up survey, led by the researcher who was the principal investigator. The survey was administered in SurveyMonkey again, to provide longitudinal data, to analyze the evolution and perceptions of the use of OSC since 2014. The online survey was distributed through the NIBS communications network and OSCC members distributed the survey to their personal contacts. The questionnaire was also sent to the University of Utah, Integrated Technology in Architecture Center construction industry professional database of 23,132 contacts developed from a pool that was constructed from 35 of the 50 US state professional licensing boards of architects, engineers, and GCs. A total of 205 participants responded to the survey, compared with 312 from 2014. The individuals that responded to the updated survey included the following AECO disciplines: CM or GC (24.75% in 2018; 46.7% in 2014), engineering (21.72% and 38.3%), trade contracting (2.53% and 27.3%), architecture (87.88% and 15%), and owners/developers (10.10% and 8.3%) (Question 10, 2018; Question 12, 2014). Multi-family housing increased in use from 24% in 2014 to 38.46% in 2018 (Question 12). The primary benefit identified in 2018, just as in 2014, was reduced overall project schedule, especially during the construction phase. Other benefits noted from respondents included the quality of product and cost effectiveness (Questions 4 and 5).

The barriers and challenges to implementing OSC are aligned with 2014, according to respondents, including transportation, clear program requirements, unions, and building types not suited for OSC. Further, the lack of supply chain integration and job site handling of OSM elements was again an issue. However, a new finding in 2018 was the challenge of late design changes as the most significant barrier in the general problem of design and construction culture (Question 2). CMs and GCs from the 2018 survey are still the primary stakeholders making decisions to utilize OSC at 47.67%, followed by architects and engineers, and then owners and clients. This finding continues to reinforce the need for education for decisions makers as well as owners who have potential to increase demand for OSC (Question 3). There is a need for these project stakeholders (owners, architects, engineers, and especially CMs) to increase their knowledge of OSC. The 2018 survey is included in Appendix B. Table 5.1 below outlines the NIBS 2014 and 2018 survey results that indicate knowledge needs in OSC in the US.

Table 5.1. NIBS Surveys knowledge needs. Mined from: (Smith, 2014; Smith and Tarr, 2018).

[redacted]

[redacted]

[redacted]

5.2 PR02 – OSC Performance Studies

In 2015, the researcher fostered parallel studies to evaluate the construction performance attributed to OSC and the contingent qualitative contextual factors by which OSC in building design and construction may be realized. The studies and resulting reports, “Permanent Modular Construction: process practice performance” and “Solid Timber Construction: process practice performance”, were identical in method and approach, with the former focused on volumetric modular construction and the latter on mass timber construction. Sponsored by a consortium of companies and organizations, the studies are structured in the following manner using a mixed-methods approach of project data analysis using a quantitative and qualitative survey, and comparative analysis as follows:

- Project Identification: The research team identified built OSC projects based on access to archival data and willingness of stakeholders to participate and offer additional data, such as diversity of project sizes, locations and building types, and the cultural significance of the buildings based on architectural impact.
- Literature Review: Each project was investigated through an initial literature review of publicly available information on project background data (size, type, location, stakeholders, year, etc.) and construction performance data (cost, schedule, and worker safety).
- Survey: Then the research team triangulated performance data from the architect, GC or CM, and the OSM manufacturer. In all cases at least two of the three parties responded. A questionnaire was distributed to the parties and then a follow up interview validated construction performance of OSC by researching and documenting built projects to record performance parameters including economics, schedule, scope, quality, risk, and worker safety. In addition to quantitative data, qualitative questions were asked during the interviews to determine the context for successful OSC deployment.
- Comparison Analysis: The development of the project profiles was then compared with projects of similar scope by Cumming Corporation, a cost consultancy firm. The data was normalized to location and cost, delivery method and precedent values. The specifics of the comparison projects and study limitations are explained in detail in the reports. This data of OSC projects was compared to the traditional site-built construction cases developed by the CM consultant to determine the added value or negative impact of OSC.

The permanent modular study respondents indicated that OSC realized a 16% cost reduction, 45% schedule reduction, 5.4 average change orders per project and 0.25 average safety incidents, when compared with traditional case comparisons. Qualitatively, the participating companies in the permanent modular study indicate that OSC was selected because of a desire to control cost and reduce schedule. The challenges to OSC were permitting schedule overruns and transportation logistics and associated schedule difficulties. Some of the lessons learned from these projects include early engagement of the modular manufacturers, using a progressive form of contract and procurement such as design-build, and ensuring that there is design phase modular research completed prior to engaging in formal design work.

The solid timber study yielded the following related findings: 4% cost reduction, 20% schedule savings, 3.7 average change orders per project and zero reported safety incidents. The STC study qualitative findings suggest that speed of construction and an owner "wood first initiative" and sustainability goals were the primary drivers. Code approval, acoustics, and connections were the challenges. The lessons learned from the solid timber study demonstrate that the disadvantages to OSC include workforce knowledge and skills, lack of research, handling, and logistical challenges onsite, poor project planning, and anticipating problems at the outset. Furthermore, respondents indicated that acoustics and vibration of solid timber was an issue, as well as job displacement due to use of OSC, codes and permits (regulatory) difficulties, wind on site and craning and handling, and onsite manipulation of prefabricated components that did not allow for flexibility.

In addition to the reports, the permanent modular study was published in the *Proceedings of the 2015 Modular and Offsite Construction (MOC) Summit* (Smith and Rice, 2015) and was included in a chapter of *Offsite Architecture: constructing the future* (Smith and Rice, 2017). The solid timber study was published in *Architectural Engineering and Design Management* (Smith et al., 2018). The permanent modular chapter and solid timber article are included in Appendix C. Table 5.2 provides knowledge needs findings from the performance studies.

Table 5.2. Barriers and challenges and associated knowledge needs in OSC. Mined from: (Smith and Rice, 2017; Smith et al., 2018)

[redacted]

[redacted]

5.3 PR03 - MBI 5 in 5 Study

In 2015, the MBI, the trade association for modular manufacturers in North America and Europe, initiated an effort to grow the commercial modular market. The goal was to increase OSC from 2.37% to 5.0% of total construction expenditure in five years' time. The researcher and co-investigator, Dr. Rupnik of Northeastern University, was retained in a research capacity to lead the development of a roadmap for strategic growth. The research was structured into three phases using a mixed-methods approach:

- SWOT Analysis: This was a facilitated workshop to determine the internal strengths and weaknesses and external opportunities and threats from the perspective of the volumetric modular manufacturers.
- Survey: This was a quantitative and qualitative questionnaire of the AECO industry.
- Contexts: Analysis of six OSC international contexts were studied including the US, UK, Australia, Poland, Sweden, and Japan, and a learning journey was taken to

companies in the US, Sweden, and Japan to identify the lessons of growth of the OSC housing markets in these geographic locations.

- Growth Plan: A four-pillar growth plan for the volumetric modular industry was developed, including a focus on data, partnerships, standards and 3Cs (competence, capacity, and capability) of the manufacturers proper.

This report on PR03 focuses on the first three phases of this project, SWOT, survey, and contexts, to further verify and clarify knowledge needs in OSC. A more in-depth discussion of the socialization CoP of the MBI 5 in 5 study is covered in Chapter 06 – CS Analysis and included in the research report included in Appendix D of this thesis (Smith and Rupnik, 2018).

The SWOT analysis was conducted over a three-hour session at the World of Modular Conference in 2017 with 32 permanent (volumetric) modular manufacturing companies represented amongst the ~210 modular OSM manufacturers in North America. The results of this SWOT demonstrated common themes and revealed modular manufacturers perceptions concerning the modular industry's strengths, weaknesses, opportunities, and threats. It also formulated the questions that would be asked in the North American survey component of this project. The research team performed a SWOT analysis and conducted the survey to identify the gaps between what the AECO determined were the challenges and opportunities of OSC for increasing uptake and what modular manufacturers were claiming as their value and difficulties to increasing growth. This gap identification pointed to the knowledge needs for OSC, particularly for the OSM manufacturers proper. A full list of the SWOT was included in the report; however, the key findings are listed in Table 5.3 below.

Table 5.3. MBI 5 in 5 SWOT outcomes. Mined from: (Smith and Rupnik, 2018).

MBI 5 IN 5 - OSM SWOT	
STRENGTHS	WEAKNESSES
safety, reuse, reduced onsite activity, year round construction, sustainability and reuse, quality, systematic approach, disassembly, disruptive industry, lack of standardization, enthusiastic	transportation regulations by state, lack of investments, lack of data, industry knowledge, less capabilities, process and skilled labor shortage, one step in supply chain, lack of R&D investment, fear of

experience, state regulatory agencies, positive picture to finance, accelerated schedules, predictable delivery model, controlled assembly process, evolution will catch up, lack of international competition, price protection, ability to address labor shortage, ability to integrated subtrades, measure performance as a manufacturing operation	change, diversity of product quality, spending too much time protecting the fleet, focusing on 3% instead of working together for 5%, finger pointing, too many stakeholders and layers or profit, financially weak, biased manufacturer infrastructure, cost in some regions, lack of automation, pricing for GC, wood heavy, no export of products, educating and training stakeholders, mentorship and workforce pipeline development, aesthetic excellence, not enough capacity, openness to change and grow with external help
OPPORTUNITES	THREATS
advanced technology, fragmentation of construction, no preconception, new application in new market, affordable housing in demand, multi-generational occupancy, 97% of the market, other stakeholders to get us to 5% (GCs), new way to build, learning from the past, healthcare, investment funding, joint ventures for larger clients, university partnerships, sustainable building response, worker shortage	Cost, wages, unions, education (higher ed), lending and finance practices, subtrades fighting OSC, architects not knowledgeable and not willing to embrace, lack of standards, transportation regulations, failure of industry to educate stakeholders and code officials, stigma, procurement process not set up for OSC, GCs not embracing, contracts and codes not written for modular, lack of education for developers and owners

The survey questionnaire was drafted prior to the SWOT workshop and then peer reviewed during the SWOT workshop with participants. Further, MBI board members reviewed the survey prior to dissemination in May of 2017 online. The survey was distributed to more than 23,000 architects, engineers, contractors, and building officials in North America. Furthermore, the survey was distributed to a selective pool of authorities having jurisdiction (AHJs) with experience in permitting and inspecting volumetric modular construction. The names for the AHJs were nominated by the MBI membership based on personal experience. A total of 793 individuals responded. The results indicate the barriers to OSC uptake for experienced AECO professionals that have performed one or more projects using OSC methods. The results are captured in Table 5.4 and listed in order of frequency of responses.

Owner respondents indicate that traditional procurement and project finance structures are limiting OSC, and they also agree that their own knowledge is a barrier. Further, code official respondents identify and admit that their own knowledge is a top three barrier to OSC in North America. OSC users also provided their qualitative experiential input through open-ended questions on what restricts modular construction from growing to 5% of the total market. The answers include problems with poor quality of the OSM products due to exterior envelope issues and dirty factories, costs being higher on initial bids, onsite set and assembly workforce skills and training, self-performing GCs not being incentivized to use OSC, and significant scope gaps between OSM and GC.

Table 5.4: Barriers to OSC adoption by AECO professionals in the US. Adapted from: (Smith & Rupnik, 2018).

MBI 5 IN 5 - AECO BARRIERS	
OSC EXPERTS	OSC NOVICES
1) owner perception and education 2) historical stigma 3) regulatory code officials and inspectors' knowledge 4) design restrictions and aesthetical limitations 5) transportation logistics 6) designer's knowledge of OSC 7) early engagement of manufacturer 8) cost estimating	1) owners not requesting it 2) lack of knowledge among project stakeholders 3) program / building type is not amenable to OSC 4) designers are not specifying it 5) regulatory challenges 6) bidding and procurement challenges 7) transportation logistics 8) cost effectiveness 9) finance difficulties 10) insurance and bonding barriers 11) construction sequencing obstacles

The MBI 5 in 5 study took this first step of a SWOT of manufacturers and an AECO barrier study to a third phase of the study, a literature review of mature OSC cultures internationally. Then, visits were made to companies in these countries to document the lessons that may be implemented in the North American context. The contexts evaluated for this study included US, UK, Sweden, Japan, Poland, and Australia. The method used for the international evaluation was a CS method through a GT methodology (Glaser, 1967). The research tactic was to gather data from qualitative interviews with company personnel and observations of manufacturers. The data was coded and then concepts and themes formed the key lessons from each of the contexts. The contexts lessons were combined to form core lessons outlined in Table 5.5.

Table 5.5: Core lessons from the MBI 5 in 5 study. Adapted from: (Smith & Rupnik, 2018).

[redacted]

The SWOT, survey, and international lessons were triangulated to form a growth plan for the MBI membership that identifies strategies and tactics to realize greater market growth. The plan has four strategies including: 1) Data – what is measured can be claimed, what is measured is improved; 2) Partners – strategic alliances extend reach and educate constituents; 3) Standards – competitiveness fosters innovation; 4) 3C – foster manufacturer competence, capacity, and capability to deliver. These strategies were mapped onto a diagram (Figure 5.1) that demonstrates the relationships between strategies. Under each strategy, a series of tactics was identified: actions that MBI and its members can take to strategically manage growth in modular construction.

Figure 5.1. MBI 5 in 5 strategies for growth. Image Credit: (Smith and Rupnik, 2018).

The first three strategies identified in the MBI 5 IN 5 growth plan - data, partners, and standards – were further identified and clarified as knowledge needs in a subsequent study by the author with US HUD to create a research roadmap in OSC housing for the industry at large, not only manufacturers. This roadmap project is reviewed in the next section.

5.4 PR04 - HUD OSC Roadmap

The HUD Office of Policy Development and Research and the NIBS partnered to develop a roadmap that could serve both HUD and the OSC industry in focusing research and development efforts on overcoming barriers to domestic OSC growth in the US housing sector. Three core objectives for the roadmap were identified by NIBS and HUD: 1) identify the current state of knowledge concerning OSC for housing; 2) identify the research areas, questions, and knowledge gaps in OSC for housing for the industry; and 3) disseminate the research needs to the industry, academia, and government. This project used a qualitative research methodology as the researchers interacted as co-producers of knowledge. Furthermore, the consensus process used inductive reasoning from a critical realist position.

NIBS structured the research into the following phases:

- Team and Topic Identification: Contract with HUD, engaging the research and co-investigators as the Project Technical Committee (PTC) Chair, and developing a preliminary list of research topics and questions with the NIBS OSCC.
- Literature Review: Conduct a literature review to refine the preliminary list of research topics, and form a PTC, a diverse group of leading experts from across the housing and OSC industry, to examine the research topics and questions.
- Workshop: Hold an invitation only-workshop to review, validate, and prioritize the research questions and the PTC to comment on draft report and finalize the roadmap and submit to HUD for publication.

In 2021, a preliminary list of core research topics and questions was developed through a review of the NIBS industry surveys from 2014 and 2015, as well as the knowledge needs identified in the MBI 5 in 5 study. These were clarified by the NIBS OSCC. The knowledge needs were then researched in a literature review of popular press and peer reviewed sources to refine the preliminary list of topics and bring the knowledge needs into clarity of current practice trends in 2021.

The PTC, made of nine experts in housing and OSC, reviewed the knowledge needs and grouped them into topics and questions through a consensus process. This involved three meetings between September 2021 and November 2021, a qualitative questionnaire, and hour-long individual meetings between the author's research team and each PTC member, who provided details for each knowledge topic. A draft roadmap of high-level research topics and a list of specific subtopics was developed and presented to the PTC and 34 invited participants, representing a diversity of housing and OSC supply chain backgrounds and expertise during a 3-hour virtual workshop. The PTC moderated breakout rooms to peer review and verify the research topics and further clarify the knowledge needs for the US OSC industry to increase in uptake and productivity. The workshop was followed up with a survey to the participants to gather any remaining data from the outcomes.

This consensus process yielded six topics that were research needs in OSC for housing. The six research needs topics are listed below and illustrated in Figure 5.2.

Topic 1 - Regulatory Framework

Topic 2 - Standards and System Performance.

Topic 3 - Capital, Finance, and Insurance.

Topic 3 - Project Delivery and Contracts.

Topic 5 - Labor and Workforce Training and Management.

Topic 6 - [redacted]

Figure 5.2. HUD OSC Research Roadmap six areas of research needs. Source: (Smith et al., 2022)

Under these six high level research need topics in OSC, a total of 46 subtopics and 184 research questions emerged through the qualitative approach with industry experts to identify the key knowledge gaps and knowledge needs in OSC. The aim was that by identifying the knowledge needs in OSC, the industry may overcome the barriers and challenges of OSC uptake in the US. The results showed that although technical topics are obstacles to OSC, most of the challenges identified through this consensus process stem from social, environmental, and economic context that negatively impacts OSC. This means that knowledge needs, according to this research, are situational, tied to building type, market, geographic location of the built work with the associated regulatory, finance, labor, and supply chain structure, and reliant on stakeholder socialization – the people. The results also suggested that regulatory, standards, capital/finance, and insurance contexts are higher priority topics to be addressed over project delivery, contracts, labor/workforce, and business models. However, the findings also indicated that these topical areas have considerable overlap and are contextually contingent.

In addition to specific knowledge needs, the participants in this study identified several key takeaways listed in Table 5.6.

Table 5.6. HUD OSC Research Roadmap key takeaways. Adapted from: (Smith et al., 2022).

RESEARCH TOPICS KEY TAKEAWAYS	
KM	Develop a research culture and knowledge sharing platform while protecting the IP of OSC stakeholders.
INTERDISCIPLINARY TEAMS	Utilize interdisciplinary and cross-cutting teams to address research needs that are at the intersection of technical means and methods and contextual/social concerns.
DATA	To claim the value performances and continually improve the practices of OSC, data needs to be collected, analyzed by OSC stakeholders, and disseminated to the broader AECO.
BEST PRACTICES	Given the unique municipal level decisions that impact OSC practice in the US, best practices and lessons learned from local programs (regulatory, finance, housing RFPs, patient capital programs, etc.) need to be collected and shared with the wider US OSC.

PILOT PROJECTS	Institute a series of pilot projects to not only test means and methods of OSC project delivery, but also and more importantly, the contextual frameworks including regulatory, standards, and finance topics.
EDUCATION AND TRAINING	At every stage of the OSC project delivery process – develop, design, permit, procure, manufacture, inspect, ship, assemble, commission, and maintain – education and training are needed early and often throughout. There is a need to fund higher education, trade schools, and apprenticeships programs for growing jobs and recruiting labor into the OSC supply chain.
LEARN GLOBALLY, ACT LOCALLY	The need for international lessons were identified under all six topical categories to determine the applicability for the US OSC.

