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EXPLORING EFFECT OF DIFFERENT RESOURCE QUALITIES ON PROCESS EFFICIENCY IN CONSTRUCTION PILE INSTALLATION

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Abstract. This paper presents the measured effects of different resource qualities on construction performance. The paper describes a recommended method, proposed with the concept of prediction by understanding the causal effect of process resources on consequent work efficiencies. The project team measured and compared the different arrangements of resources and their effects on on-site work efficiencies. The paper includes a field study of 15 operations (40 piles) in Melbourne, on several worksites of prefabricated piles and installations. It aimed to determine the causality between the set of delivered prefabricated piles and relevant work efficiencies. This field includes its purpose of generating and providing scientific evidence in effectively implementing an offsite operation. One of the critical factors affecting the efficiency of the installation process was confirmed to be the location of the longest section in the sequence. It took 21.8 minutes longer with the middle part of the installation if the longest section was designed to be in the middle of the whole prefabricated steel pile. The findings confirmed the need for holistic communication along the supply chain. The originality of this project is to provide a case study that offers archival evidence of the proposed model in a practical situation.

Keywords: early supplier involvement, strategy development, distribution and logistics, offsite construction, work efficiency.

Introduction

The purpose of project management (PM) is to complete a product that can satisfy the end-user while minimizing the risk of dangers and problems throughout the supply chain (Lock, 2007; Moon et al., 2015). For this purpose, a project can be defined as sequenced tasks to accomplish pre-defined objectives, and the success can be measured by how closely the project outcome matches the objective(s) (Field & Keller, 1998; Kerzner, 2009). The objective is represented as different aspects of project quality, such as customer-oriented and value-oriented qualities (Abuhav, 2017; Mukherjee, 2006). This holistic understanding of quality has been an essential part of the long-term success of PM (Ferreras & Crumpton-Young, 2017; ReVelle, 2016).

Many industries have achieved considerable advancements through understanding quality in PM. The success of Japanese manufacturing in the 1970s–1980s, for example, stemmed from their effort to create a quality product that met the market's expectations (Ferguson, 2017; Mahadevan, 2009). However, the construction industry has not embraced quality as a holistic aspect of PM when compared to other advanced industries (Ashford, 2002). An empirical study found, through interviews with twelve construction quality managers, that quality is often seen as a "bureaucratic imposition" and is an unwelcome part of managerial aspects (Mccabe, 2014). The research for this paper started at this point, with the assumption that the

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*Corresponding author. E-mail: *sungkon.moon@gmail.com* sluggish adoption of quality in construction may exacerbate the industry's lack of advancement.

Offsite construction is a growing trend these days (Engineers Australia, 2020), and this requires a holistic approach for harmonious relations along the supply chain. Considering this, the literature review of this paper presents the characteristics of offsite construction and supply chain management (SCM). In addition, the paper presents an attempt to understand the current state of construction by conducting a field study on offsite pile installation. The findings will create a foundation not only to provide evidence to understand the state of construction but also to suggest a future direction of management studies in general construction combined with offsite-manufactured construction.

1. Literature review

1.1. Offsite construction and supply chain management

Today, the concept of offsite construction has been actively established. It is also referred to as factory-made construction, manufactured construction, installation (panelized) construction, mixed construction, preassembled construction, or hybrid-system construction (Dettenmaier, 1997; Emmitt, 2018; Lu, 2009; Smith & Quale, 2017). The products produced by offsite suppliers are called assemblies, units, modules, or pods (Gibb, 1999), but practitioners are using more general terms, such as parts, sections, or components. Most offsite construction projects follow standard procedures: (a) manufacture, (b) deliver, and (c) install (Hou et al., 2020; Smith & Timberlake, 2011; Moon et al., 2020).

Different categories of offsite construction are extrapolated from current practices and literature reviews according to different specifications, technologies, and the completeness-level of assemblies (Gibb, 1999). Table 1 shows a comparison between the different categories and levels of offsite completeness. The total efficiency and work intensity for each phase can be determined by the category selection.