5.5 OSC Knowledge Priorities Verification

Chapter 03 - OSC Knowledge identified knowledge needs and priorities in OSC. Chapter 05 – Data Mining is focused on verifying and clarifying these knowledge needs for OSC housing. Data was mined and analyzed PR projects conducted by the researcher. The projects that were evaluated include: PR01 – Industry Surveys, PR02 – OSC Performance Studies, PR03 – MBI 5 in 5 Growth Plan and PR04 - HUD OSC Roadmap. A summary of each of these projects is included below with overall findings and conclusions provided for knowledge needs and priorities in the US OSC housing industry.

PR01 – Industry Surveys: NIBS 2014 survey found that to grow the OSC sector, the industry needed to address the following knowledge areas: 1) education and knowledge of the AECO stakeholders, 2) transportation logistics, 3) regulatory navigation (permits and inspection), 4) building program not amendable to OSC, 5) workforce and labor unions, 6) standards for process and product, 7) CS of construction performance – cost and schedule, 8) manufacturing knowledge, 9) project delivery sequence and scope definitions, and 10) adversarial culture of construction.

In 2018, the NIBS survey confirmed the 2014 findings and further discovered that 11) design knowledge (DfMA) and 12) education for code officials and other stakeholders, pointing to the continuing challenge of regulatory processes in the US, was needed to increase uptake. PR02 OSC Performance Studies corroborate some of these findings from the industry surveys, including the need for knowledge in regulatory navigation, transportation logistics, CS examples on successes and data, standards, and education. Unique to the performance study findings was the desire that respondents have for data and a platform to both gather and disseminate industry relevant data and information, furthering evidence of the need for KM in OSC.

PR03 - MBI 5 in 5 Study SWOT analysis and survey revealed that the US OSC industry, specifically modular construction, needed knowledge to overcome barriers to growth. The knowledge areas included owner perceptions, project delivery, regulatory navigation, transportation logistics, design for offsite, finance, and insurance and bonding. Furthermore, the study concluded with four strategies to increase OSC modular uptake in the US as follows: 1) strategic partnerships with government, academia, and industry, 2) data to measure and improve and claim performance, 2) standards in regulatory and project delivery processes, and 3) an increase in competence, capacity, and capability of the OSM modular manufacturers themselves to foster a more reliable and quality supply chain of subassemblies. Of the four strategies for increasing OSC modular growth, standards, data, and partners were also identified as key knowledge areas in the HUD Research Roadmap project.

PR04 – HUD OSC Roadmap was focused directly on knowledge needs (research categories) for the US OSC housing industry to increase uptake and evolution. It used literature gathered from the previous studies by the researcher (PR01 – PR03) and the NIBS OSCC membership opinion (see CS01) on research needs to frame several questions for the project technical committee and expert workshop. The outcomes of the HUD Roadmap identified the primary knowledge needs of US OSC in order of priority including: 1) regulatory and policy revision and clarification, 2) standards development and diffusion, 3) data to mitigate OSC project finance and insurance risk factors, 4) project delivery methods and contracts that are OSC oriented with performance data on project outcomes in OSC, 5) labor and workforce skills and knowledge, education and training, and 6) business models (vertical and horizontal integration, joint venture) including knowledge about investor positioning in OSC.

PR01 – PR04 data mining projects were analyzed through frequency occurrences of key knowledge needs (see Table 5.7). The OSC knowledge needs and priority categories for Objective 03 – Data Mining that appeared in 50% or more of the projects are listed below:

- Regulatory navigation (100%)
- Transportation logistics (83%)
- Stakeholder knowledge and skills (83%)
- Project delivery methods and contracts (67%)
- Standards development (67%)
- Factory management (67%)
- CS examples (67%)
- Project and industry performance data (50%)
- Culture of construction (50%)
- Organized labor and unions (50%)
- On-site management (50%)
- Process improvement (50%)
- Supply chain (50%)
- Procurement (50%)
- Programmatic requirements (50%)
- Technology development (50%)

Each core knowledge category was assigned a TOE dimension (Toransky & Fliescher, 1990) to further evaluate if the knowledge needs were technological, organizational, or environmental in principle and remain consistent with the OSC knowledge needs approach from SR sources covered in Chapter 03. The findings from the PR data suggested that the main barriers to uptake and thereby knowledge needs in OSC are overwhelmingly environmental and organizational, pointing further to the need for KM frameworks to support inter-organizational knowledge exchange.

Table 5.7: Data mined OSC knowledge needs frequency analysis and the associated TOE framework.

Technology Organization Environment (Tornatzky & Fleischer, 1990)	OSC KNOWLEDGE NEEDS	Verification Studies						TOTALS
		(NIBS) Smith, 2014	(NIBS) Smith, 2018	Smith & Rice, 2015, 2017	Smith et al., 2018	Smith & Rupnik, 2018	Smith et al., 2022	
E	Regulatory factors	1	1	1	1	1	1	6
E	Transportation	1	1	1		1	1	5
O	Knowledge & skills	1	1	1		1	1	5
E	Project Delivery	1	1	1			1	4
E	Standards	1	1	1			1	4
O	Factory management	1	1			1	1	4
O	Case studies (need)	1	1	1			1	4
E	Project and Industry Data			1		1	1	3
E	Culture	1	1				1	3
E	Organized Labor	1	1				1	3
O	Site management				1	1	1	3
O	Process improvement	1	1				1	3
O	Construction Performance			1		1	1	3
O	Supply chain	1	1				1	3
O	Procurement			1		1	1	3
O	Programmatic requirements	1	1			1		3
T	Technology development				1	1	1	3
T/O	Design (DfMA)		1	1			1	3
E	Finance & Insurance					1	1	2
O	Expierence			1		1		2
O	Early engagement			1		1		2
O	Planning				1		1	2
E	Sustainability						1	1
E	Factory capital						1	1
E	Aesthetic limitations					1		1
E	Geographic differences						1	1
E	Context					1		1
O	Business models						1	1
O	Stakeholders						1	1
O	Logistics						1	1
O	Operational performance						1	1
O	Product platform						1	1
O	Economies of scale						1	1
O	Partnerships					1		1
O	Customer Centric						1	1
O	Scope gaps						1	1
OE	Multi-family housing						1	1
OE	Single-family housing						1	1
T/O	ICT/BIM						1	1

5.6 SR and PR Validation

The development of OSC knowledge needs was performed through a barriers analysis to OSC adoption and uptake. The analysis reviewed extant literature and data mined PR projects conducted by the researcher. Chapter 03 was an assessment of literature on OSC knowledge need categories from journal articles and research roadmaps written by scholars and industry experts. The knowledge categories were then analyzed through a literature review and frequency analysis of OSC knowledge needs. These needs were verified and clarified by data mining the research projects presented in this chapter.

Table 5.8 compares SR02 literature review with PR01 – PR04 Data Mining for knowledge needs. Knowledge categories were coded as knowledge barriers and therefore knowledge needs. Any knowledge category that appeared in 50% or more of the samples (literature source or research project) is listed to demonstrate the verification of the need or divergence.

Table 5.8. OSC housing knowledge needs and priorities from SR02 and PR01-PR04.

OSC Housing Knowledge Needs and Priorities	
SR02 – OSC Knowledge Needs from extant literature (Chapter 03, Section 3.7)	PR01 – PR04 Data Mining from PR (Chapter 05)
• On-site management of OSC assembly • Process improvement of OSC delivery • Quantifying construction performance (cost and schedule) of OSC • Knowledge and skills of OSC stakeholders	• Regulatory navigation (100%) • Transportation logistics (83%) • Stakeholder knowledge and skills (83%) • Project delivery methods and contracts (67%) • Standards development (67%) • Factory management (67%) • CS examples (67%) • Project and industry performance data (50%) • Culture of construction (50%) • Organized labor and unions (50%)

	• On-site management (50%) • Process improvement (50%) • Supply chain (50%) • Procurement (50%) • Programmatic requirements (50%) • Technology development (50%)

The SR02 – OSC Knowledge and PR01 – PR04 Data Mining found that the knowledge needs for OSC are environmental and organizational and much less technological. Environmental knowledge refers to the social and contextual knowledge, organizational knowledge suggests operational and managerial knowledge, and technological knowledge references means, methods, and system knowledge. This finding is important because environmental and organizational knowledge is primarily concerned with the tacit domain of knowledge, emphasizing "how-to" knowledge. This research demonstrated the importance of KM in tacit knowledge conversions, further demonstrating the need for the research aim of this thesis – development of an inter-organizational KM framework. Therefore, the OSC knowledge needs found in the extant literature and the projects reviewed in this chapter are epistemologically consistent with SR01 - KM theory and the theoretical framework that emerged from the GT methodology.

The emergence of this framework is reviewed in subsequent chapters. The identification of OSC knowledge needs and priorities from the primary and SR provides a confirming context for Objective 04 – CS Analysis, presented in the next part of this thesis, Chapter 06, and the theoretical framework development explained in Chapter 07.

CH 06 – Case Study Analysis

This chapter presents Objective 04 for this research containing four CSs that were analyzed using GT tactics including CS01 – NIBS OSCC, CS02 – Scotland Hub, CS03 – Built Environment Exchange, and CS04 – MBI 5 in 5. The CSs served as test bed contexts to investigate KM in OSC. The CoP CSs overlapped in sequence of time in which they were established and operated, as well as the period of duration in which the researcher participated in the CSs.

In the sections that follow, the CS Analysis steps are presented through the example of CS01 – NIBS OSCC to demonstrate how GT tactics were implemented for this research that led to the formation of the TM3. Then each CS (CS01 – CS04) is presented individually to explain how the specific CSs led to the development of the TM3 framework. The chapter ends with a summary and connection to the last Objective 05 of this research – theory building.

6.1 CS Analysis Steps

While participating in the CoP contexts, the researcher recorded data from events through memoing to obtain the theoretical sampling. Constant data comparisons were made as the data was collected and analyzed concurrently. Concepts were developed that led to categories until theoretical saturation was reached. The concepts and categories were analyzed for relations within and between CSs and triangulated within the extant literature (Objective 02) and data mined projects (Objective 03). These categories formed core theories that became the theoretical framework – TM3 – for inter-organizational KM in OSC. Figure 6.1 illustrates how the researcher analyzed the CSs in this research using a GT tactic.

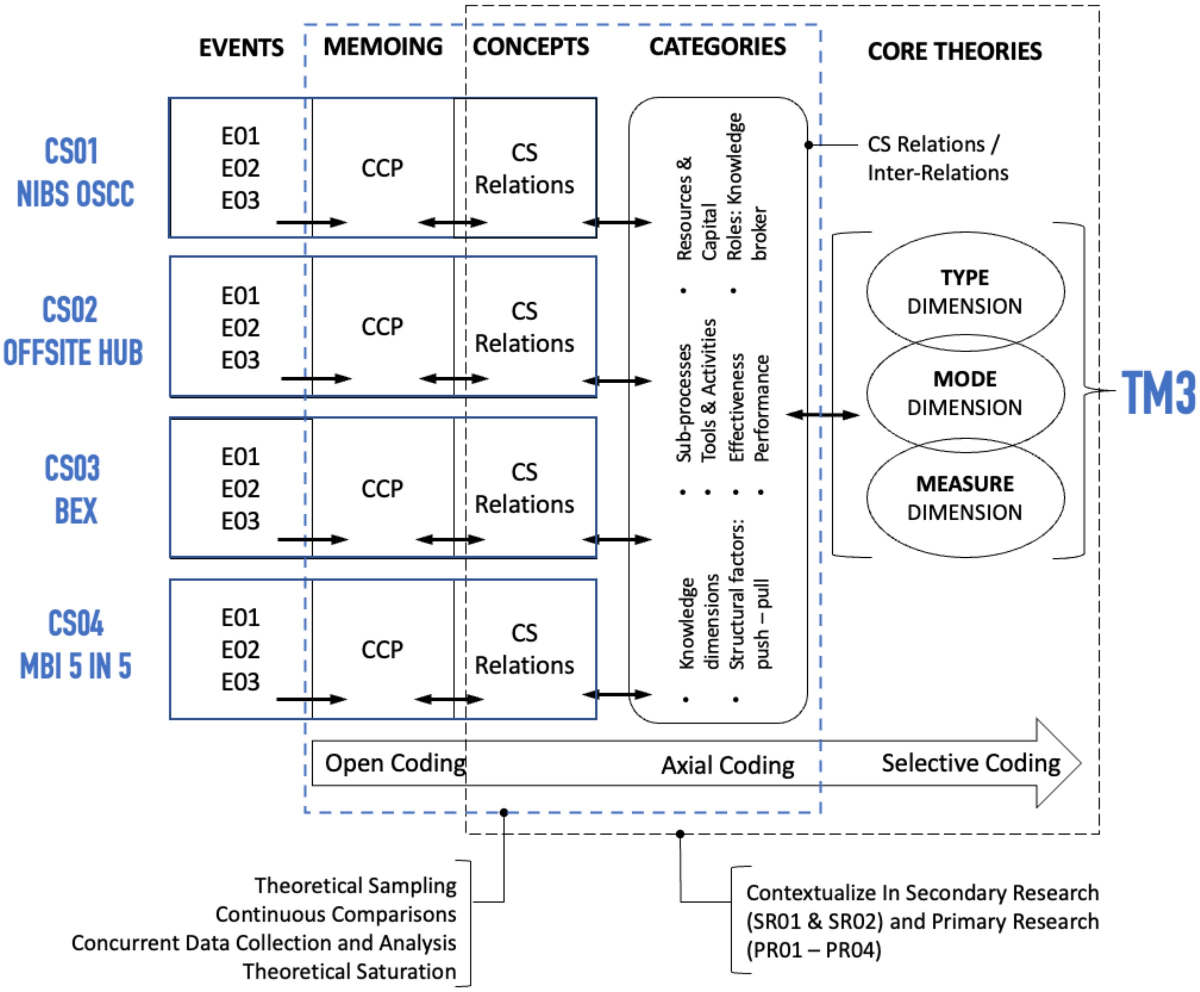

Figure 6.1. CS Analysis employed through a GT tactic.

NIBS is an independent non-government organization that was established by the US Congress in the Housing and Community Development Act of 1974 (Public Law 93-383) to serve as an interface between government and the private sector as a convening resource to the AECO industry. NIBS has both a public and private mission – it provides private sector support through voluntary, membership-based councils on specific topics related to the built environment that are of national concern. NIBS also provides research and educational services using subject matter experts and academics, with and for federal, state, and other governmental and non-governmental organizations to address building science issues. It maintains the *Whole Building Design Guide*, a website, with over 500,000 monthly users through an Advisory Committee of industry and 25 government representatives. NIBS hosts the Building Research Information Knowledgebase with over 3000 research entries (NIBS, 2022).

In considering a way to foster a socialized network of OSC professionals that could share knowledge perpetually between companies, government and academics, the researcher, with the MBI, approached NIBS to address OSC KM through the establishment of a voluntary council. Councils within NIBS already existed including the Consultative Council (executive and legislative recommendations), Building Seismic Safety Council, Multi-Hazard Mitigation Council, Building Enclosure Council, Facilities Management and Operations Council, and the Building Information Management Council. Given board approval, the NIBS Off-site Construction Council (OSCC) was established in 2013 with a threefold mission of research, education, and outreach (Table 6.1), and the researcher served as the inaugural chair. The council elected a board of directors from the membership and appointed a NIBS staff lead to the council. The council, as part of NIBS, collaborated with other councils within the organization on initiatives when appropriate.

Table 6.1. Three-fold purpose of the NIBS OSCC – Research, Education, and Outreach.

CS 01 - NIBS OSCC PURPOSE	
RESEARCH	To continue to research and improve numerous productivity benefits of OSC – specifically in the areas of labor, scheduling, cost, quality, and safety. Research activities conducted by the council – industry research survey reports to identify barriers and challenges, best practices and lessons learned, and research topics identification.
EDUCATION	To educate the benefits and applications of OSC, which is characterized by an integrated planning and supply chain optimization strategy. Educational activities include hosting conference sessions and webinars and producing reports and publications.
OUTREACH	To promote relevant and current information on offsite design and construction for commercial, institutional, and multifamily facilities. The council takes the research and educational activities and disseminates and publishes content on their website, and hosts information on the *Whole Building Design Guide*.

6.1.1 Events

The NIBS OSCC was the first CS in which the researcher participated. The CS provided preliminary understanding of the role and value of CoP in KM. Further, through the process of the CoP establishment and initial meetings, the researcher and stakeholders recognized the need for a framework that would provide a more systematic approach to addressing the KM process through the various activities and engagements of the CoP. This was corroborated in the PR01 2014 survey, the first research endeavor by the council, in which OSC knowledge and education was identified by respondents as a need. As knowledge needs would be clarified in the future, the council sought ways in which to determine how to produce, exchange, and then share knowledge between CoP members and with industry to improve OSC practice and increase the uptake and adoption rate.

Since 2014, the council has engaged in the following events:

- Organized sub-committees that change every few years based on industry need (i.e., research, education, standards, labor, etc.).
- Met once a quarter at-large and as sub-committees.
- Conducted three surveys – two industry-oriented surveys (PR01) to gauge uptake statistics, barriers to adoption, and knowledge needs and one survey on BIM adoption in OSC (NIBS, 2016).
- Produced seven codified publications on OSC knowledge domains including an overarching research needs report and an OSC glossary to address the need for terminology clarity in the industry.
- Conducted three webinars on OSC topics including volumetric modular construction, precast construction, and navigating the regulatory process in OSC.
- Organized and moderated three sessions at the National NIBS Conference.
- Advised on research projects with Fannie Mae (national housing finance), American Institute of Architects, US HUD, and Veteran Affairs (federal veteran health care provider).

The researcher participated in a total of 46 unique events from 2014 - 2018 and collected data as stakeholders interacted in the CoP to accomplish a particular research, education, or outreach project. This does not include the countless email exchanges and quick videoconferences to convey information related the CoP operations. The data from the events was classified into the CCP framework (Pettigrew, 1985) – context, content and process as a memoing tactic, a filter, to parse incoming data and group it into meaningful format.

6.1.2 Memoing, Coding, Concepts and Categories

Each event was recorded with memos in a medium sized notebook dedicated to the CS qualitative documentation. Through notetaking, sketching and diagramming, the meeting minutes were recorded on the right side of the spread and the CCP parameter memos were recorded on the left as shown in Figure 6.2.

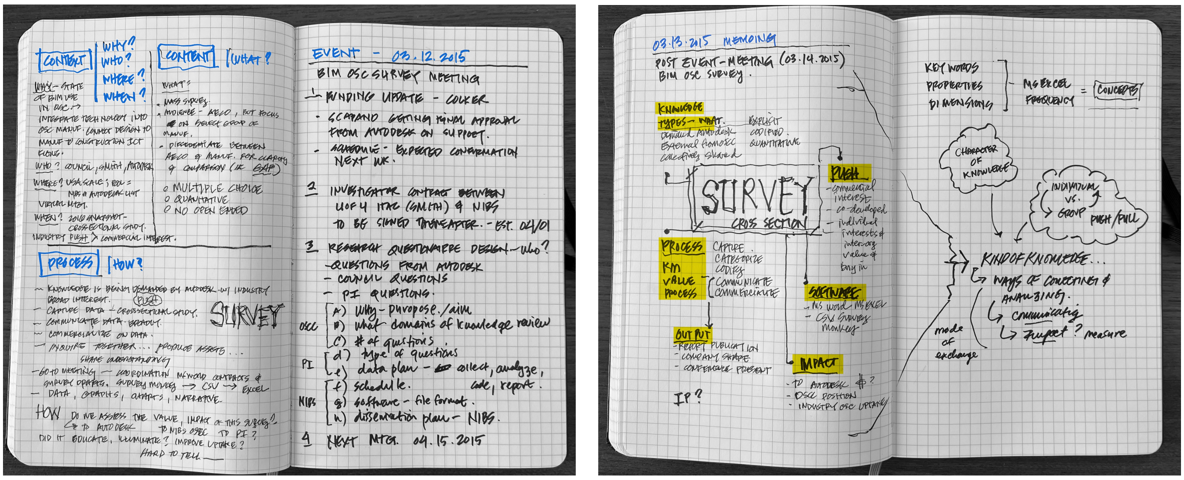

Figure 6.2. Event minutes and memos (left) taken during a meeting and post-event memos (right) recorded the next day regarding a building information modeling OSC survey project related to CS01 - NIBS OSCC.

After the Event, the researcher reviewed the minutes and memos taken during the meeting, reflected on the observations, and developed a post-event memo in which themes emerged and were clarified. The post-event memo was then entered into an MS Excel spreadsheet by theme and sub-theme, tagged with properties and dimensions, keywords, and descriptions with the aim of finding key concepts that could emerge for the CS CoP. This open coding method of documenting all perceptions, observations, and speculations allowed for a large amount of qualitative data to be sourced and fostered forming perspectives on how the CoP operated as an inter-organizational KM entity.

This process of memoing and analyzing event data continued throughout the engagement with the CoP during the period of data collection. A frequency analysis was conducted of the themes in MS Excel periodically through the data gathering time to identify emerging concepts within the CS (Figure 6.2 right). New and existing data was compared for relationships of concepts that were emerging within the CS CoP using axial coding. The most frequent concepts that emerged from this research formed the most granular components, level three (L03) of the TM3 framework. The concepts from each of the CSs were then combined to form categories, level two (L02) of the framework. Categories were developed through another frequency analysis, this time for all the concepts across the CSs. These emerging categories were mapped into a relational diagram and analyzed for their relations through descriptive narratives about each category. The CS leading concepts were compared for similarities and differences using axial coding. This resulted in the following L02 categories:

- Types of knowledge
- Reciprocity between inter-organizational and individual actors (Latour, 1996)
- KM cycle processes
- Tools, technique, and technologies used by the CoP
- Activities, engagements, and shared learning
- Impact – effectiveness and performance
- Roles

6.1.3 Contextualize

The emerging concepts were contextualized in the extant literature SR01 and SR02 and data mining in PR01 – PR04. The reference to the literature on KM theory provided the researcher with vocabulary and terminology to name the themes, concepts, and categories that emerged from the CS research. The coded data from the CSs and emerging concepts and categories was compared with what scholars had discovered in their research on inter-organizational KM. This proffered the literature to have a confirming function to frame the CS analysis – to support the dependability, transferability, and applicability of the qualitative research beyond the experiences of the CS samples alone (Corbin & Strauss, 2015).

Further, the CS analysis was further grounded in the PR that was mined in Chapter 05. PR01 – PR04 triangulated the OSC knowledge need literature review from SR02. Further, the data mining of this research provided insights regarding the CS happenings, value of the CS outcomes, and overall intellectual and knowledge contribution of OSC and KM intersection for which the data mining provided validation.

This process of contextualizing the GT approach in literature was iterative – oscillating between the CS engagement and literature review as both were conducted simultaneously. Both the literature review and the CS coding reached a point of theoretical saturation in which reoccurring concepts were repeated regularly in the literature. Experiences in the CoP were likewise offering little additional data that was significantly different from the substantive emerging theory. The resulting L02 Categories with the corresponding contextualized literature are outlined in Table 6.2.

Table 6.2. L02 categories clarified and confirmed by the extant literature on KM theory.

Categories Contextualized by Literature Review		
L02 Categories	Contextualizing Literature	Confirming and Clarifying Theory
Knowledge Dimensions	Nonaka et al. (1994), Nonaka & von Krogh (2009), Anumba et al.(2005), Laudon & Laudon (2000), Henderson & Clark (1990), Matusik & Hill (1998)	• Ownership, Private and Public, Individual and Collective • Auxiliary and Critical, Slow and Rapid • SECI knowledge conversions
Structural Factors: Reciprocal	Loebbecke et al. (2016), Gibbons et al. (1994), Milagres & Burcharth (2018), Scarbrough et al. (1999), Brookes & Leseure (2000)	• Pull and Push • Individual and Inter-organizational reciprocity • Location of knowledge • Uni-lateral / Bi-lateral exchange
Sub-Processes and Time	Holsapple & Joshi (1999), Heisig (2009), Mohajan (2016), Dalkir (2011), Meyer & Zack (1996), Bukowitz & Williams (2000), McElroy (1999), Wiig (1993), Dalkir (2005), Kotabe et al. (2003), Dyer & Hatch (2006)	• KM cycle scope clarification: contextualizing, commercializing, continuing knowledge • Co-production • Time considerations in KM sub-processes
Tools	Al-Ghassani et al. (2005), Al-Ghassani (2002), Gallupe (2001), Ruggles & Holtshouse (1999)	• Techniques versus technologies • Cross-project learning • Bi-lateral learning

Activities	Wenger (1998), Wenger (2009), Karner et al. (2011), Lewin (1951), Kolb (1984)	• Shared learning activities: formal / informal, from / with • Experiential learning
Effectiveness and Performance	Robinson et al. (2005), Wenger (1998), Robinson et al. (2005), Grimpe a& Sofka (2016), Herstad et al. (2014), Frankort (2016), Tsai (2009), Bose (2004), Polley & Smith (2007), Robinson et al. (2005), Edison et al. (2013)	• Process, role, trust, communication, socialization evaluations • CoP success factors • Metrics, economics, market value • Stocks and flows • Forms of capital
KB	Wenger et al. (2002), Etkowitz & Leydesdorff (1995), Gibbons (1994), Matusik & Hill (1998), Jackson-Bowers et al. (2006), Wenger et al. (2009), Meyer (2010), Gould & Fernandez (1994)	• Contingent worker • KB roles, strategies, and skills • Leader, champion, facilitator

6.1.4 Core Theories

At this step in the GT approach, the researcher took the categories, contextualized them in the extant literature, and formed core theories that could provide the defining theoretical framework for the TM3. The core theories constituted level 01 (L01) of the framework and were the substantive theory for the TM3. The development of the framework from the analysis of each of the CSes is presented in the following sections organized by L01 core theories: type, mode, and measure.

6.2 CS01 – NIBS OSCC

6.2.1 CS01 Type

When soliciting support for the creation of the NIBS OSCC, the response from AECO stakeholders was that the value of a CoP focused on OSC was in the creation and sharing of knowledge of OSC market performance (know-why) and implementation guidance (know-how). Therefore, the knowledge needs for the industry for the NIBS OSCC were concerned with market data, to make an argument of why OSC was important and to determine the barriers to OSC adoption and innovation diffusion in the US. This was focused on 'environmental' factors from the TOE framework (Tornatzky et al., 1990). Once the base knowledge was benchmarked through surveys (discussed in the mode section below), the council focused on 'know-how' resources. Referencing the SECI model (Nonaka, 1994), ‘socialization’ conversions between tacit knowledge held by actors in the council and ‘externalization’ conversions from tacit and explicit knowledge were conducted through the council between the members. This occurred by capturing knowledge from the actors’ project-based experience and then codifying the knowledge into publications, webinars, and other outputs. Therefore, the CoP council used a bi-lateral reciprocal sharing structure (Loebbecke et al., 2016).

The researcher served as a KB in the CoP, guiding, shepherding, and initiating direction for the council. The co-chair, a trade association executive director, served as a leader, fostering financial support and networking to increase the council membership numbers and diversify the disciplinary background of industry representatives from the various subassembly manufacturers and other AECO professionals that manage OSC practices. Further, in addition to industry members, the actor recruitment was strategically aligned with the triple helix of innovation (Etkowitz & Leydesdorff, 1995); including members from government (US Veteran Affairs, US Army Corp of Engineers, US General Services Administration), university researchers focused on OSC, and industry participants across the supply chain of OSC. The staff liaison from NIBS assigned to the council was the only paid position amongst the CoP participants. The council runs to this day from volunteer efforts of the members. The staff liaison was also enthusiastic, hands-on, and fulfilled the role of facilitator in the council. The council started with a dozen members and in two years grew to over 150 members. There were three sub-committees established in the CoP: a research group that focused on the surveys and knowledge instruments, an education group that worked on the development of written and webinar resources, and an outreach group that addressed recruitment, communication, lobbying, and advocacy.

6.2.2 CS01 Mode

The KM cycle sub-processes used in the NIBS OSCC have varied over time depending on the knowledge being managed. The OSCC evolution can be viewed in three phases of development and lifecycle (Wenger et al., 2002) as follows: Stages 1, 2, and 3 -- potential, coalescing, and maturing, Stage 4 – stewardship, and Stage 5 – transforming. During the first phase, the council focused on producing knowledge to answer questions of ‘why OSC’. This was managed by the research sub-committee, led by the author to conduct a series of surveys to benchmark the AECO industry and their views on OSC as well as the barriers to adoption and maturation. The knowledge outcomes of these surveys were discussed in PR01 (Smith, 2014, 2018). The surveys provided the data of the barriers and challenges as well as what AECO respondents were seeking from the council.

The education sub-committee created a series of webinars, publications, and reports, as well as hosting conference sessions at the NIBS annual meetings and other venues on various OSC technical topics. These addressed 'know-how' related to project delivery, specific sub-assemblies, and regulatory navigation. The selection of these topics was in direct response to the knowledge needs requested by respondents to the industry surveys from the research committee. Publications from this effort included a glossary of terms and a "Offsite and Modular Construction Explained" by the author hosted on the *Whole Building Design Guide* website. The outreach sub-committee took the work of the other two committees and disseminated the results to a wide audience using their networks, workshops, and conferences. Furthermore, the sub-committee used the resources to advocate for regulatory changes that can accommodate OSC and lobbying efforts to change the language in US government departments that historically limited OSC use due to stigma and misunderstanding of OSC delivery.

In the second phase of the CoP - stewardship, following the initial phase of CoP development (2012 – 2015), the researcher stepped down as chair due to domain concerns (temptation of ownership) (Wenger et al., 2002), and the NIBS staff liaison left for a position in a code organization. A new leadership group and board stewarded the council over the subsequent years (2015 – 2021). During this phase, although some core members of the council sought to sustain the CoP, the membership slowly eroded. This occurred because the purpose of the group diminished. OSC was increasing in uptake and 'know-how' was spreading across the industry. The sub-committees lost their function and importance and enthusiasm waned. Also, some of the initiatives that the council started were taken up by members of the CoP and their organizations through specific projects that fostered new CoPs involving the council members and others but were outside of the structure of NIBS (leaky knowledge) (Wenger et al., 2002).

In the final phase – transforming, the NIBS OSCC again found purpose. In 2021, the researcher, who continued to participate as a member of the council was engaged to lead a project to develop a OSC Research Roadmap for the US HUD (See PR04 in Chapter 05). This reengaged members of the OSCC to write a preliminary list of research needs in OSC for housing. Furthermore, the council has served as a peer review body (government, industry, and academia) for the consensus process of developing the report. This has spurred resurgent interest in the council and a new staff liaison has invigorated fervor as a facilitator. A new chair has been nominated, a developer, to take the OSCC in a new direction.

6.2.3 CS01 Measure

The outcomes of NIBS OSCC have included fostering a body of members that have established common terms through a glossary, codified publications, trust, communication, and a network of participants. The government, industry, and university members that have participated have gone on to improve their respective organizations. No metrics, economic analysis, or market value assessment have been conducted to evaluate the performance impacts of the NIBS OSCC; however, the qualitative impact on human capital and knowledge stocks is seen in the outputs and stakeholder career advancement in OSC. From the NIBS OSCC, the US Army and US Veteran Affairs initiated OSC programs for housing and hospital construction respectively. Further, the US HUD is orienting their strategic spending in alignment with NIBS OSCC recommendations for research planning. The measured outcomes of the NIBS OSCC deserve additional research and analysis to assess the actual impacts of the NIBS OSCC on individuals and their organizations.

Table 6.3 outlines the L01 – concepts, L02 – categories and L03 - core theories for CS01 – NIBS OSCC.

Table 6.3. CS 01 - NIBS OSCC concepts, categories, and core theories.

CS 01 – NIBS OSCC		
TYPE (L01)	**Dimensions (L02)**	**Structural Factors (L02)**
	L03: • Purpose A) Know-WHY – data on performance • Purpose B) Know-HOW – technical operations • SECI Conversions: Socialization and Eternalization	L03: • Triple-helix and CoP • Bi-lateral Reciprocal • NIBS host of CoP • KB, Leader, Facilitator (from host org.) • Research, Education, Outreach committees • Lifecycle: phase 1 – start-up, phase 2 - wane, phase 3 - revival
MODE (L01)	**Sub-processes (L02)**	**Tools and Activities (L02)**
	L03: • Creating - Capturing • Categorizing • Codifying • Communicating	L03: • Stories • Document sharing • Project reviews • CSs • Guests • Conferences • Workshops • Joint events • Documenting practice • Models of practice • Mutual benchmarking • External benchmarking
MEASURE (L01)	**Effectiveness (L02)**	**Performance (L02)**
	• Surveys • Implementation guide • Glossary • Advocacy	• New CoP development of special interests • Fostering of members into leadership roles in organizations • Market uptake of OSC

6.3 CS02 – Scotland Offsite Hub

6.3.1 CS02 Context

From 2013-2014, the researcher spent a sabbatical year on secondment in the Center for Offsite Construction and Innovative Structures at Edinburgh Napier University, which was Directed by Dr. Hairstans. The fellowship was underpinned by a grant from the European

Regional Development Fund for a project titled, *Low Carbon Building Technologies Gateway*, in which the author fostered growth, knowledge, and communication of companies and products that addressed decarbonization of the built environment. This immersive experience also provided opportunities to take the research that was being performed in COCIS and codify it into a series of continuing professional development modules. The author led the process of creating knowledge transfer standards for professional presentations and co-hosted events to communicate the findings of the engineering researchers in the center.

The fellowship year in Scotland was, unbeknownst to the researcher at the time, a socialization experiment wherein both technical and contextual knowledge concerning Scottish OSM was absorbed by the researcher through firsthand participatory experience. During this time in Scotland, the researcher aided in a proposal to respond to the UK Commission for Employment and Skills scheme to encourage an R&D approach to workforce development and operational OSC skills development that was ultimately funded. The research outcomes were reviewed in Chapter 03 on OSC knowledge needs. The project, *Offsite HUB (Scotland)*, aimed to answer the need for changes in construction culture including multi-skilling, interdisciplinary collaboration, and greater flexibility within several job roles in OSC (Goulding & Arif, 2013; UKCES, 2013) by creating a collaborative regional framework; a 'hub' of academic and industry partners to facilitate knowledge exchange.

The events recorded in this CS02 research sampling were from five interviews conducted during a knowledge exchange to the US with the seven core companies and Dr. Hairstans, the academic lead. The data was recorded during the interview and afterward as memos and then coded for emerging concepts. Furthermore, the minutes and outcomes recorded during the Hoshin Planning Session were shared with the researcher from Dr. Hairstans, and the assessment of the Hub work and outcomes was codified in a co-authored publication (Hairstans & Smith, 2017).

6.3.2 CS02 Type

The Scotland Offsite Hub is an inter-organizational CoP, developed through a short seven-month funded project by the UK Commission for Employment and Skills to respond to low productivity in their 2014 – 2017 strategy and the UK Futures Program to encourage an R&D approach to skills and development application. The Hub was one of five funded projects by UK Skills titled 'Offsite HUB (Scotland)' to create a 'hub' to define and showcase skills requirements and encourage collaboration between professionals around Scottish timber offsite enhanced panel systems. The knowledge types and needs that were addressed in the Hub CS include training materials for two panelized industry partners in the project, generic training materials in OSC, and international knowledge for scaling and impact. The industry partners in the Hub were two of the largest competitors in the Scottish panelized market – Stewart Milne Timber Systems (SMTS) and Campbell Construction Group (CCG) OSM (Figure 6.3), accounting for 40% of the market share. The project codified existing and disintegrated explicit knowledge on 'know-what' and uncovered tacit knowledge 'know-how' contained and embedded in the employees' knowledge stocks. SMTS was focused on training materials for the on-site assembly process and CCG OSM was focused on training content for the factory operators. The generic materials developed in the project were fostered in partnership with non-government and government organizations, led by the university entities. The content included 'know-what', 'why' and 'how' of OSC.

Figure 6.3. CCG OSM job site assembly of enhanced timber panels. Source: (Dr. Hairstans, Edinburgh Napier University).