Four levels of offsite completeness are identified from site observations and literature reviews (Arif & Egbu, 2010; Gibb & Isack, 2003). Subassembly (Level #1) presents the most traditional method of factory-oriented construction. Generally, it refers to the customized material resources on site, such as ready-mixed concrete, tile, and brick. This level usually does not require intensive communication between the supplier(s) and construction site, only general information, such as amount, date, and quotation. The second of the four levels, 2D-Preassembly (Level #2), indicates the products supplied offsite, which require post-processing on site to generate 3D-elements. An example of this level is a prefabricated cage or pile that is typically cut and bent according to on-site drawings and is required to be placed before pouring concrete (Moon et al., 2015).

3D-Preassembly (Level #3) refers to manufactured products, which are ready to be installed as parts of a whole structure, as an element of a space. Examples of this category are staircases manufactured by steel fabricators and temporary scaffolds (Hou et al., 2017; Kim et al., 2018; Moon et al., 2016). The last volumetric system (Level #4) represents the highest level of offsite completeness, such as a completed bathroom module, which is ready to be installed on site as an independent part of a whole structure (Gosling et al., 2016; Luo et al., 2020). In many practical cases, different levels of methods can be combined to meet the project requirements as a hybrid approach.

The manufactured modules and products can also be divided according to 2D or 3D configurations (Goulding & Rahimian, 2019). Level #1 in Table 1 does not have its shape of configuration, while level #2 consists mostly of 2D configurations, and levels #3 and #4 are produced with 3D configurations (Emmitt, 2018). The products in level #2, such as precast concrete, are delivered, erected, and assembled on site to configure a pre-designed geometry (Cooke & Williams, 2013; Han et al., 2015; Nawy, 2008). However, the products in levels #3 and #4 are to be positioned, assembled, and fixed, since they arrive as 3D, volumetric shapes (Lawson et al., 2014).

Higher levels of offsite completeness can minimize on-site activities (Yu et al., 2013). Similarly, rough completeness offsite can offer inexpensive options and less-

Table 1. Different levels of offsite construction

Offsite Levels	Description	Characteristic	Category examples
Subassembly (#1)	Items (mostly materials) produced in a factory, but does not create shape	Limited offsite, but rather traditional onsite construction	Brick, tile, prefabricated rebar, mass-timber
2D-Preassembly (#2)	2D-based component, but requires post-process to complete	Most commonly-using methods, post-work to create space(s)	Precast concrete, prefab. cage, cold formed steel, panels, walls
3D-Preassembly (#3)	3D-based component, but requires post-process to complete	Independent spaces, sometimes with structural part	Prefab. pile, scaffold, skeleton, steel parts (e.g., stair, frames), structural nodes
Volumetric system (#4)	3D-based shape with equipped system/services	Independent part of whole structure, ready to use after installation	Facilities, shower booth, module toilet

Note: based on Smith and Quale (2017), Goulding and Rahimian (2019), Hairstans (2010), International Federation for Structural Concrete (fib) (2002), Hong (2019), Knaack et al. (2012), Emmitt (2018), Arif and Egbu (2010), Gibb and Isack (2003).

demanding deliveries, whereas higher levels of offsite construction require considerable planning, information, and related skills while reducing labor costs for on-site installations (Eastman et al., 2011; Moon et al., 2020). This means offsite construction risks could incur expensive process waste when it does not have proper supply chain management.

1.2. Pile installation: Level #3 offsite construction

The case study in the presented paper is about a pile prefabricator and its installation in Melbourne, Australia. Even though the traditional method of pile installation was able to be produced according to the required dimensions, it is known to be time-consuming and expensive (Durdyev & Ismail, 2019). Therefore, the concept of offsite construction was introduced, and it is advancing significantly as the construction industry develops (Chiheb, 2017). Offsite construction enables construction workers to reduce the construction time and cost while reducing construction waste, as the extra material can be reused in the factory (Chiheb, 2017; Durdyev & Ismail, 2019). Studies show that the efficiency, in terms of time and cost, has improved by 34% and 19%, respectively, due to embracing offsite construction instead of the traditional methods of construction (Durdyev & Ismail, 2019).

It is generally inconvenient to produce sections of the original length in a factory since the pile lengths usually go up to a length of 30–40 m or higher (Zayed & Halpin, 2004). Therefore, as shown in Figure 1, the sections are produced in several smaller sections for workable handling in production, transportation, and installation (Luo et al., 2020; Zayed & Halpin, 2004).

The piles are usually lengthy but are managed by designing in pile cage sections of variable lengths (Chen et al., 2018). These are fabricated offsite in a horizontal manner, then transported to a site, lifted with the help of cranes (by one or two, depending on the length of the piles) to the vertical position. These are then lowered to the drilled pile holes. When the cages, being lengthy, are vertical, they are highly susceptible to lateral loads due to wind and other constructional activities (Casey & Urgessa, 2013).

Figure 1. Prefabricated steel piles on the case site (taken by the authors)

The process resource index, such as consumable material measured by length and weight, affects the handling of the pile cages (Atherinis et al., 2017). Proper temporary systems are essential for such situations to effectively resist the transverse loads and to improve rigidity during the construction process. Absence and/or failure of such systems could result in catastrophic scenarios (Builes-Mejia et al., 2010; Casey & Urgessa, 2013; Urgessa et al., 2016). There is difficulty in deciding the level of completeness required for manufacturing cages along the supply chain.

The geometry of intermediate cages does affect the effectiveness of sequenced tasks that could make site work(s) more difficult in utilizing delivered cages. An appropriate lift plan is required considering the weights and geometry of the pile cage, including the anticipated deflections and site constraints (Billodeau, 2010). Consequently, lifting of heavily-weighted cage sections can result in serious problems, requiring a higher number of cranes and handling with more sophisticated temporary supports (Bishop & Uriz, 2015; Bishop et al., 2015; Temporary Works Forum, 2013).

The usual efficiency of the pile installation process is already slow at an average maximum of two piles per day (Metro Tunnel, 2018). This was also evident from the initial observation during the presented research project. The mentioned literature identifies an important aspect that the length and weight do affect pile cage handling on site, but such parameters are not usually considered during the designing phase. This not only creates instability (buckling) issues (Temporary Works Forum, 2013) but also increases the handling costs and the risk of disastrous failures.

The literature review in this sub-section and also in the other sub-sections above ultimately present a research need for analyzing causality between the resource quality of cages and the relevant work efficiency. The consideration needs to be taken during the design phase, to reduce any risk of relevant accidents and to improve work efficiency during site installation.

2. Research gap and problem statement

The research gap of this presented project stems from the increasing numbers of offsite construction. As studied during the previous section, this phenomenon requires high level of supply chain management. The focus of management needs to be advanced from product to process and early stage-involvement between the part manufacturer and the construction site engineer. The indirect cost of inspection and rework would naturally increase the total project costs by approximately 12%, and the additional cost of rework is reported to be six times greater than the

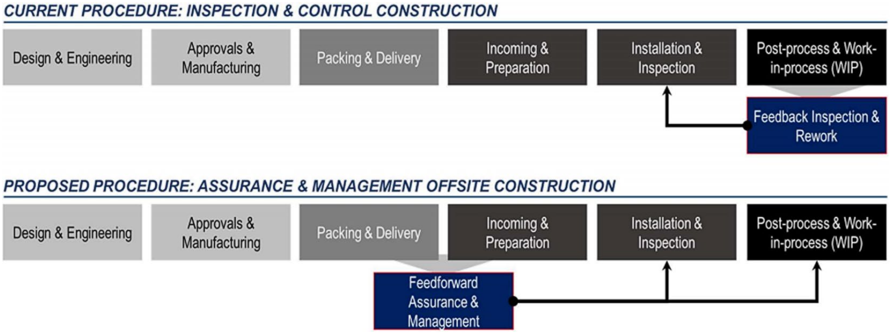

Figure 2. Proactive supply chain model for offsite construction

related recovery cost (Davis et al., 1989; Love, 2002; Eze & Idiake, 2018). Thus, the early-stage involvement and its assured actions are required. Figure 2 presents a comparison between two different implementations. Instead of the current procedure that has the risk of the high additional cost of rework, the field study in this paper presents an implementation of the proposed procedure as shown in the bottom of the figure.