The Hub, as the name suggests from the literature (Youtie & Shapira, 2008), was structured as a triple-helix model of innovation involving government, industry, and academia. As a Hub, the CS02 was university led with Edinburgh Napier University as primary with support from Heriot-Watt University and supported by industry and government (Etzkowitz & Leydesdorff, 1995). The Hub 'core' industry membership was made up of companies including SMTS, CCG OSM, ScotFrame, Oregon Timber Frame, Alexander Timber Design, Carbon Dynamic, and MAKAR. The project involved a steering group from Construction Scotland Innovation Center, Skills Development Scotland, Construction Industry Training Board, Scottish Enterprise, Scottish Development International, Link Housing Association, Equate, Colleges Scotland, Architectural Design Scotland, the Scottish Government, and Homes for Scotland. The Hub used a bi-lateral reciprocal structure for KM content development and transfer.

6.3.3 CS02 Mode

The knowledge sub-processes used in this CS included capturing, creating, clarifying, categorizing, codifying, communicating, and continuing to foster the two company specific training materials. The techniques employed in the development of the training content and the generic materials included text, animations, videography, and mock-up demonstration samples. The focus was on 'people' drivers and human capital development (Davenport, 1993; Goulding & Arif, 2013).

For the generic materials process, Scottish Development International and Scottish Enterprise, with Construction Scotland Innovation Center, funded a workshop convening government, university, and industry partners. In addition to the two original companies in the project, five companies joined, constituting an OSC core group. The core group and government and university partners participated in a 'hoshin planning' session, using the technique to identify the 'vital few' priority goals agreed upon by the CoP members to scale OSC domestically and internationally (Bechtell, 1996). An external facilitator, a KB and contingent worker, was retained as a third-party to encourage cross-organizational collaboration and sharing of knowledge. The core group signed a memorandum of understanding, a shared exchange agreement of collaboration and exchange of knowledge that is not commercially sensitive, with an aim to create new business innovation and foster knowledge transfer.

The knowledge needs analysis for the generic material creation was conducted over six months with the core group being surveyed through an online questionnaire and live interviews. The survey covered the knowledge topics of technical, skills/culture, branding/marketing, business models/strategies, and internationalization. The CoP project was published in the *Journal of Architecture Engineering and Design Management* (Hairstans & Smith, 2017) included in Appendix E and briefed in a report by 3rd party evaluator from SQW Consultants (Agur et al., 2015). To establish the theoretical basis for the Scotland Hub project, the researcher performed a literature review of inter-organizational KM that was published in a conference paper on KM epistemology and CoPs (Smith & Hairstans, 2017).

6.3.4 Measure

Following the success of the project, CCG OSM has implemented an advanced training process for their operational personnel and SMTS has launched a training academy at their facility, both emphasizing offsite enhanced panel systems. This has improved the performance for their respective companies. The generic materials resulted in several outputs. First, *Building Offsite: An Introduction* (Hairstans et al., 2015) came from this project as a general introduction published and disseminated by RIBA with links to the video content resulting from the Hub project. Additionally, the project has resulted in a follow-on effort to develop online content for a training program called “Offsite Ready”, administered by Construction Scotland Innovation Centre. This focused on human capital development using a competency framework and a host of readings, videos, and other media to address digital skills, procurement, health and safety, management and planning, factory operations, and site operations as core competencies in OSC. Both *Building Offsite* and ‘Offsite Ready’ were discussed in SR02 included in Chapter 03.

The Hub project was effective as an isolated KM effort and for the companies involved and, according to participants, provided the basis to partner with other Hub manufacturers to compete against the conventional construction. At the end of the Hub project, the participating core seven companies and a few others were invited to join Hairstans and Smith on a learning journey to the Northeast US to tour factories and participate in a symposium at Babson College with OSC stakeholders in Boston, Massachusetts through a professional exchange called 'Offsite International'. This fostered inter-organizational knowledge sharing between the companies from Scotland, and with US based OSC organizations. Furthermore, a Swedish company, Lindbäcks, and Northeast US OSC industry members joined to exchange knowledge concerning business and product platforms.

Table 6.4 outlines the L01 – concepts, L02 – categories and L03 core theories for CS02 – Scotland Offsite Hub.

Table 6.4. CS 02 – Scotland Offsite Hub, categories and core theories.

CS 02 – SCOTLAND OFFSITE HUB		
TYPE (L01)	**Dimensions (L02)**	**Structural Factors (L02)**
	L03 • Purpose – A) Training materials for specific panel companies • Purpose - B) Generic training materials • Purpose - C) Internationalization • Focus on Know-How, tacit knowledge • Conversion: Externalization and Internalization	L03 • Hub – university centered CoP • Triple helix • Bi-lateral Reciprocal • KB / Contingent Worker
MODE (L01)	**Sub-processes (L02)**	**Tools and Activities (L02)**
	L03 • A) Capturing, Clarifying, Categorizing, Codifying, Communicating • B) Creating, Categorizing, Codifying, Communicating, Contextualizing, Continuing	L03 • Workshops • Document sharing • Training • Mutual benchmarking • Documenting practice • Hoshin Planning • Memorandum of understanding

MEASURE (L01)	Effectiveness (L02)	Performance (L02)
	L03 • Shared knowledge base for CoP members • Contextually relevant to the region • MOU platform for non-sensitive knowledge exchange	L03 • A) Advanced training process and training academy for workforce • B) Performance improvement for core seven • *Building Offsite* publication • 'Offsite Ready' generic training program • Uncertain of generalizable impact to industry outside of Scotland

6.4 CS03 – Built Environment Exchange

6.4.1 CS03 Context

Following the Offsite HUB (Scotland) project in 2015, the researcher and Dr. Hairstans envisioned a platform for continued knowledge sharing and workforce training in OSC. To this end, the Built Environment Exchange (BeX) was developed. BeX aimed to accelerate change in construction culture by fostering talent through industry embedded experiential learning and research opportunities. Students were matched with participating companies for an international internship, master's scholarship, and/or employability project that was paid through funded research or industry sponsorship. Furthermore, BeX provided leadership and training support for students, and encouraged BeX students or 'scholars' to mentor younger school age children to aspire for OSC jobs in the future. Table 6.5 outlines the goals of the BeX program.

Table 6.5. Goals of the BeX.

GOAL	DESCRIPTION
OFF-SITE CONSTRUCTION BUSINESS DEVELOPMENT	To develop the future technical and business leaders who will modernize the built environment sector and spearhead the drive for sustainability and efficiency, enabling the sector to deliver the sustainable communities of tomorrow.
WORKFORCE DEVELOPMENT	To provide companies and industry lead organizations with opportunities to engage talented graduates on innovation and development projects.

STUDENT DEVELOPMENT	To provide opportunities for graduates and talent in the built environment to develop higher-level technical and business/entrepreneurship skills, and to gain international experience.
FACULTY DEVELOPMENT	To develop academic practitioners who will integrate with industry to direct future research and deliver long-term skills development.
INTERNATIONALIZATION OF OFF-SITE CONSTRUCTION	To internationalize research collaborations and increase global industry impact.

From 2016 to 2020, BeX ran successfully in the UK and internationally through student exchanges between universities in France, Canada, and the US in summer research experiences. The researcher provided and hosted students in the summer of 2016, 2017, and 2018 between Edinburgh Napier University (ENU) (UK), La Rochelle University (France), University of Alberta (Canada) and the researcher's institutions, University of Utah, and Washington State University in the US. These student exchanges were either embedded in an industry partner company or at the university proper working in a laboratory with research students, centers, and institutes in the host institution on OSC topics. In 2018, a culminating partnership was the ENU and Harvard Graduate School of Design academic exchange in which Harvard Graduate School of Design students travelled to Scotland to collaborate on OSM timber questions with Edinburgh Napier University students, industry, and government partners. Final projects were publicly exhibited and defended by students at Harvard in Cambridge, Massachusetts in the US with BeX faculty mentors present, including the researcher.

The Bex events recorded for this research included planning meetings with Saltire Foundation and ENU, as well as separate meetings amongst the university partners via videoconferencing. The events also included the embedment experiences of interacting daily with student researchers during summer months over the three years of exchanges. Finally, event data was coded from the post-event debrief with students and faculty mentors.

6.4.2 CS03 Type

In two of the years, students from Edinburgh were hosted by the researcher's university center and stayed on campus, working with other students in the US on OSC industry relevant research. One of the years, an ENU student was embedded in a company and lived close to the OSM factory supporting the day-to-day DfMA and project management process in the OSC firm. Furthermore, students from the University of Alberta, following an employability project with a local panelizer in Alberta, were placed in the researcher's center to support a company migrating from prefabricated trusses to wall panels and floor cassette manufacturing. Students from the researcher's center, in reciprocal sharing, were placed at ENU and the University of Alberta to work with student researchers and faculty in the respective locations on timber OSM projects with industry partners.

The type of knowledge fostered in this program was technical, organizational, and environmental (TOE). Students engage in technical 'know-how' research questions that were couched in a unique organization and framed by that organization's needs ('know-who' and 'know-what'). The participating organizations exist and operate in a unique environmental, business and culture context ('know-why' and 'know-when'). Although the emphasis is on explicit knowledge development and transfer as a research outcome, the embedment of students in a unique company culture or country condition for a duration of time provided both explicit and tacit learning (Smith & Hairstans, 2017). Faculty acted as mentors and facilitated the exchange/internship program. The host companies provided mentoring and technical training as well. Knowledge was shared unilaterally between the student and company. However, students participating in the program also shared knowledge with one another and the faculty in the universities they attended through a formal network, encouraging bilateral and reciprocal exchange.

6.4.3 CS03 Mode

BeX was a co-production knowledge platform. It leveraged what Gibbons et al. (1994) refer to as mode 2 knowledge production, generating knowledge in the very action of performing industry related tasks. As this was a university led initiative, it was also a Hub approach to knowledge creation and dissemination (Youtie & Shapira, 2008). BeX was unique as a CoP because it did not start with the question of knowledge needs; rather, it began on the premise of the desire to foster workforce talent and skills. The sub-processes, techniques and activities of the KM effort were the primary drivers to the formation and sustenance of the program. The knowledge needs, topics, and structure of the CoP was secondary to the overarching goal of changing construction via change agents of students. Therefore, unlike the other cases in this chapter, the mode dimension in this CS leads, while the type dimension follows.

The sub-processes employed in the BeX CS included creating, codifying, communicating, contextualizing, and commercializing knowledge. The BeX partners were actively seeking methods that will allow for continuing knowledge from year to year in an improvement cycle. However, company specific IP concerns and the challenge of itinerant nature of the BeX scholars made this challenging. The techniques and activities employed in the BeX project included social media, stories, visits, field trips, learning projects, problem solving, practice transfer, training, workshops, and literature review (Karner et al., 2011; Wenger et al., 2009).

BeX students operated as contingent workers, allowing the partnering companies to integrate and apply knowledge in a migratory fashion (Matusik & Hill, 1998), taking advantage of the network and university knowledge and research base to which the students belonged. Companies participating in BeX were careful to identify projects that were public knowledge specific and not at risk of IP leakage. However, by participating in the exchange, the organizations also understood that this is a CoP that had 'mutual engagement' and a 'shared repertoire' (Wenger, 1998). Students in the BeX were also KBs (Meyer, 2010) as they operated as both 'gatekeepers' for the companies in which they were placed and as 'representatives' for the companies as short-term employees/contingent workers (Gould & Fernandez, 1994).

BeX would not have succeeded without a leader and champion as well as a facilitator and co-facilitator of the program (Wenger et al., 2002). Dr. Hairstans at ENU engaged companies, underpinned by the support of ENU, Saltire Foundation and Entrepreneurial Scotland, whose mission aligned with BeX, to foster international growth of Scottish skills and entrepreneurship. Also, the partnering university faculty acted as co-facilitators in their respective locations through hosting and mentoring students in the international exchange, and host companies, likewise, mentored students in career development and relevancy of the research for company advantage.

6.4.4 CS03 Measure

Post-exchange questionnaires of companies and students that participated in BeX demonstrated positive impacts for individuals and the organizations to which they belonged. Students indicated that BeX improved their overall level of confidence, professional network, leadership capabilities, level of independence and desire to 'give back'. Human capital development, as the emphasis of BeX, allowed companies likewise to invest in their R&D while also 'giving back' socially through fostering next generation workforce skills development. The BeX program fostered both 'hard' and 'soft' OSC knowledge and skills in students (Nadim & Goulding, 2010).

A significant testament to the importance of the BeX program was the engagement with Harvard Graduate School of Design students through a collaborative learning with ENU students. Architecture students in Cambridge, Massachusetts spent a week in Scotland learning from and with ENU students, culminating in a workshop in June of 2018 to tackle a problem of 'vacant and derelict land' development using site sourced timber and OSM systems. This work was also displayed at the Industrialized Wood Building Conference in Boston, MA in 2019 by Dr. Hairstans and Harvard professor George Legendre. Also, BeX was recognized in the Herald Higher Education Awards in 2018.

The challenges and obstacles of sustaining BeX were related to the significant effort required of the leader and facilitator, as well as the co-facilitators in the program. Furthermore, the program required continued investment to secure company funding or public funding to support student exchanges and placements (travel, lodging, per diem, etc.). Also, year to year, students, universities, and company participants were mutable and inconsistent making each year's ramp up a heavy lift for partners. Student ability and knowledge were diverse, and company and university partners did not always receive what they hoped for or conversely, were pleasantly surprised and gained more value from the engagement than initially anticipated. The flow of knowledge was not consistent, and stocks of knowledge were not captured regularly or fully communicated post the student exchange (Robinson et al., 2005).

Measuring the metrics, economics, and market value of the BeX program was challenging (Robinson et al., 2005). Anecdotal evidence from partnering companies suggested that there was value qualitatively, but this has not been quantitatively assessed to date. The intellectual capital could have been more carefully managed and evaluated to demonstrate and improve BeX in the future. This would have also provided data to demonstrate the program's value that will be necessary to sustain the program financially with investors and donors moving forward.

Table 6.6 outlines the L01 – concepts, L02 – categories and L03 - core theories for CS03 – BeX.

Table 6.6. CS 03 - BeX, categories, and core theories.

CS 03 – BUILT ENVIRONMENT EXCHANGE		
TYPE (L01)	**Dimensions (L02)**	**Structural Factors (L02)**
	L03 • Purpose 1 – workforce skills development • Purpose 2 – knowledge for companies • Knowledge – how, who, what, why and when • Conversions: full SECI spectrum with emphasis on externalization and internalization	L03 • Hub and Triple Helix CoP • Mutual engagement, shared repertoire • Mode 2 co-production of knowledge • Unilateral exchange between student and company • Bi-lateral exchange between students in the BeX program • Leader and facilitator, Dr. Hairstans at ENU • Co-facilitated by partnering university faculty • Students as contingent worker / KB • Company mentors
MODE (L01)	**Sub-processes (L02)**	**Tools and Activities (L02)**
	L03 • Mode led process, followed by Type contingency dimension • Creating, codifying, communicating, contextualizing, and commercializing	L03 • Social media • Stories • Visits

	• Future = 'continuing' on a platform	• Field trips • Learning projects • Problem solving • Practice transfer • Training • Workshops • Literature review
MEASURE (L01)	**Effectiveness (L02)**	**Performance (L02)**
	L03 • Sustaining BeX requires significant effort and resources • University and company partners are mutable and inconsistent • Student ability and knowledge are diverse • Flow year to year is challenged • Stocks not captured and communicated post-exchange	L03 • Students: hard and soft skills, confidence, professionalism, independence, and volunteerism ethic • Companies: give back mentality, talent acquisition and pipeline, fostering change culture in construction to OSC • Metrics, Economics and Market Value uncertain

6.5 CS04 – MBI 5 In 5

6.5.1 CS04 Context

This CS was presented as a PR source (PR03 – MBI 5 in 5 Study) in the comparative analysis of knowledge needs in Chapter 05. Beginning in 2017, the project was a two-year project investigated by the researcher and co-investigator Dr. Rupnik of Northeastern University. CS04 was supported by the volumetric modular manufacturer trade association, MBI, to foster a growth plan to increase the volumetric modular industry market share from 2.37% to 5.0% of the total expenditure of US construction in five years. The study consisted of four phases outlined in Chapter 05 in detail - SWOT analysis, survey, CS of international contexts, and the development of a growth plan for modular in the US.

The project was envisioned as way to foster a CoP, a committee assigned to the researchers to aid in facilitating the engagement of MBI members and the board in providing information, peer review, feedback, and connection to networks for data gathering. The project was championed and led by the leadership of the MBI who recognized a need to transition their membership orientation and value toward permanent modular construction for housing to respond to changing market forces (Wenger et al., 2002). The research project extended the reach of the CoP beyond the researchers, as contingent workers, and facilitating committee, to a network of international partners that the researchers continue to engage today. The researchers, as contingent workers, fulfilled the role of 3rd party itinerant KBs, and representative brokers to bring knowledge to the group from outside the organization (Meyer, 2010).

A total of 10 Events generated the qualitative data for this CS included in the following engagements over the two-year CoP project:

- Four one-hour MBI board meeting presentations.
- Five board represented project review committee meetings.
- A three-hour manufacturer SWOT workshop. (Figure 6.4)
- Numerous email exchanges within the review committee.
- Five unique meetings with parties in Japan and seven in Sweden. (Figure 6.5)
- Discrete virtual interviews with seven individuals internationally from Poland, Australia, and the UK.

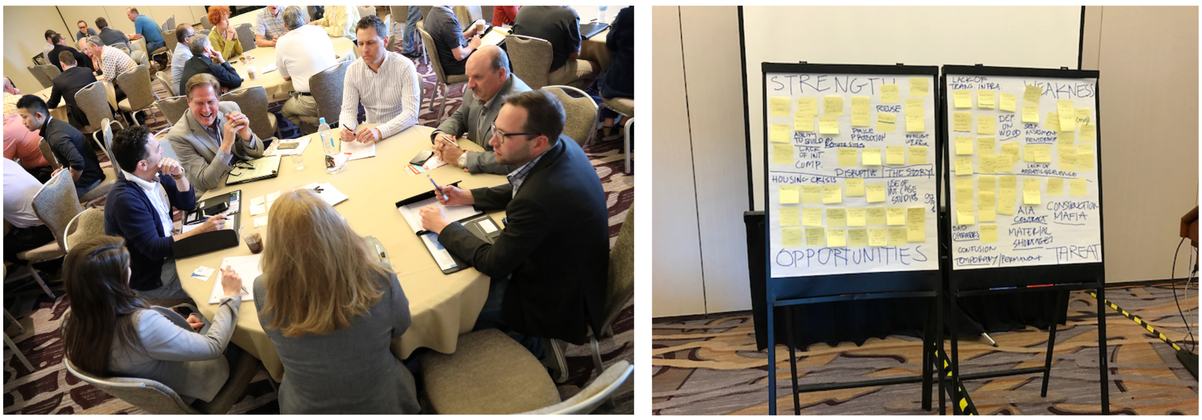

Figure 6.4. MBI 5 in 5 SWOT analysis with modular members. Source: (Smith & Rupnik, 2018).