The feedforward data collection is required to do the assurance and management in the case project. From reviewing the relevant traditional methods, the need was also identified to understand and predict the sequenced effect of the earlier entities on following procedures during a project. In other words, the bottom model in Figure 2 presents a proactive mode of action, while the traditional model above focuses on a reactive mode of rework/recovery that could cause an increase of total project duration/cost. In short, this project presents a trial to activate proactive model for a steel manufacturer and their offsite construction projects in Melbourne, VIC, Australia. The on-site performance needs to be compared to the quality of manufactured parts as a causality. This information can result in findings to actualize the concept of holistic management in construction.

The novelty of this project is related to understanding the prefabricated rebar as a process resource instead of a product supplied from a factory. The different arrangement of this resource needs to be assessed and measured as a link to work efficiency during the relevant tasks on site. The lack of this concept keeps generating obstacles in advancing the capacity of SCM in construction, especially for offsite projects. The field study in this paper, thus, presents an example of the offsite construction in Melbourne, and it aims to present an implementation of holistic management in offsite construction.

3. Proposed method

The method in this paper is an empirical study of a case in Melbourne, Australia. This section describes the fundamental principles of this study and its procedure. Four job sites showing similar job properties were selected for experimental consistency. From this selection, 40 operations in the four sites were observed, from pile deliveries to installations.

3.1. Principles of data collection

The initial observation aims to confirm that the current practice of a project in Melbourne shows active aspects of the concept between control and assurance eras. The need that the managerial ranges require can be consolidated to be extended to supplier and customer industries from their supply chains. The second part of the field study is dedicated to gauging the sequenced effect of different process-resource qualities (PRQs) on work efficiencies during the installations. PRQ refers to the measurement of the resource preparedness to ensure a waste-minimized process (Moon et al., 2015).

This quantified effect finally aims to validate the need for assurance and management eras in construction, concerning holistic viewpoints along the supply chain. Work efficiency of the pile installation was measured and analyzed by utilizing access to construction sites, in collaboration with a pile construction company (*anonymity requested*). The PRQ will be measured in conjunction with project-specific requirements. This conjunction allows a comparison of the efficiency of the pile installation across projects as well as in each project.

3.2. Field study procedure

The field study was initiated and designed with an in-depth conversation between observers and site-based staff members. The field study procedure consists of three parts: (1) resource quality identification, (2) measuring operation efficiencies, and (3) data analysis. Firstly, the components of the process resource quality were chosen through the conversation. Further conversation confirmed that the chosen components dictate the installation performance. The specific project requirements and PRQ are shown in Table 2. It was observed that the pile installation heavily depends on the material attributes and their work method. Thus, out of the six requirements in Table 2, four (#2–5) are related to the pile material attributes, and the other two others (#1 and 6) are to do with their installation method. These characteristics were measured and compared to the relevant installation efficiencies.

A continuous time study was adopted to assess the efficiencies of the installation. To accurately measure the efficiency of the installation process, the work activity has also been broken down into individual tasks. The operation of installing the prefabricated steel reinforcement has been broken down into 22 tasks to allow evaluation of the efficiency of the process. The tasks have been separated into five classifications: value-adding effort, contributory effort, ineffective time, unproductive time, and personal time (Bernold & AbouRizk, 2010). The task classifications are shown in Table 3. As shown in the table, the tasks are repeated for each section of prefabricated steel cages. The task list was created with the assistance of pile construction site-based staff through consultation and initial observations on several occasions.

Finally, the records were analyzed to find the causality and identify the sequenced effect of different resource qualities on process efficiency in pile installation. The final analysis aims to identify the root causes of inefficient work conduct by comparing PRQs and measured work efficiencies. After finding the most inefficient work group(s), a further analysis was conducted to determine what factor(s) account for this unacceptable work performance. The Hawthorne effect was additionally considered and mitigated while observing the installation of the prefabricated steel reinforcement sections. To mitigate the risk of the Hawthorne effect, the observer would be positioned at a distance and would be unknown to the subjects (Fernald et al., 2012). In addition, a staff member from the pile construction company assisted with some part of the data collection. This was effective in eliminating the risk of the Hawthorne effect as the work crews had no effect on the research observation.

Table 2. Project requirements and process resource quality

Project requirement/Process resource quality		Measurement unit
1	Number of sections	Numbers
2	Length of pile	Meters
3	Length of longest section	Meters
4	Diameter of pile	Millimeters
5	Weight	Tonnes
6	Method of splicing	–

Table 3. Classification of prefabricated steel installation (extended from Bernold & AbouRizk, 2010; Moon et al., 2018)

Category of work task		Classification
A	Searching for correct cage section	Ineffective time
B	Inspect cages	Contributory effort
C	Move piling rig	Ineffective time
D	Track crane to lay down area	Contributory effort
E	Move materials to access cages	Ineffective time
F	Attach hanging mechanism from top of cage	Value-adding effort
G	Lift cage section and track to pile	Value-adding effort
H	Lower cage section into pile	Value-adding effort
I	Add spacers to cage as it is lowered	Value-adding effort
J	Secure cage section at top of pile	Value-adding effort
K	Splice	Value-adding effort
L	Waiting for next section of cage	Unproductive time
M	Inspect cage in hole	Contributory effort
N	Idle	Unproductive time
O	Lower to correct height and adjust height via mechanism	Value-adding effort
P	Surveyor to setup	Contributory effort
Q	Surveyor to check height	Contributory effort
R	Correct alignment of cage	Unproductive time
S	Unhook	Contributory effort
T	Breaks	Personal time
U	Non work-related communications	Personal time
V	Not observable	Personal time

4. Field studies and validation

4.1. Project description and data collection

In the field studies, four different jobsites that utilize the same piling technique and constructing piles of similar size were selected for the data collection. The number of data sets was dependent on the work hours of the company. 15 set (40 piles in total) of operational data were produced by the collection of data, from the observation on the four project sites. The projects were carried out from different jobsites but conducted by the same contractor. Table 4 presents the list of these operations, including ten three-section operations and five two-section operations. The table includes information about the lengths of each consisting pile and the sequence of splice methods.

Table 5 and Table 6 present two of these data sets. The data from each set was collected using a data collection sheet given to the project member(s). There were two types of operations: three-section and two-section configurations. Table 5 is one of the three-section operations, while Table 6 depicts one of the two-section operations.

Table 5 presents the result of continuous time data. The job of this three-section pile installation started from 12:35 PM and finished at 16:40 PM, taking 4 hours and 5 minutes in total. The total length of the pile was 33.78 m, which consists of three sections: 9, 15, and 9.78 m, respectively. The job was designed in the order of "shortest-longest-middle" length sequence, which means the longest section (15 m) was to be located in the middle of the final completion. The total work durations of each section were: 1 hour and 13 minutes (9 m section); 1 hour and 19 minutes (15 m section); and 1 hour and 25 minutes (9.78 m section). The additional eight minutes stem from two periods of intermission time between the different sections, thereby totaling 4 hours and 5 minutes.

Another sample data of a two-section pile installation is presented in Table 6. The job started at 13:02 PM and was completed at 15:42 PM. It took 2 hours and 40 minutes. The completed pile was 25.7 m long, which consisted of two sections of 15 and 10.7 m, respectively. The

15 m section took 58 minutes, while the 10.7 m section was completed in 1 hour and 42 minutes. It differed from the other sample in Table 5, as there was no intermission time; the two section-installations were carried out continuously. A considerable amount of time in both Tables 5 and 6 was spent on "value-adding effort" and "contributory effort," so it may result in a high performance compared with the traditional understanding of PM. However, in this research, further analysis aims to calculate any unrecognized areas to improve the current work-tendency.