[redacted]

Figure 6.5. MBI 5 in 5 international factory tours and interviews in Japan and Sweden. Meeting with Professor Matsumura at the University of Tokyo (left) and meeting tour with Helena Lidelöw at Lindbäcks (right). Source: (Smith & Rupnik, 2018).

6.5.2 CS04 Type

CS04 used a unilateral approach. Although the CoP committee, the MBI members, provided feedback and guidance, the knowledge sharing was from the researchers to the CoP primarily, in one direction. The type of knowledge shared in this project was 'know-what', explicit in principle. However, the researchers were required to gather and interpret qualitative and quantitative data using tacit means. The SWOT analysis was a socialization activity to build consensus around the unique challenges facing modular manufacturers in North America. Also, during the visits to international locations, the researchers performed interviews, inferred findings through observation, and then interpreted these findings to the conditions discovered in the SWOT and industry survey. This was mediated by an iterative process of back-and-forth dialogue with the 5 in 5 facilitation committee.

6.5.3 CS04 Mode

During the research project, several sub-processes were employed to gather, interpret, and disseminate knowledge including the following: creating and capturing knowledge, clarifying, categorizing, codifying, communicating, contextualizing, and continuing. Although the MBI members and the committee exercised 'mutual engagement', there was not a 'shared repertoire' or 'joint enterprise' function to the CoP (Wenger, 1998). It was purpose built for the research engagement and then was dissolved thereafter. The results of the research were codified in a report to the MBI members that constituted a strategic plan for growth including four strategies – data, partners, standards, and 3Cs (competence, capacity, and capability). The techniques and activities of the CoP included stories, CSs, field trips, conferences, workshops, literature review, external benchmarking, internal benchmarking, boundary collaboration, and documenting practice.

6.5.4 CS04 Measure

The 5 in 5 Report, delivered in 2018, served as the strategic plan for the MBI for the next five years. Under each strategic topic a series of tactical recommendations was suggested. MBI took the report recommendations and created several committees to work on the strategic efforts – data, partners, standards and 3Cs. For example, to respond to the recommendation of the need for industry data, a committee was formed to focus on developing the Awards of Distinction program managed each year for their members as a platform to gather industry wide performance data. MBI has extended their reach to partner organizations and addressed OSC more broadly in their participation in the NIBS OSCC and the development of Offsite Expo events in cities throughout the US and Canada.

MBI, to address the mounting challenge of OSC enclosed subassembly regulatory navigation in the US, partnered with International Code Council (ICC), the US code body, to create a regulatory standard that can be adopted by AHJs in the US. The standards development process was orchestrated through a unique CoP of industry stakeholders to build consensus. ICC and MBI leadership were interviewed for this research with the results discussed in the next chapter with respect to the TM3 framework. This standard (ICC/MBI 1205-2021 Standard for Off-site Construction: Inspection and Regulatory Compliance) outlined the inspection and approval process for enclosed construction. This standard has already demonstrated success in Salt Lake City and City of Seattle to smoothing code official obstacles and roadblocks to using OSC delivery and OSM subassemblies for housing. The partnership between ICC and MBI has also fostered two additional standards to address challenges in project delivery and MEP integration in OSC (ICC/MBI 1200 and 1210). The MBI has also partnered with the Associated General Contractors (2020) to develop a contract structure in the US, *Standard Prefabricated Construction Agreement Between Constructor and Prefabricator*, as a means of improving procurement and project delivery in OSC.

The MBI members have already experienced a performance benefit from the research project. Market adoption has increased since these efforts were initiated, with volumetric modular achieving 5%+ (up from 2.5% in 2015) of the market expenditure in 2021 (MBI, 2021). Furthermore, the MBI 5 in 5 report outcomes have been quoted and included in several publications reaching a developer and investor audience that has been instrumental in the growth of the OSC sector in the US (Bertram et al., 2019; McGraw-Hill, 2020; Wilson, 2019; Fannie Mae, 2020, 2021; and ICC, 2021). As a result, there have been several new start-up modular companies, investment flowing into the sector, and OSC housing project are seeing a significant growth (MBI, 2022). Likewise, the MBI membership has become more diverse, including supply chain stakeholders outside of their manufacturer member base, to create ongoing CoP exchange through the annual conference and ICC partner efforts.

Table 6.7 outlines the L01 – concepts, L02 – categories and L03 - core theories for CS04 – MBI 5 in 5.

Table 6.7. CS 04 – MBI 5 in 5, categories, and core Theories.

CS 04 – MBI 5 IN 5		
TYPE (L01)	**Dimensions (L02)**	**Structural Factors (L02)**
	• Purpose – 'Know-what' (explicit) to identify strategic plan for growth • Conversions: Combination and Externalization	• KB – researchers • Leader – MBI directors • Facilitator – CoP committee • External and internal stakeholders • Unilateral – researchers to MBI • SWOT participation of members • Mutual Engagement only
MODE (L01)	**Sub-processes (L02)**	**Tools and Activities (L02)**
	• Creating and capturing • Clarifying • Categorizing • Codifying • Communicating • Contextualizing	• Stories • Case studies • Field trips • Conferences • Workshops • Literature Review

		• External benchmarking (Survey and international visits) • Internal benchmarking (SWOT) • Boundary collaboration (partners) • Documenting practice
MEASURE (L01)	**Effectiveness (L02)**	**Performance (L02)**
	• Fostered committees to address strategic topics • Recognition of 3C challenges in the membership • Strategic plan revision in 2023	• 5% growth in 5 years achieved • Data through awards program • Partnership with NIBS OSCC and HUD • Standards – ICC and NRC, AGC Consensus Docs • HUD Research Report • MOD X KM company • Follow-on study in OSC environmental factors

6.6 Chapter 06 Summary

This chapter presented four CSs (CS01 – CS04) that were analyzed using a GT methodology. The research progressed through structured steps of gathering data from Events through memoing and coding to form a theoretical Sampling. The data was collected and analyzed simultaneously as the researcher participated in the CS CoPs and through open coding. This fostered concepts that were constantly compared with one another for their relationship and frequency within a discrete CS. Categories were then created through evaluating the interrelationships between the four CSes using axial coding. The KM categories were then contextualized in the extant literature (SR01 and SR02 and PR01 – PR04) to provide a vocabulary to the researcher and to test the credibility of the emerged qualitative research. The concepts, categories, and contextualization in literature continued until the data in the CSs and SR sources researched a point of theoretical saturation. The categories were likewise combined through frequency analysis to form the core theories of the TM3 – type, mode, measure, and the emergence of the theoretical framework.

The next chapter discusses the results of the theory building research - the development of the TM3 framework. The framework components and testing with CS participants and peer researchers is discussed.

CH 07 – Theoretical Framework

The results of this research are presented in this chapter. The specifics of the TM3 framework are reviewed in sequence of type, mode, and measure. The three-level structure is explained and the theoretical application in CoPs is detailed. A review of the framework amongst CS participants and peer researchers is then discussed with refinements to the framework outlined.

7.1 Framework Structure

The emerged theory for the TM3 was grounded in the CS analysis that resulted in a three-level structure of concepts (L03), categories (L02), and core theories (L01). The core theories provided the substantive justification of this research and constituted the type, mode, and measure model – TM3 framework. Despite the name, TM3 is a theoretical framework, as opposed to a model, in that the researcher aim was to describe factors that were believed to influence the outcome of KM in OSC (Nilsen, 2015). The research resulted in a theoretical framework, a hypothesis intended for inter-organizational KM application that described KM categories and how they relate to one another to augmenting KM applications in CoPs.

Figure 7.1 is the TM3 framework, designed from grounded CSes and contextualized in the extant literature (Objective 02) and primary data mined projects (Objective 03) reviewed in Chapters 02, 03, and 05. The TM3 framework is presented in the following sections, organized by core theory. The core theories are the contingency dimensions of the framework including type, mode, and measure. The core theories are the highest in order of in the levels of detail, signified by level 01. Sub-levels 02 categorize the operational concepts of level 03. This structure provides organization and depth for CoP participants to navigate and apply to inter-organizational KM environments.

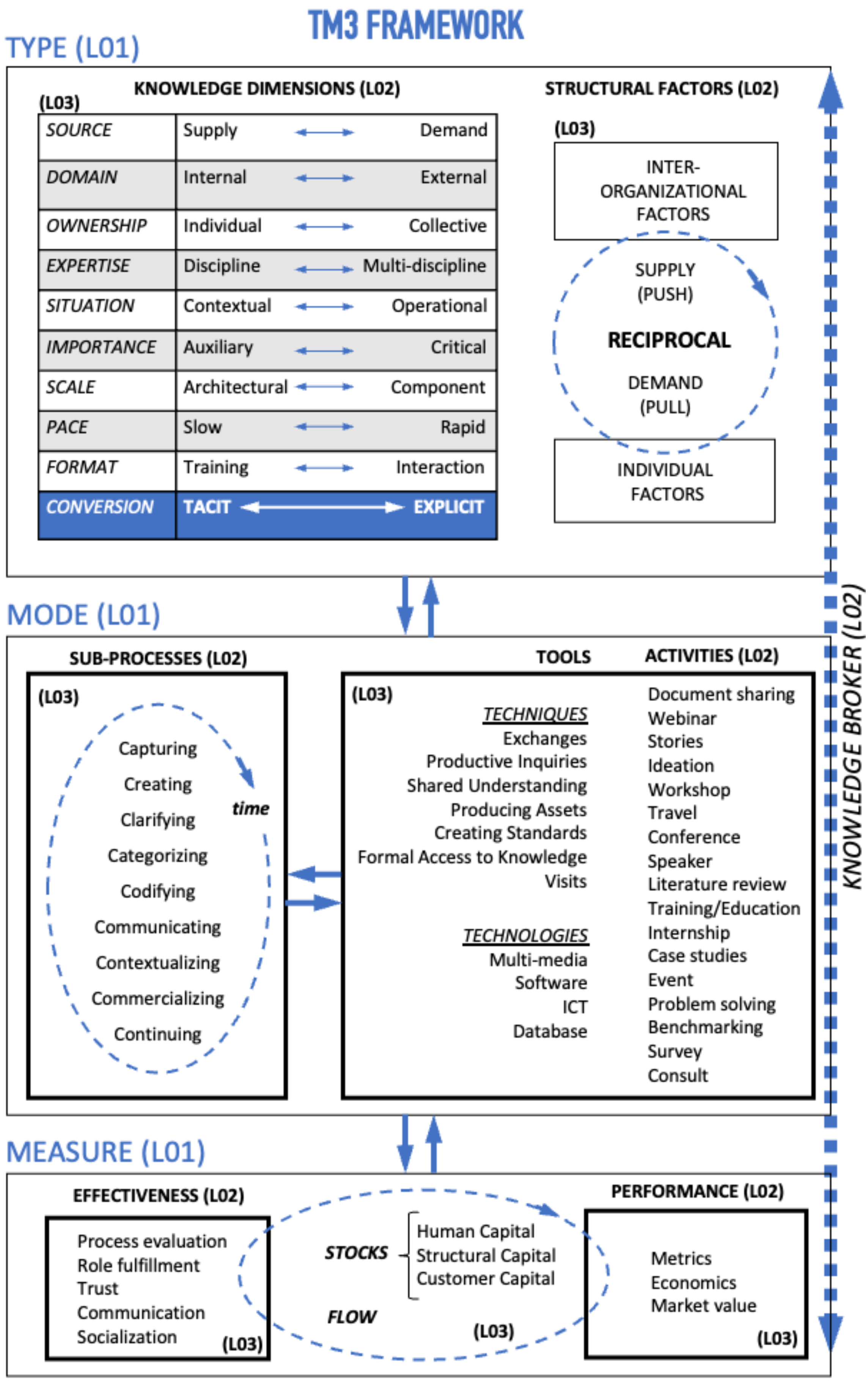

Figure 7.1. TM3 inter-organizational KM framework for OSC in housing. Source: (Author)

7.2 Type Dimension

The TM3 framework may be applied to any stage in the CoP lifecycle, thus establishing a new inter-organizational CoP during the “potential” and “coalescing” stages, or maintaining an existing CoPs during “maturing,” “stewarding,” or “transforming” stage during a management cycle (transfer) iteration (Saint-Onge & Wallace, 2012). It can be used to assess how knowledge may be managed and handled in a CoP or in the very act of sharing and exchanging knowledge within a CoP. The type dimension of the framework aids participants in the CoP to establish the purpose, need, and format in which the CoP will operate.

7.2.1 Knowledge Dimensions

There are two categories (level 02) of knowledge type to consider in the TM3 framework. First is the “knowledge dimensions” spectrum to evaluate the characteristics of the knowledge that needs to be managed. This includes ten (10) dimensions developed from the CS analysis and considered with reference to the literature. The dimensions include the following (see Table 7.1):

1) Source (supply – demand);
2) Domains (internal – external);
3) Ownership (individual – collective);
4) Situation (contextual – operational);
5) Innovation (architectural – component);
6) Expertise (discipline – multi-discipline);
7) Importance (auxiliary – critical);
8) Pace (slow – rapid);
9) Format (training – interaction); and
10) Conversion (tacit – explicit).

The TM3 knowledge dimensions are meant to be representative based on the need experienced the researcher in OSC CoPs. However, not every KM transfer iteration or CoP will use all ten dimensions and there may be additional dimensions that need to be considered depending on the situation and context. The goal of characterizing knowledge was to determine if the knowledge is principally tacit or explicit. This is not a polar definition, rather, a spectrum of evaluation. However, understanding if knowledge is more tacit (embedded, know-how and know-who) or explicit (codified, know-what and know-why) guides CoP agents to select the appropriate conversions that may need to occur to move from tacit knowledge to explicit or tacit to tacit forms of exchange. As this thesis has discussed, construction, OSC included, generally is a tacit knowledge practice. Therefore, it necessarily relies on CoPs and socialized models of KM to transfer between tacit and explicit knowledge types.

Chapter 03 OSC Knowledge provided an assessment of SR sources together with Chapter 05 Data Mining that delimited OSC specific knowledge categories, needs, and priorities. The findings indicated that there are ways in which OSC knowledge has been organized in the literature based on several qualifiers:

1) WHY (explicit) versus HOW (tacit) with much emphasis on tacit domain knowledge;
2) OSC knowledge can be categorized by two fundamental distinctions: contextual knowledge (know-why) versus operational knowledge (know-how);
3) Knowledge needs differ by OSC national and regional location due to differing barriers and challenges to be overcome and which are tied to the uniqueness of the locale;
4) Disciplinary specific knowledge (architect, engineer, developer, general contractor, manufacturer); and
4) Unique OSC project delivery phase knowledge.

This assessment from chapters 03 and 05 found that the needs for OSC knowledge in the U.S. are environmental or contextual. As part of the TM3 framework, the research has developed a “knowledge dimensions matrix” (KDM). This KDM (Table 7.1) is envisioned as a support tool for comparing OSC knowledge needs with the “knowledge dimensions” in the TM3 as a means of characterizing knowledge and determining the tacit or explicit nature and conversions that may need to take place in each KM scenario. The matrix charts the knowledge dimensions developed from the CS analysis and frameworks and models referenced in the literature (Anumba, Kamara, & Carrillo, 2005; Matusik & Hill, 1998; Nonaka et al., 1995) against the OSC knowledge priorities identified in SR02 and PR01-PR04 outlined in chapters 03 and 05.

To demonstrate the utility of the KDM, an example is provided from the leading US OSC knowledge priority identified in Chapter 05 Summary. Considering "regulatory factors" the CoP can ask the following questions using the knowledge dimensions:

- Source – Is regulatory knowledge being supplied or demanded by the CoP?;
- Domain – Does the specific regulatory knowledge exist within or outside of the CoP?;
- Ownership – Is the regulatory knowledge individually held or collectively shared and are there IP concerns around the knowledge?;
- Expertise – Is the regulatory knowledge disciplinary-specific or multi-disciplinary and which disciplines does it involve?;
- Situation – Is the regulatory knowledge contextual (linked to specific project types, locations, etc.) or operational? What aspects of the knowledge are context dependent and what are independent of the situation?;
- Importance – How significant and urgent is the regulatory knowledge to address problems and barriers?;
- Scale – Is the regulatory knowledge architectural (global) or component (discrete and detailed)?;
- Pace – How slow or fast does the regulatory knowledge change, adapt, and get updated? How quickly can the knowledge travel or be absorbed?;
- Format – Which method can the regulatory knowledge be managed through--formal training or more adhoc interaction?; and
- Conversion – Given all factors, is the regulatory knowledge in question tacit or explicit? And what needs to be done to convert the knowledge to a more digestible format?

Table 7.1. Knowledge dimensions matrix (KDM) compares the parameters characterizing knowledge to the knowledge needs.