Table 4. Summary of observed operations: Number of sections/lengths/splice methods

	Pile #1	Pile #2	Pile #3	Pile #4	Pile #5
Project #1	Three sections/ 15×8.8×9.12 m/ U-Bolt + Weld	Two sections/ 15×10.7 m/ U-Bolt + Weld	Two sections/ 15×10.92 m/ U-Bolt + Weld	Two sections/ 15×13.12 m/ U-Bolt + Weld	Two sections/ 15×10.7 m/ U-Bolt + Weld
Project #2	Three sections/ 9×15×9.78 m/ U-Bolt + Weld	Three sections/ 12×15×9.78 m/ U-Bar + Weld	Three sections/ 14.1×12×12.2 m/ U-Bar + Weld	Three sections/ 10.5×15×9.1 m/ U-Bolt + Weld	Three sections/ 9×15×9.8 m/ U-Bolt + Weld
Project #3	Three sections/ 15×10.5×8.5 m/ Weld + U-Bolt	Three sections/ 15×12×7.9 m/ U-Bar + Weld	NA	NA	NA
Project #4	Two sections/ 12×7.45 m/ U-Bolt + Weld	Three sections/ 12×15×5.9 m/ U-Bolt + Weld	Three sections/ 12×15×6.7 m/ U-Bolt + Weld	NA	NA

Table 5. Sample data of three section-combined operations, Project #2-Pile #1

Task	Classification	Section 1		Section 2		Section 3	
		Length	9 m	Length	15 m	Length	9.78 m
		Start time	Finish time	Start time	Finish time	Start time	Finish time
A	Ineffective time	12:35	12:45				
B	Contributory effort	12:45	13:15				
C	Ineffective time						
D	Contributory effort						
E	Ineffective time						
F	Value-adding effort	13:21	13:25	13:52	13:57	15:15	15:18
G	Value-adding effort	13:25	13:35	13:57	14:20	15:18	15:28
H	Value-adding effort	13:35	13:43	14:50	15:05	15:40	15:50
I	Value-adding effort	13:35	13:43	14:50	15:05	15:40	15:50
J	Value-adding effort	13:43	13:45	15:05	15:09	15:50	15:55
K	Value-adding effort			14:20	14:50	15:28	15:40
L	Unproductive time						
M	Contributory effort					15:55	16:10
N	Unproductive time						
O	Value-adding effort					16:10	16:17
P	Contributory effort					15:30	15:55
Q	Contributory effort					16:17	16:27
R	Unproductive time					16:27	16:35
S	Contributory effort	13:45	13:48	15:09	15:11	16:35	16:40
T	Personal time						
U	Personal time						
V	Personal time						

Table 6. Sample data of two section-combined operation, Project #1-Pile #2

Task	Classification	Section 1		Section 2	
		Length	15 m	Length	10.7 m
		Start time	Finish time	Start time	Finish time
A	Ineffective time	13:02	13:10		
B	Contributory effort	13:10	13:20		
C	Ineffective time	12:45	13:05		
D	Contributory effort			14:00	14:08
E	Ineffective time				
F	Value-adding effort	13:20	13:21	14:08	14:10
G	Value-adding effort	13:21	13:35	14:10	14:18
H	Value-adding effort	13:35	13:54	14:36	14:51
I	Value-adding effort	13:35	13:54	14:36	14:51
J	Value-adding effort	13:54	13:58	14:51	14:55
K	Value-adding effort			14:18	14:36
L	Unproductive time				
M	Contributory effort			14:55	15:00
N	Unproductive time				
O	Value-adding effort			15:00	15:12
P	Contributory effort			13:50	14:05
Q	Contributory effort			15:12	15:20
R	Unproductive time			15:20	15:40
S	Contributory effort	13:58	14:00	15:40	15:42
T	Personal time				
U	Personal time				
V	Personal time				

4.2. Data analysis

The analysis aims to determine the critical factors from the 15 operations (40 piles) of instances that affect the efficiency of the installation process of the prefabricated steel pile cage sections. The collected samples were collated into a spreadsheet to determine defining factors such as the total time taken to install and how long each section took to install. From analyzing these figures, it was agreed to focus on two separate conclusions: three-section and two-section piles. The data and information were further analyzed to determine the critical factors affecting efficiency.