Technology Organization Environment (Tornatzky & Fleischer,	OSC KNOWLEDGE NEEDS	Knowledge Dimension																							
		Source		Domain		Ownership		Expertise		Situation		Importance		Scale		Pace		Format		Conversion	
		Supply	Demand	Internal	External	Individual	Collective	Discipline	Multi-discipline	Contextual	Operational	Auxilary	Critical	Architectural	Component	Slow	Rapid	Training	Interaction	Tacit	Explicit
E	Regulatory factors																								
E	Transportation																								
O	Knowledge & skills																								
E	Project Delivery																								
E	Standards																								
O	Factory management																								
O	Case studies (need)																								
E	Project and Industry Data																								
E	Culture																								
E	Organized Labor																								
O	Site management																								
O	Process improvement																								
O	Construction Performance																								
O	Supply chain																								
O	Procurement																								
O	Programmatic requirements																								
T	Technology development																								
T/O	Design (DfMA)																								
E	Finance & Insurance																								
O	Expierence																								
O	Early engagement																								
O	Planning																								
E	Sustainability																								
E	Factory capital																								
E	Aesthetic limitations																								
E	Geographic differences																								
E	Context																								
O	Business models																								
O	Stakeholders																								
O	Logistics																								
O	Operational performance																								
O	Product platform																								
O	Economies of scale																								
O	Partnerships																								
O	Customer Centric																								
O	Scope gaps																								
OE	Multi-family housing																								
OE	Single-family housing																								
T/O	ICT/BIM																								

7.2.2 Structural Factors

The type of knowledge characterized by the dimensional qualifiers that lead to tacit and explicit determinizations are influenced by other aspects of the TM3 framework, including the structure of the CoP. In addition to the knowledge dimensions, the second level 02 category of the type dimension was "structural factors". The structural factors in the type dimension consider the kind of the actors in the CoP. These include the individuals and companies or organizations to which they belong, as well as their personal and organizational interests, expertise, and motivations for participating in the CoP. Further, the structural factors consider the inter-organizational goals of the CoP, the entity manages the CoP, and to which disciplinary stakeholder group in the supply and service chain or to which sector the managing entity belongs (industry, government, university). This foundation is important in determining the roles and responsibilities actors will play in the CoP such as leader, facilitator, sparker, and synthesizer (Saint-Onge & Wallace, 2012; Wenger et al., 2002) and the need for and the functional role of a KB (Meyer, 2010).

Moreover, the structural factors in the Type Dimension also aid in establishing the relationship between the actors in the CoP and the flow of knowledge. This may include unilateral sharing, or bi-lateral "reciprocal" sharing (Loebbecke, van Fenema, & Powell, 2016). In the latter, a common element of the CSes was the co-production of knowledge through sharing and volunteerism for the purpose of improving the knowledge base of participating individuals and organizations to which they belong, as well as improvement of the construction industry in which they are seeking to innovate via OSC (Gibbons et al., 1994). Related to the flow of knowledge between actors in the CoP is consideration of whether the knowledge for the CoP is coming from within the CoP or outside the CoP, and if the knowledge is demand-based (pulled) in the transfer or supply-driven (pushed) through the CoP.

Using the regulatory barrier and knowledge needs example previously referenced in the knowledge dimensions, the CoP can consider if addressing regulatory knowledge gaps should occur within the current CoP or if a new CoP needs to be developed to address the specific gap. In the case of regulatory knowledge needs, this is an issue that affects all disciplines in the OSC supply chain and, therefore, relies on a bi-lateral and reciprocal relationship and knowledge share/flow between the CoP members and their organizations. A new CoP was established to address this knowledge need through the development of the ICC standards (ICC/MBI, 2021).

Characterizing the type of knowledge through the KDM, potential conversions, and then the structure of the actors, their relations and the resulting flow of the knowledge determines the basis to move to the next stage in the TM3 - mode.

7.3 Mode Dimension

7.3.1 Sub-Processes

Mode is another L01 contingent dimension in the TM3 framework. It refers to the method and approach of knowledge transfer. This includes the "sub-processes" (L02) in the KM cycle. As with the knowledge dimensions spectrum considerations, the sub-processes used are determined by the character of the knowledge being managed. For the TM3 framework, the researcher referenced literature on KM cycle and investigated processes through CS analysis to provide a list of potential cycle activities, including creating, clarifying, categorizing, codifying, communicating, contextualizing, commercializing, and continuing KM. Descriptions of each sub-process are included in SR01 literature review. Examples of how this is used in the construction CoP context is included in the SeLEKT project (Al-Ghassani et al., 2002) also reviewed in SR01. The KM sub-process from this list that is selected and used depends on the type-- knowledge dimension, the characterization as tacit or explicit-- and the structural factors that determine the format for the knowledge cycle activity or process.

Returning to the example of regulatory knowledge in the mode dimension, ICC/MBI standards development process fostered a unique CoP of constituent stakeholders discussed in CS04. According to an interview with Ryan Colker of ICC and Tom Hardiman of MBI (Colker & Hardiman, 2021), the sub-processes used for the standards development include *creating* new knowledge bi-laterally through consensus building and *capturing* knowledge in the process from the project experiences of the stakeholders. Also, the CoP categorized the regulatory knowledge into AECO professional knowledge and AHJ knowledge respectively. The knowledge was assembled through a socialization process and then codified into a standard by the ICC. This is currently being *communicated* to AHJs and AECO professionals through word of mouth, formal trainings and will be referenced in a new version of the IBC and IRC code. The standard, as codified explicit knowledge, will be continued and improved in three-year cycles.

7.3.2 Tools

Another aspect of the mode dimension in the TM3 is applying the sub-processes to select the tools (L02) (techniques and technologies) to facilitate the transfer of knowledge in the CoP. Although there are a variety of tools that can be employed, the TM3 suggests a list of technique and technology categories for consideration. There was not evidence in the literature or in the small sample of CSes analyzed concerning which tools are appropriate depending on the type dimensions and sub-processes. Therefore, the tools need to be considered and determined by the CoP members. A key aspect of socialized KM using CoPs is the learning community aspect to support tacit knowledge exchange, co-production of knowledge, and reciprocal transfers. Although technologies are important to any KM enterprise in the advancing network economy (Mikhailov & Kopylova, 2019), techniques lead in tool decision making and selection as they address intention by which technology application may be leveraged.

CS01 – CS04 identified several techniques (L03) used for KM that were confirmed by literature (Karner et al., 2011; Wenger, 2009) and included in the TM3 framework. The techniques of the TM3 include 1) exchanges, 2) productive Inquires, 3) building a shared understanding (shared learning), 4) producing assets, 5) creating standards, 6) formal access to knowledge, and 7) visits. These technique categories support the sub-processes being used on a particular KM iteration.

7.3.3 Activities

Once a technique is selected, associated shared learning activities (L03) can be determined to serve that technique. A list of shared learning activities is provided in the TM3 framework, although these are simply representative of the experiences of the researcher and those found in literature. These activities are techniques that responded to the need for the CS CoPs to foster inter-organizational KM to be learning communities that have feedback loops between the professional experiences of the individuals (actors) in the CoP and the CoP activities discrete to its operation. The experiential or social learning framework in CoPs using these techniques allow for the co-production and refinement of knowledge, learning with and from others, that stems from the context in which the CoP is situated (i.e., place and time) and the unique attributes of the CoP members themselves (Argyris, 1982).

In the regulatory example of ICC/MBI standards development (Colker & Hardiman, 2021), the CoP used the techniques and activities of the TM3 framework including 1) exchange – word of mouth and document sharing; 4) producing assets – documenting practice (project-based sharing); 5) creating standards – problem solving, mutual-benchmarking and external benchmarking; 6) formal access to knowledge – literature review, workshops, and practice transfer; and 7) visits – guests with CoP external individuals and organizations being invited into the discussion for industry buy in, inclusivity, and consensus building. The other technique areas of 2) productive inquires and 3) building a shared understanding were less important for this case but may be more applicable in a different iteration. These techniques and activities are mapped onto the shared learning activity in Figure 7.2.

In the mode dimension, the CoP actors may use experiences from their own projects to bring into the group and members of the group potentially will have shared knowledge in working on these projects together, so knowledge is shared between the CoP actors and the rest of the CoP members (Leseure and Brookes, 2000). Therefore, the mode dimension in the TM3 framework emphasizes continual learning with consistent flow over time. Figure 7.3 illustrates experiential learning through projects among the members of the CoP that can then be shared within the CoP as experienced by the researcher in CS01. In the NIBS OSCC, project-based learning was shared in the CoP. Different stakeholders in the CoP engaged in different projects outside of the CoP and overlaps between members of the CoP was shared with the larger group. In this way, knowledge was fostered and socialized. Figure 7.3 is a diagram developed after workshop Event in which A1 (Architect One) participated in Project 'A' and 'B' with M1 (Manufacturer One) and C1 (Contractor One) and C2 (Contractor Two). A2 (Architect Two) participated in Project C with M1 - Manufacturer One and C1 –

Contractor. Therefore, the knowledge brought to bear in the CoP was contextualized from the respective project-based learning using cross-project and shared learning tactics.

[redacted]

Figure 7.2: Techniques and activities used in the regulatory knowledge need CoP iteration for the ICC/MBI standard development (Colker & Hardiman, 2021). Adapted from: (Karner et al., 2011; Wenger et al, 2009).

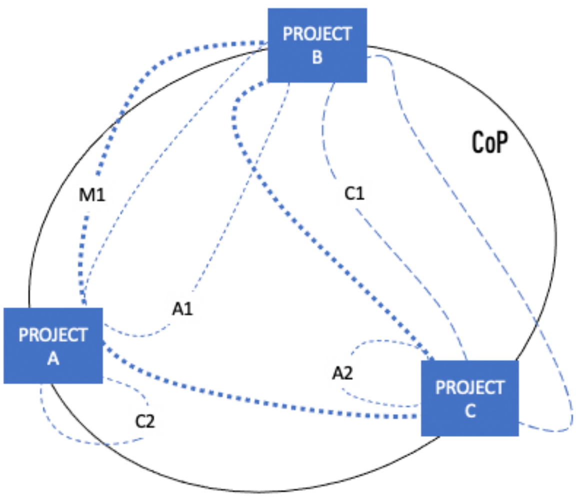

Figure 7.3. Shared and cross-project learning diagram that resulted from an event in CS01.

7.4 Measure Dimension

The last contingent dimension of the TM3 framework is measure – evaluating the outcome of the inter-organizational KM effort. The effort can be evaluated once the knowledge need is characterized in the type dimension, structured in a CoP, applied a mode dimension of sub-processes and then techniques and activities to foster KM. The outcomes of KM in the TM3 are related to the CoP operation and to the CoP members. The first outcome of the TM3 framework is to analyze the effectiveness of the CoP proper including, but not limited to, flows of knowledge and morale. These are listed in the TM3 framework as:

1) Process Evaluation – How well did CoP perform? Was the timeline met for the KM goals set forth by the individuals in the CoP during the type dimension step? Was the quality of knowledge needed created, clarified, and communicated (or other sub-processes used)? Were the knowledge needs clearly articulated and characterized in the type dimension? Were the sub-processes, techniques, and activities effective?;
2) Role Fulfillment – How effective were the CoP members at their various roles? What gaps were present in the operation of the CoP during the different stages of the TM3 (type, mode, and measure)? Was the project manager, facilitator, or KB effective? Did the structure function well?;
3) Trust – Are relationships stronger at the end of the KM iteration than at the beginning? What can be done to rectify trust and morale challenges?;
4) Communication – Was communication flowing and were stakeholders participating and contributing at the levels they want to? How can communication be improved?; and
5) Socialization – Did community learning occur and were all stakeholders satisfied with the outcome? What is left wanting and how can this be addressed in the next iteration of the TM3 framework with this CoP?

The other outcome to be measured is performance of the CoP on the individuals and the organizations to which they belong. Performance evaluation in the TM3 framework is broken down into “metrics,” “economics,” and “market value” (Robinson et al., 2005). Based on CS Analysis experiences, these three aspects of performance can be evaluated at the organizational level (actors in the CoP) and the industry level (OSC industry as a whole). For the individual organizations in the CoP, the metrics may include how the knowledge affects their day-to-day operations and ability to problem solve and overcome company-specific challenges. For economic performance, the financial impact of the knowledge is assessed and may include other types of capital in addition to monetary capital, including human and intellectual affects. Market value is the last performance dimension in the TM3 framework. The individual participating organizations may assess their value to the market because of integrating the knowledge from the CoP. Further, there may be an assessment of the performance outcomes (metrics, economics, and market value) for the industry at large to determine how the knowledge produced or shared in the KM effort ultimately leads to the goal of OSC uptake and innovation to realize greater access and affordability of housing. These performance measures can be documented longitudinally through time. In the case of the Regulatory example, the development of a standards out of a CoP process had an impact on the organizations that aided in the development as well as the industry as a whole – both can be measured for performance through metrics, economics, and market value analysis.

In the evaluation of the two aspects of the measure dimension– effectiveness and performance– Robinson et al. (2005) indicate that stocks (what knowledge is being managed) and flows (improvement of the value of the knowledge) need to be assessed. In the TM3 framework, the stocks are the assets of the knowledge and consist of human, structural, and customer capital that surround knowledge production and employment. The flows are then the measurement of how the knowledge is used and the impact of such. The CSes demonstrated that stocks and flows can be for both the CoP enterprise proper and the individual organizations that participate in the CoP. Finally, the measure dimension of the TM3 is the least developed contingent dimension in the TM3. There is a lack of evidence in the literature about measuring inter-organizational KM and the lack of measurement data available through the CSes documented in this thesis. Although the measure of impact of effectiveness on the CoP was documented in the CS analysis as shared outcomes of the industry, the performance impact on companies’ bottom lines is not subject collective knowledge. The measure dimension performance evaluation tactics warrants further development through research.

7.5 Knowledge Broker

The KB role in the TM3 framework can occur at any one of the contingent dimensions or steps: type, mode, or measure. During the type stage, the KB can coordinate the assessment of knowledge needs against the knowledge dimension matrix with CoP actors, leveraging the unique expertise and knowledge of the stakeholders. Furthermore, the KB can play a key part in structuring the CoP to benefit the individuals and organizations that they represent with the overall inter-organizational goals of the CoP. If there are gaps in the expertise of the CoP, the KB may build capacity by inviting others to participate with the CoP consent. Although important during the type activities, KBs are often needed most during the mode dimension.

It is during the sub-processes and techniques and activities that the KB must act as a mediator, suggesting, selecting, and building consensus around the specific methods and approaches that will be used to address the knowledge question. CS analysis revealed that a KB may take on a more substantial role as the primary researcher and author if there is a codified report or presentation to develop as an outcome of the KM iteration. Lastly, during the measure stage of the TM3 framework for KM, the KB may lead in the assessment of the outcomes of the KM effort and suggest how the CoP can improve.

The KB may be part of the CoP or a contingent worker (e.g., consultant) hired as a third party to manage the CoP indefinitely or, more likely, for the knowledge question being addressed. If the OSC knowledge need is related to finance, for example, the KB may be from the project banking and lending industry or a consultant on financing projects that uses innovative methods of construction. In the regulatory example discussed previously, the KB may be from the code official or AHJ discipline, as was the case with the ICC CoP that was brokered by an ICC attorney, Ryan Colker. For this knowledge need of Regulatory barriers, the KB acted as a both a “coordinator,” belonging to the CoP that was developing the standard, and as a “liaison” during the public comment period to answer questions from external parties and assimilate into the codification process of the standard (Figure 7.4). The KB may be the facilitator and/or leader in the CoP or be a different individual altogether. The benefits of each of these structures depends on the type of question and structure of the CoP. Finally, KBs are not necessary and can be managed by committee in some CoP arrangements depending on the nature of the knowledge needed. However, as the complexity of the knowledge need increases and the number of stakeholders grow, so does the need for an effective KB.

[redacted]

Figure 7.4. KB role in the ICC regulatory standards project included working within the CoP as a Coordinator and then through the public comment period as a liaison with external parties. Adapted from Karner et al. (2011).

7.6 Validation and Testing

7.6.1 Participant Verification

The TM3 was both validated and tested to increase its dependability and applicability. The TM3 was developed throughout the research period of study from 2015-2022 as a theory-building project from CSes as concepts, categories, and then core theories were developed and the researcher participated in CoPs. Simultaneously, the literature review was being conducted to frame the concepts that were emerging from the CSes and confirming their validity in the extant scholarship. Concurrent with the development of the framework and literature review, the researcher shared components of the emerging concepts (L02) and categories (L03) with CS01 NIBS OSCC participants for validation (Strauss & Corbin, 2015).

The KDM was shared with NIBS OSCC membership and stakeholders during a quarterly meeting. They clarified verbally that the CoP needed to address the domain dimension between external and internal knowledge as the KM would need to handle knowledge that existed outside of the CoP, combined with internal knowledge to create value for the participants and the OSC industry. This motivated further investigation by the researcher into the reciprocal push and pull factors of knowledge, including how it is situated, who is demanding the knowledge and how it will flow. In CS04 – MBI 5 in 5, for example, the participants (modular manufacturers) were asked to provide knowledge that was combined with AECO data from outside of the CoP. This CS observation work was augmented by literature review. Prior to that point in the research, the situatedness of the knowledge was considered, but not properly researched.

The discussion on knowledge "directionality" led to a debate on the ownership dimension and a focus on concerns in the CoP regarding IP. This concern emerged during CS02 and CS03 events as well. IP and CoP is concern that deserves additional investigation into the boundaries of IP, terms of stakeholder engagement, and removal of inhibitions of actors for open knowledge sharing within OSC KM contexts.

The NIBS OSCC also validated and clarified the shared learning activities they thought would be most effective to KM practices of the CoP, with particular attention to the role of active (workshop) versus passive (survey) engagement of participants, the relative value for KM effectiveness, and the desire of the CoP for one mode over another depending on the nature of the question. The NIBS OSCC also aided in identifying the fundamental difference between creating or communicating contextual knowledge (know-why) with operational knowledge (know-what and how). Although the membership considered operational knowledge to be the most effective way for participants and the larger industry to improve on OSC delivery performance, they also deemed the early engagements of the CoP to conduct industry surveys to have been appropriate in establishing contextual knowledge of the industry and thereby orient activities and priorities of the CoP as it matured to foster operational knowledge.

NIBS OSCC members validated the component approaches but were challenged to understand the relations and connections of the framework concepts and categories. They did not credit this to a lack of validity of connections between the different levels of detail in the framework (L01, L02, L03), rather that the framework needed to be tested through multiple iterations. They also verified that a KB was likely necessary to enact the TM3 for effectiveness of the CoP.

7.6.2 Sample Verification

The framework was presented in a videoconference interview regarding ICC/MBI standards (Colker & Hardiman, 2021). The interviewees went through the CS of establishing a CoP relative to the development of the standard, explaining the knowledge type, mode, and measure dimensions. Their feedback pointed out the challenge of measuring performance of KM initiatives on the participant companies and larger industry beyond qualitative assessments and CS storytelling of AHJ adoptions. However, the participants explained that although the actual impact is unknown, is still important and necessary to keep verification of such in the framework.

7.6.3 Peer Clarification

The TM3 framework components were also shared with peer researchers and colleagues for validation of the approach. The peers did not offer validation as the domain is a subject that is laden with much precent knowledge and literature outside of their immediate expertise, however, they did indicate that the need for clarifying language to describe the framework. As the framework constitutes Implementation Research, more tactical than even applied research, attention needs to be paid to the audience that will consume the research. The peers suggested that there be a framework descriptive narrative to aid CoP participants in enacting and applying the framework to their context. This recommendation became the narrative for this chapter. A simpler tactical guide will need to be developed so that CoPs may apply the framework and its components effectively.

Both NIBS OSCC members and peer colleagues indicated that additional testing and validation is needed to confirm, apply, transfer, and verify the dependability of the framework considering CoP stakeholder make-up, scale, and OSC knowledge areas, among others. More on testing and validation is included in Chapter 08: Conclusions.

7.7 Chapter 07 Summary

TM3 was envisioned as a framework by which OSC professionals from different organizations across regions, nations, or internationally may establish a new KM effort and/or maintain a KM CoP when considering OSC knowledge needs. The framework was not intended to address specific situations (organizational types or geographical locales), rather it aimed at providing a generalizable structure for inter-organizational knowledge engagement practices.

TM3 considered a wide array of OSC knowledge concerns; different ways to structure the KM program, processes, tools, and activities; as well as approaches to measure and assess outcomes of KM efforts. TM3 development focused on the application to CoP network organizations including formal and self-organizing (Coakes & Clarke, 2005). Further, it was intended to be applied to research projects, trade association committees, university centers, adhoc task forces, non-government organizations, and governmental and commercial environments in which CoPs have strived to manage knowledge. The framework is a proposal for augmenting KM practices; one born from the naturalized experience of the researcher. As a hypothesis, the TM3 requires further testing and evaluation on the transferability and applicability in future KM environments.

The type dimension of the TM3 framework included knowledge dimensions to demonstrate how CoP members can take knowledge priorities in OSC and evaluate the characteristics of the knowledge through the knowledge dimensions matrix (KDM). The characterization of knowledge leads to tacit and explicit knowledge determinations and then conversions that may need to take place to account for tacit to tacit and tacit to explicit knowledge exchange between individuals in the CoP. Within the type dimension are also structural factors to determine how the CoP is formed, roles of members, and how knowledge is exchanged one way or reciprocally between members.

Modes were outlined in the TM3 framework, including sub-processes in the KM cycle and the tools and activities that CoPs can leverage to address the specific knowledge needs being managed. The measure dimension affords methods to assess effectiveness and performance of the CoP for CoP improvement proper and for participating individuals and organizations. KBs may be used across the three dimensions, with particular importance in the mode dimension in coordinating the sub-processes, tools, and activities of the CoP. KM teams in the CoP need to consider the ownership IP implications of KM efforts at the beginning of the process during the knowledge dimensions stage and make efforts to mitigate risk through NDAs or other means. IP is then a parameter for determining the structure and mode/measure dimensions.

Chapter 08: Conclusion provides an overview of this research. The discussion includes the key research findings, value of the work, assumptions, limitations, and future validation and refinement of the TM3.

CH 08 – Conclusion

This chapter summarizes the motivations, aim, objectives and methodology for this research. The findings are presented and an explanation of the associated knowledge contributions to the field and the significance and impact of the work are claimed. Validity of the research is discussed and then assumptions and limitations of the research are related. Lastly, future research opportunities are presented.

8.1 Aim, Objectives, and Methodology

The U.S. and UK are experiencing a housing crisis due to lack of supply (Henderson, 2019; Goddard, 2021). OSC is a key strategy that has been identified as a solution to housing affordability and access (Barbosa et al., 2017; Miles & Whitehouse, 2013). Previous studies have documented the benefits of OSC, including increasing productivity, cost performance, schedule reductions, improved worker safety, upskilling opportunities, and environmental impact reduction (Barbosa et al., 2017). While OSC has slowly grown in recent years and despite the documented benefits, uptake and adoption in the U.S. and UK have a fractional impact compared to international contexts of Sweden, Japan, and Central Europe (Bertram et al., 2019).

OSC, at the intersection of manufacturing and construction, is an innovation that requires knowledge and skills generally outside of conventional construction practice (Hjort et al., 2014; Tatum et al., 1987). One reasons for the lack of housing market penetration of OSC has been attributed to the lack of contextual and operational knowledge of the domain and a lack of knowledge sharing culture and infrastructure across the sector (Firestone & McElroy, 2003; Smith, 2014). As a social sector, construction knowledge is held by and flows through individuals and organizations (Bresnen et al., 2005; Lindgren, 2018). Knowledge in OSC is fragmented and compacted, produced tacitly through project-based engagements, and shared most often by experience (Annan, 2012; Barlow, 2000; Chimay et al., 2007).

KM is creating, sharing, using, and managing knowledge of an organization. Literature suggests that KM is effective at fostering knowledge production and exchange that can lead to market growth and commercial opportunities (Firestone & McElroy, 2003). KM theory and practice have been applied to sociology and management fields for some time and more recently to construction practice (Egbu et al., 2005; Rezgui & Miles, 2011). Applying KM to inter-organizational communities is less common than within a discrete company (Easterby-Smith et al., 2008). This research aimed to develop a framework for non-project based inter-organizational KM in OSC. In identifying the research aim, the following questions emerged:

- What is KM?;
- Why is KM needed in OSC?;
- What are the OSC knowledge categories and needs to be used in KM?; and
- How can knowledge be exchanged in OSC?

To answer these questions and develop the KM framework, this thesis had five objectives by which the research was structured and undertaken. The first was to identify the research aim and methodology. The researcher participated in an inter-organizational KM CoP (Wenger, 1998) and observed the need for improvement of knowledge sharing between OSC stakeholders. Because the research was focused on the development of a Theoretical Framework through the CS experiences of the researcher and given the familiarity of the researcher using qualitative methods, Constructivist GT was determined to be the appropriate research methodology (Glaser & Strauss, 1967).

The second objective was to perform a literature review of SR sources organized into two parts: SR01 provided a literature review of KM theory as applicable to the dimensions of inter-organizational KM. SR02 - OSC Knowledge presented literature on how OSC can address housing needs in the U.S. and UK and how KM can support the uptake and adoption of OSC. SR02 continued with a review of the extant literature on OSC knowledge characterization, categories, and priorities.

The third objective was to data mine PR of four projects conducted by the researcher. This data mining effort triangulated the OSC knowledge types and needs from SR02 literature review. Objective four of the research was to analyze four KM socialization contextual CSes using GT tactics. The CS findings were confirmed and Contextualized in the primary and secondary sources of the literature review (Corbin & Strauss, 2015).

Finally, objective five was theory-building. In the process of applying the GT tactic, referencing literature and data from concurrent research on OSC knowledge, a rhetorical framework emerged and was titled the type, mode, measure model (TM3). This framework was intended for use in inter-organizational KM CoPs for OSC housing. TM3 was reviewed by the participants in the CSes and peer researchers. In the end, the framework is a theory - a hypothesis developed through a constructivist GT methodology.

8.2 Findings

This section reviews the findings from this research. Each research question is listed with a narrative of the findings and a discussion of how well the aim was met. A discussion on the value and shortcomings of this research is then presented, along with additional, unexpected findings.

8.2.1 Research Questions

Question 01: What is KM?

To investigate KM in OSC practices, the researcher needed to become familiar with KM theory. This was accomplished through a literature review of the theory and practice of KM, first outside of the construction knowledge domain and then within. SR01 was a systematic review of articles, papers, and books until the researcher reached a point of theoretical saturation, and themes, concepts, strategies, tactics, tools, and frameworks developed by scholars were being repeated with regularity. The literature review was narrowed to inter-organizational KM, a distinct sub-category of KM theory for which this research was targeted.

The scholarship was organized from general to specific, starting with KM definitions, purposes, and uses, followed by the processes in KM. The research revealed specific strategies for establishing and sustaining KM organizations including CoPs, as well as tactics for CoPs to operate effectively. Key tools were identified in the literature from leading inter-organizational KM scholars that provided structure and logic to the data being gathered, coded, and categorized in the CS analysis. Therefore, the answer to "What is KM?" became more specific to the ongoing engagements of the researcher in the CS CoPs. Events in CS experiences influenced the search for additional resources to frame the phenomena of what was being observed with terminology and conceptual clarity. Below are the key findings from SR01 that answered the question of what KM is and served a functional support to the GT approach:

- KM cycle and evolution of knowledge;
- Explicit / tacit knowledge conversions;
- Inter-organizational KM: type, mode, measure contingent dimensions;
- Strategies: CoPs, triple-helix, hub, co-production;
- Tactics: cross-project, bi-lateral exchange, shared learning, contingent worker, KB;
- Tools: taxonomy of knowledge, SeLEKT, CLEVER; and
- Measuring KM: effectiveness and performance, stocks and flows.

The answer to "What is KM?" depends on who is asking. The researcher found that KM is contextually contingent. This means that the function of KM depends on the position of the actors. It is made up of two words: knowledge, connoting epistemology, and management, meaning to plan and organize people. As such, KM is both theory and practice, rooted in a specific context with demands and needs, people and organizations. KM is both conceptual and pragmatic. Moreover, the researcher discovered that KM provides a philosophical frame for viewing the people, process, and products of OSC as well as an applied set of strategies, tactics, and tools by which to enact meaningful knowledge exchange. This was helpful in developing a KM framework because it allowed the researcher to oscillate between asking questions of "why" and "what" (theory) while applying theory to answer questions of "how" and "who" (practice) to KM in OSC.

Question 02: Why is KM needed in OSC?

The literature review from SR02 answered this question. The extant sources on OSC knowledge focused on the characterization of construction and OSC as being fragmented, geographically dispersed, and litigious (Liu, Mao, & Wang, 2020; Merton, 2013). Further, the research showed that knowledge exchange can aid in creating more shared understanding, standards, and routines by which the industry can be more efficient and productive (Egbu & Robinson, 2005). Second, the literature revealed that in construction, the stocks of knowledge are primarily tactic and held by individuals and organizations and this knowledge has been developed through project-based learning (Barlow, 2000; Chimay et al., 2007). This embedded knowledge is challenging to elicit, codify, and convert to another individual or organization. KM presents strategies and tactics to convert knowledge between entities. Lastly, the literature defined OSC as an innovation (Davenport, 1993; Goulding & Arif, 2013), requiring new knowledge regarding products, processes, and people for both manufacturing and construction domain knowledge. Ergo, OSC has struggled to increase markedly due in part to the lack of knowledge about how to logistically deliver the innovation of OSC for housing. The need for KM and inter-organizational KM specifically applies to construction and, by extension, in OSC (Egbu & Robinson, 2005).

Research from the CSes (CS01-CS04) found that the CoPs in action often sought a more systematic and structured way to address knowledge exchange. Although not stated in those terms by the participants, the engagement in the CoP were actors essentially searching for knowledge and a desire to share knowledge for individual or organization benefit or a genuine desire to improve the construction sector to be more productive and innovative via KM. The concerns about developing or sharing knowledge that emerged during the CS engagements included:

- Where did the knowledge come from?;
- How was it produced?;
- How was it going to be used?;
- How reliable was the knowledge?;
- Who owned the knowledge?; and
- How impactful was the knowledge?

Question 03: What are the OSC knowledge categories and needs to be used in KM?

This question requires two points of research. The first is about knowledge categories – how OSC knowledge can be classified and organized by topic and theme. The second question is concerning the knowledge needs and priorities in OSC. The SR01 study of knowledge categories and characterization found that the most frequent topics that emerged in books and reports from specialist and popular publications included:

- Construction culture changes in OSC;
- Barriers and challenges in OSC;
- Stakeholder roles in OSC;
- Housing solutions in OSC;
- Market and organizational drivers for OSC;
- Cost and schedule performance of OSC;
- Manufacturing principles in OSC;
- Benefits of OSC; and
- Supply chain alignments in OSC.

Furthermore, the literature revealed the following insights regarding OSC knowledge categories and characterization:

- Knowledge Type: The majority of OSC literature focuses on explicit knowledge (know-what and know-why) and less on tacit knowledge (know-how), although tacit knowledge dominates in construction practice.;
- Knowledge Situatedness: OSC knowledge is more organizational and environmental and less technological considering the TOE framework for innovation.;
- Contextual vs. Operational: OSC knowledge can be categorized by the context in which it operates such as the regulatory framework, economy, unique supply chains, and workforce and labor conditions. Operational knowledge are the skills to design, manufacture, and construct OSC housing. The operational knowledge and skills are more generalizable while contextual knowledge is location dependent and situationally contingent.;
- Project Based Work: OSC knowledge is organized in the literature by the project delivery phases and the knowledge needs of traditional stakeholders in construction. OSC is the intersection of manufacturing and construction, however, the literature indicates that OSC is being evaluated and studied primarily from the perspective of manufacturing knowledge into construction, with construction delivery knowledge

still serving as the base. As such, there continues to be a lack of long-term planning and long-range vision for how OSC knowledge can be approached as a continuous improvement practice, more aligned with KM efforts in production industries.; and

- Disciplinary Knowledge: There is a lack of consistency in the topics that OSC researchers are addressing in the literature due to the unique perspectives and interests of the researcher and the discipline for which they belong or come from (i.e., architecture, construction management, manufacturing, etc.). Therefore, there is a dearth of evidence that OSC disciplinary knowledge is building and improving through researcher iterations.

The second part of the question is concerned with OSC knowledge needs and priorities. This was answered through the SR02 literature review and PR01-PR04 data mining research activities. The literature review consulted journal articles and research roadmaps to determine the most frequently identified barriers to OSC uptake. The literature was triangulated with PR data from projects conducted by the researcher that was evaluated through a barrier analysis to OSC adoption and uptake that yielded the knowledge needs and priorities listed in Section 5.6.

The OSC knowledge needs and priorities finding is a unique intellectual contribution to the field. It further clarifies what many scholars have found before and uniquely claims the U.S. specific knowledge priorities to be addressed by inter-organizational KM, among other approaches. The culmination of this systematic review of OSC knowledge needs provides researchers with a starting point to frame their own research questions; funding agencies in positioning their calls for proposals; and practitioners in understanding the obstacles to look out for in working on OSC projects. The leading knowledge need for the U.S. OSC industry is regulatory navigation. This finding has already had significant impact on the subsequent work of the researcher and the orientation of the OSC industry in the U.S. toward solving the fragmented code context. ICC/MBI standards are beginning to address this challenge as an explicit means of knowledge creation and communication, and U.S. HUD is actively involved in solving this barrier to OSC uptake through research support (ICC/MBI, 2021; Smith et al., 2022).

The SR02 – OSC Knowledge and PR01 – PR04 Data Mining found that the knowledge needs for OSC are environmental and organizational and much less technological. This finding is important because environmental and organizational knowledge is primarily concerned with the tacit domain of knowledge, emphasizing "know-how" knowledge. This research demonstrated the importance of KM in tacit knowledge conversions in OSC, further confirming the need for the research aim of this thesis– that is, development of an inter-organizational KM framework.

Question 04: How can knowledge be exchanged in OSC?

The research resulted in a three-level theoretical framework that corresponded to and was a direct outgrowth of the GT steps of development: concepts (L03), categories (L02), and core theories (L01). Core theories are the contingent dimension of type, mode, and measure to form the TM3 framework. L02 and L03 sub-topics are organized under these contingent dimensions. This research found the following L02 Categories, organized under the L01 core theories to answer the question of how knowledge can be exchanged in OSC as outlined in Table 8.1.

Table 8.1 TM3 L01 core theories, L02 categories, and L03 concepts.

TM3 L02 Concepts	
LO1 TYPE	L02 Knowledge Dimensions: Knowledge has dimensions that need to be considered before addressing the way in which the knowledge is managed. These knowledge dimensions were observed in the CSes and then confirmed and clarified in the extant literature. Ten unique dimensions were found in this research; however, depending on the CoP context, or knowledge exchange iteration, fewer or additional dimensions may be considered applicable. The dimensional characteristics of the knowledge are key determinants in the conversion scenario considering tacit and explicit transfer. To support CoP participants in making knowledge type dimension determinations, the researcher developed a KDM that is a supplement to the TM3 framework.
	L02 Structural Factors: Knowledge is exchanged next based on structural factors. This considered the actors in the CoP and their individual and organizational interests, expertise, organizational sector, responsibilities, and the flow of knowledge as push or pull based, as well as bi-lateral reciprocal sharing or not.

L01 Mode	L02 Sub-process: Knowledge is exchanged in the framework by considering the process of KM, such as creating, clarifying, categorizing, and communicating. This is the KM cycle operation being performed by the KM community. The research found that being specific about the cycle operation fostered clarity in the purpose of iteration and its relationship to other operations in the cycle.
	L02 Tools: Selection of techniques and technologies to facilitate the exchange of knowledge through the CoP. Those developed in the framework include exchanges, productive inquires, shared learning, producing assets, creating standards, formal access to knowledge, and visits.
	L02 Activities: Shared learning activities that respond to CoP strategy are organized within the tool headings to allow for co-production and refinement of knowledge. This can occur through experiential learning considering the degree to which the activity is formal or informal and from outside or within the CoP.
L01 Measure	L02 Effectiveness: Evaluating the outcome of an exchange iteration is important to determining how effective the CoP is at their approach in order to continuously improve their KM practice. These effectiveness parameters include process evaluation, role fulfilment, trust, communication, and socialization.
	L02 Performance: The exchange iteration can also be evaluated for the metric, economic, and market value performance to the organizations that participate in the CoP and the OSC industry at large.
L01 KB	The TM3 also identified that the role of a KB was important, especially in the mode operations of navigating the techniques and activities of the CoP to perform the KM functions. In this role, the KB serves as a coordinator among CoP members and liaison to external parties, speaking on behalf of the CoP, and connecting the CoP to macro-movements in the OSC industry.

8.2.2 Meeting the Aim

The outcome of this research was a framework that combined the theory of KM with the application of a KM tool. The framework is, therefore, both instructive and reflective (Ruth, 2015). It is instructive because it teaches CoP participants as they engage with the dimensions, categories, and concepts about KM principles, strategies, and tactics and how to use these approaches in KM operations. Thus, it is functional. The framework is also reflective as it encourages participants to think deeply and carefully about knowledge and how it is created, clarified, exchanged, and evaluated and their individual and organizational relationship to the knowledge.

The TM3 is most useful in the categories that are created at the L02 level and their sub-topic Concepts in L03. These individual sections or components of the TM3 are distinguishable, discretely definable, and operationally clear. The interrelations of the concepts (L03) and categories (L02) is logical. However, the TM3 is not as effective at the relations between the categories (L02) in the framework and between categories (L02) and contingent dimensions (L01). It was less understood by participants in reviewing the TM3 framework how the categories and dimensions were related to one another and how actors in a sequence of KM iteration may navigate the framework. The theoretical framework emerged from the CSes in which the levels emanated from the data gathering, memoing, and coding that fostered concepts, categories, and core theories. This structure produced a framework that is useful within a discrete component (i.e., L02 sub-process), but is less serviceable between components within a contingent dimension.

Testing and validation are needed to uncover additional opportunities and refinements within an L02 component and, more importantly, testing is needed to detect the specific challenges of inter-component navigation in the framework.

8.2.3 Frame within Literature

The three level components of the framework (L01, L02, L03) emanated from the three steps in the GT tactics and data approach: concepts, categories, and core theories (Pettigrew, 1985). TM3 was contextualized in the literature continuously that sensitized the research to KM theory and practice. SR01 KM Theory literature review resulted in a similar level of detail consisting of a framework for understanding KM applications for CoPs organized by the same contingent dimensions that comprised the framework. This was accomplished as the CSes progressed concurrent to the literature review of KM theory. The researcher simultaneously coded CS data and literature review data into type, mode, and measure sections and sub-sections that provided confirmation of the CS evolving theory. In the following parts, the research findings are presented to validate, clarify, and differentiate this work from the extant literature.

Validate to new CoP CSes: This research draws from the extant scholarship on KM theory and practice in SR01, and offers a unique intellectual contribution by validating, clarifying, and differentiating knowledge in KM. The research validates this scholarship as it operationalizes KM theories, strategies, tactics, and tools to a new context of the TM3 framework. Both the CS findings and the framing literature were validated as they were in dialogue through the research progression and evolution. Key literature that helped shape the CS analysis and led to L01 core theories of the contingent dimensions of type, mode, and measure, include:

- Type, mode, measure, and context (Loebbecke, van Fenma & Powell, 2016);
- Inter-organizational KM framework (Milagres & Burcharth, 2018); and
- CoP (Wenger, 1998).

The L02 and L03 components of TM3 framework development as they relate to the extant literature are shown in Table 7.1 of Chapter 07. Below is a summary of the key topics and authors that provided contextualization for the L02 and L03 components listed in Table 7.1 in detail:

- KM cycles of activity (Mohajan, 2016);
- SECI Model for knowledge conversion (Nonaka, 1994) that contextualized the knowledge dimensions;
- Shared Learning (Karner et al., 2011);
- KB (Gould & Fernandez, 1994);
- Taxonomy of Knowledge (Matusik & Hill, 1998);
- SeLEKT (Al-Ghassani, 2002); and
- CLEVER (Anumba, Kamara, & Carrillo, 2005).

Clarify to OSC: The research helped to clarify the extant literature in KM practice by integrating the KM terminology to be able to situate the CS emerging theory within the field. The research clarified how KM theory is applied to the construction knowledge domain and illuminated specific knowledge dimensions that were oriented at OSC knowledge. These include ownership, private versus public, and individual and collective that is pertinent to OSC knowledge characteristic given the innovation dimension of the domain (Matusik & Hill, 1998; Oliver & Ebers, 1998; Raza-Ullah, 2016). Furthermore, the subprocesses that emerged in the CSes that clarify KM theory include contextualizing, commercializing, and continuing knowledge responding to the need for OSC that is contextually contingent, commercially interested, and struggling to unpack project-based embedded knowledge (Dalkir, 2011; Mohajan, 2016). The research found that the techniques more than technologies are prioritized in OSC KM with the associated shared learning activities (Al-Ghassani et al., 2002, 2005). The techniques and shared learning activity priorities in OSC are productive inquires, exchanges, creating standards, and visits (Karner et al., 2011).

Differentiate from KM theory: The extant literature on KM is separated into two major categories: theory and practice. This research created a new approach to KM frameworks integrating the tactics and tools associated with KM practices with the overarching theoretical framework. This operationalizes KM to apply to a lay CoP context that may not be familiar with KM theory and practice. This is accomplished through the levels of the framework that emerged from the CS analysis GT methodology and associated steps of concepts (L03), categories (L02), and core theories (L03). This research was unique as it brought together the epistemology of KM theory and the tactics of GT qualitative methods to create a novel, layered framework of theory and practicality. This is distinct from the extant literature on KM.

Differentiating this research from the KM theory scholarship, this research created clarity regarding OSC knowledge. The SR02 literature review sorted the extant literature into characterization, categorization ,and needs/priorities of knowledge. This unique approach sorted extant literature on OSC knowledge into useful groups for this research and provides scholars in OSC knowledge key topics for further investigating and clarifying OSC knowledge domains. Further, this research offered a unique intellectual contribution by combining the SR and PR to claim the OSC knowledge needs and priorities. These are reported in Chapter 06: Data Mining. This research fills the gap in determining the knowledge needs in the U.S. so OSC stakeholders are aware and can plan for barriers and challenges facing OSC uptake.

8.2.4 Significance and Impact

This research is significant because it provides a documented process of taking a general theory of KM and applying it to a specific situation of OSC KM through theory-building. The framework may be applied to OSC and construction-oriented CoPs immediately to support KM practice. The research is significant because it integrates KM theory with tactical, actionable tools and techniques. Frameworks are part of implementation research that states there are three levels of assumptions by scholars: frameworks, theories, and models (Nilsen, 2020). A framework is the broadest implement. It describes but does not explain factors that are believed to influence an outcome. It provides an overview of descriptive categories and how they might relate to another. A theory helps to predict and examine which factors influence an outcome and specifies which parts of the framework are useful to explain a range of outcomes and relationships. It makes general working assumptions toward this end. A model simplifies the process of translating research into practice. It uses precise assumptions about a few variables (motivations of actors and structure of situations) within a theory to examine consequences of these assumptions. Models often result in algorithms that can describe relationships.

Frameworks, theories, and models are nesting layers of detail and relation (Figure 8.1). The assumptive implement that emerged from this research was a theoretical framework. It is a framework because it describes factors that influence KM outcomes as an overview. It contains descriptive categories and demonstrates how they relate to one another (i.e., L01, L02, L03). However, the TM3 is also a theory in that it predicts and examines the factors that influence a range of outcomes and relationships and provides working assumptions. The TM3 is not a model because it does not provide procedures for how to navigate the framework and apply the theory due to the number of unknown variables that require inductive engagement. Despite the intention to develop a theoretical framework, the TM3 is more framework than it is theoretical. Therefore, next steps in this research will focus on making the TM3 more actionable for CoP participants to be able to implement it with ease and utility.

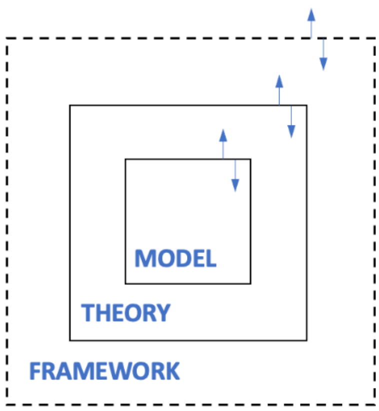

Figure 8.1. Relationship between framework, theory, and model.

8.2.5 Other Findings

In addition to achieving the aim of this research, an additional unexpected finding resulted in the application of the CCP (Pettigrew, 1985) parameters during the initial memoing of events from CSes. This approach was discovered during the literature review on KM theory. Although not applicable to research in the main, the parameters were identified as appropriate for recording memos by asking the fundamental journalistic questions from the event: context (who, why, where, when), content (what), and process (how). The employment of these parameters was outlined in Chapter 06: CS analysis.

8.3 Validity

This research derived theory from qualitative analysis of CSes. Using GT methodology, the researcher began with a research problem and questions that were derived from professional experience and preliminary literature review that valued KM in OSC inter-organizational CoPs. Validation in quantitative research is concerned with reliability, generalizability, and objectivity. This is contrasted to validation in this GT project that aimed at determining validity through credibility, applicability, transferability, dependability, and confirmability (Corbin & Strauss, 2015). Further, validation in GT explains plausible interpretations of the data (Cullen & Brennan, 2021).

The efforts to strengthen the credibility and dependability of this research resulted in selecting multiple CSes that served as sources for the sampling that had the most likely chance to lead to theoretical saturation. Further, having multiple scenarios for the KM data to emerge increased the dependability of the TM3. Repeatability of the methodology in another research setting is yet another evaluation of validity. A study at the scale of this research with multiple CSes and flows of coded data would be challenging to repeat because of the number of years required to collected data across unique CS samples and the time commitment by the researcher. However, a research team could use a similar approach if there was a structured procedure for memoing and coding data and this workload was distributed among team members.

Furthermore, the research project was uniquely tied to the opportunities that were available to the researcher through the PR01-PR04 data mining projects and the CS01-CS04 CS engagements. Indicative of engaged qualitative research, it would be difficult for any researcher, including the author of this work, to duplicate a theoretical sample pool that could result in the same outcome. However, the GT methodology using events, concepts, categories, and core theories leading to a framework is transferable to another research initiative. This approach is outlined in detail in Chapter 04: Research Methodology and Chapter 06: CS Analysis.

The methodology was rigorous and the researcher sought to have multiple CSes and multiple PR data points to mine for the OSC knowledge needs analysis. The OSC knowledge needs literature review triangulated with PR data mining comparison (Chapter 03 and Chapter 05) validates the OSC knowledge findings.

The applicability of this research to OSC KM communities outside of the CS sample in this research is unknown. Next steps in the research need to test this framework hypothesis in different scales, types of CoPs, geographic locations, and formats. Furthermore, the findings of this research reveal that the TM3 needs to have an interpretive narrative so CoPs can understand how to apply the framework more readily in their respective contexts.

The quality of GT can be related to three distinct areas: 1) the researcher's expertise, knowledge, and research skills; (2) methodological congruence with the research question; and (3) procedural precision in the use of methods (Birks & Mills, 2015). This research was successful in the first and second instance. The researcher used qualitative methods extensively (PR01 – PR04) prior to engaging in this research and employed GT on a previous project. Also, the methodology was congruent to the research aim. However, the structure of the research evolved in the first couple of years of the period of study until an approach that was effective was identified. The matching of CS data gathering, specific coding approach, creation of concepts, categories, and core theories and how they related to the framework levels of detail, emerged during the research progression.

8.4 Assumptions and Limitations

There were several assumptions made in this research. First, this research assumed that an increase in OSC uptake would result in an increase in housing supply at scale. Although OSC productivity and performance metrics have been demonstrated in the literature (Barbosa et al., 2017; Smith & Rice, 2015), there is not a known correlation or causation between an innovative approach to construction and an increase in construction volume. Housing supply is subject to several factors. Design and construction management are only two of the factors.

Second, there was an assumption that KM will directly benefit the market uptake of OSC. The null hypothesis to this point is that although OSC knowledge has increased in recent years, the rate of increase in the OSC sector has marginally increased. Furthermore, there is no evidence that the increase of OSC during the latter part of the 20th century in Sweden and Japan was a result of the increase of context and operational knowledge amongst OSC stakeholders. Certainly, knowledge is a component of innovation and growth of a sector; however, it may not be cause for it.

Third, the researcher assumed that barriers to adoption and uptake of OSC is directly related to knowledge needs in OSC. This presumption was the basis for both the SR02 OSC Knowledge literature review and the PR01-PR04 data mining objectives of this research. Further research is needed to confirm that there is a correlation between barriers and obstacles to uptake and knowledge needed to address that challenge.

In addition to assumptions, the following limitations were recognized. Regarding SR02 OSC knowledge literature review, there were limitations because there were a finite number of references that documented U.S.- and UK-specific knowledge needs and, therefore, the researcher sourced from a wide array of authors. The only delimiters were barriers, needs, and priorities. This research was targeted at OSC knowledge in the U.S. and UK as it relates to OSC housing uptake. There was a misalignment of the samples that were taken in the literature sources and the sample that was needed by the researcher. The researcher worked to balance this with the PR01-PR04 verification studies that all were U.S.- and UK-based projects.

The limitation in the PR01-PR04 data mining studies was that the data was not always congruent. Therefore, although the studies themselves were discrete research projects with methods, samples, data, and results, integrating the outcomes each into an aggregated finding regarding OSC knowledge needs and priorities was limited by the sample of related but not identical studies. This required the interpretation of the researcher to determine the findings of each PR and their offering to answer the question "What are the OSC knowledge needs?".

Objective 04 CS analysis presented some challenges and, therefore, limitations to this research. This work used multiple CSes as a vehicle for producing qualitative data. Singular CS analysis, especially in GT is more contained and would not have yielded as divergent of a data set. Although the use of multiple sources of events presented a novel opportunity for triangulation between sample pools, multiple CSes also compounded the amount of data coding to be performed. Trying to engage in events for the purpose of the meeting, workshop, or webinar while also memoing presented logistical challenges. The implementation of this methodology and the use of multiple CSes was rich, layered, complex, and fruitful; however, it was also tedious, challenging, and lengthy. The advantage of qualitative research is the quantity of data incoming; however, this presented data processing challenges that competed with the day-to-day work of the researcher in CoP practice.

The CSes differed in their composition. CS01 – NIBS OSCC and CS03 - BeX were established as a sustained CoP that provided an infrastructure for numerous KM iterations, while CS02 – Scotland OSC Hub and CS04 – MBI 5 in 5 were built for the purpose of research. The disciplinary background differed in the populations between CSes, as well as the number of participants in each CoP. The level of engagement of the participants was not consistent between CSes either.

Another limitation was that the CSes selected were those in which the researcher was participating, resulting in the potential for researcher bias. Because the researcher played either a key role or a KB role in CoP, the researcher had to be careful and conscious to avoid forcing ideas onto the data gathering from CSes that was being identified in the literature. Also, the researcher periodically experienced intellectual conflicts of interest between the interests of this research and that of sustaining a vibrant CoP network. A final limitation in this research was relying on memoing from events as a participant alone with no additional methods used within the GT approach.

8.5 Future Work

The future work of this research is related to the unexpected findings and limitations. Future research can address researcher bias by identifying CoP pools that are a step removed from the researcher. In employing GT tactics, in this scenario the researcher still participates but takes a more passive role. Another way to address this limitation of researcher bias is to have co-investigators engaged where one is KB and the other gathers data. Also, the CSes selected for future research may be determined by objective criteria that is not based on convenience of access by the researcher alone, but on intentional criteria for the data sample. This is assuming there are CoPs willing to accept researcher involvement and that there are enough CoPs in existence for a particular type of KM evaluation.

Although the CS approach was a consistent method used in the research, there is potential in the future to include mixed methods of qualitative data gathering such as participant surveys, including questionnaires and interviews. Further, in coding the research that had this many events and data inputs, the researchers could employ a qualitative software tool that would help to create concepts and categories with relations and interrelations through a database and diagramming platform (e.g., NVivo). This would increase the number of data points that can be catalogued and help to code and sort the data more consistently and accurately.

The SR literature review identified knowledge ownership as a potential inhibitor of inter-organizational KM. Moreover, during testing and validation of the TM3, CS01 participants highlighted obstacles regarding the ownership domain and whether knowledge was individual or collective. This pointed to concerns regarding IP in OSC KM. As OSC innovation consists of people, processes, and products, IP is a central concern. This was verified in CS02 as well among Hub participants. Additional research is needed to understand and address IP concerns in OSC KM practices.

There is an opportunity to extend this research to include additional testbeds of CoPs that can further validate the TM3 framework. Ideally, this would be tested at different scales, populations, purpose types, geographic locations, and formats. The key is that additional testing is needed to confirm the utility of the framework and further refine it to be more applicable to OSC CoPs. The framework should also be tested in CoPs that are focused on other topics within construction (i.e., information technology, labor, lean construction, carbon neutral, etc.) and outside of construction to evaluate the transferability of the framework.

Lastly, an area that warrants future research responds to participant feedback that the TM3 Framework provide more guidance on how to navigate through the levels to produce a meaningful outcome, and then measure the KM exchange for impact. This may include creating a more theoretical direction to TM3 or creating a model implementation layer (Rosetta Stone) to the framework. Although this research has addressed the measure dimension, the data gathered during events in the CoPs and the literature on the subject is scant, and CoP participants identified this as an area in which they needed more guidance in the framework as well. Thus, future research can address the need for additional knowledge around the theory and practice determining the effectiveness and performance of OSC KM engagements.

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APPENDICES

The appendices herein constitute key peer reviewed publications and reports that codify the research that contributed to the knowledge base for the development of this thesis.

Appendix A – NIBS Survey 2014
Smith, R.E. & National Institute of Building Sciences (2015) "Off-site Construction Industry Survey 2014". *National Institute of Building Sciences*.

Appendix B – NIBS Survey 2018
Smith, R.E. and Tarr, K. (2019) "Offsite Industry Survey 2018". *National Institute of Building Sciences.*

Appendix C – Performance Studies
Smith, R.E. and Rice, T. (2017) "Permanent Modular Construction: construction performance". In *Offsite Architecture: constructing the future*. Smith & Quale (Eds.) Routledge Taylor and Francis: 123-142

Smith, R.E., Griffin, G. & Rice, T. (2017) Mass timber: evaluating construction performance. *Journal of Architecture, Engineering & Design Management*. Vol 14:1-2.

Appendix D – MBI 5 in 5 Report
Smith, R.E. and Rupnik, I. (2018) *5 in 5 Growth Initiative: research roadmap recommendations*. Modular Building Institute. Final Report. May 2018.

Appendix E – Offsite HUB Scotland
Hairstans, R. & Smith, R.E. (2018) Offsite HUB (Scotland): establishing a collaborative regional framework for knowledge exchange in the UK, *Architectural Engineering and Design Management*, 14:1-2, 60-77.

Appendix A – NIBS Survey 2014

Smith, R.E. & National Institute of Building Sciences (2015) “Off-site Construction Industry Survey 2014”. *National Institute of Building Sciences*.

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Appendix B – NIBS Survey 2018

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Offsite HUB (Scotland): establishing a collaborative regional framework for knowledge exchange in the UK

Robert Hairstans & Ryan E. Smith

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