(1) Work efficiencies of the entire operations

Table 7 presents the measured work efficiencies of 40 pile installations. The data includes the work classification, and it shows a very high efficiency of 66.6% when compared to the traditional onsite construction. At the same time, the data indicates 26.1% of contributory effort while showing just 7.3% of non-value adding effort, with no personal time during the observation. This could be due to the work crew's experience with the installation process and the pile construction company developing a construction procedure with very little process waste.

This pattern also verifies the benefit of using the off-site method, which results in much higher work efficiency when compared to traditional onsite construction. The generally recognized work efficiency in the traditional construction is approximately 20–50% (Thomas et al., 2003; Ellis Jr. & Lee, 2006; Bernold & AbouRizk, 2010; McKinsey Global Institute, 2017; Moon et al., 2018), from which over 15% higher efficiency was measured with the field cases. Even though it shows 66.6% of work efficiency, some of the work tasks can still be minimized to reduce the total work time. For instance, Work task G, H and I are related to handling of the piece of prefabricated pile, which can be further optimized by a proactive control on different PRQs of each pile.

Table 8 summarizes another descriptive analysis of 40 pile installations, which is a comparison for each job requirement and resource configuration, PRQ. The installation of the piles was taken at 39.4 min as an average of the entire jobs from the 15 operations. As expected, the shorted length of pile showed a faster installation by 36.4 min, while the installations of the longest piles took 44.1 min. The two section-installation was smoother than the three-section, by approximately six min of difference, for each installation of an individual pile. In addition, Project #3 had just one job of three-section installation but presented the fastest process among the four different jobsites. Meanwhile, the three other jobsites resulted in similar performance in terms of time-spent, by 39–40 min taken for each pile installation.

Table 7. Work efficiency distribution of 40 pile installations

Category of work task	Classification	Percentage	Total
Splice	Value-adding effort	15.7%	66.6%
Lift cage section and track to pile	Value-adding effort	13.9%	
Lower cage section into pile	Value-adding effort	12.8%	
Add spacers to cage as it is lowered	Value-adding effort	12.8%	
Secure cage section at top of pile	Value-adding effort	4.3%	
Attach hanging mechanism from top of cage	Value-adding effort	4.2%	
Lower to correct height and adjust height via mechanism	Value-adding effort	3.1%	
Inspect cages	Contributory effort	11.0%	26.1%
Surveyor to setup	Contributory effort	5.9%	
Surveyor to check height	Contributory effort	4.3%	
Unhook	Contributory effort	3.4%	
Inspect cage in hole	Contributory effort	1.2%	
Track crane to lay down area	Contributory effort	0.3%	
Searching for correct cage section	Ineffective time	3.2%	4.7%
Move piling rig	Ineffective time	1.2%	
Move materials to access cages	Ineffective time	0.3%	
Correct alignment of cage	Unproductive time	2.6%	2.6%
Waiting for next section of cage	Unproductive time	–	
Idle	Unproductive time	–	
Breaks	Personal time	–	–
Non work related communications	Personal time	–	
Not observable	Personal time	–	

Table 8. Descriptive analysis of 40 pile installations and their resource entities

Groups	Sub-groups	N	Average durations
Length	Short (m < 10)	13	36.4 min
	Middle (10 < m < 14)	13	37.5 min
	Long (14 < m)	14	44.1 min
Number of sections	Three sections	30	40.9 min
	Two sections	10	34.8 min
Different jobsites	Project #1	11	39.0 min
	Project #2	15	40.2 min
	Project #3	3	35.7 min
	Project #4	11	39.7 min
Total		40	39.4 min

(2) Root causes of inefficient work conducts

An important note is that the further data analysis identified a severely ineffective performance (56.7 min on average of ten installations), with the middle section from the 'three sections' operations, as seen in Figure 3. The top section from the two-section-pile also shows a long time spent for the installation, but just by 42.6 min. This analysis presents a verification that the longer worktime from the three section installations stemmed from the middle part of the construction.

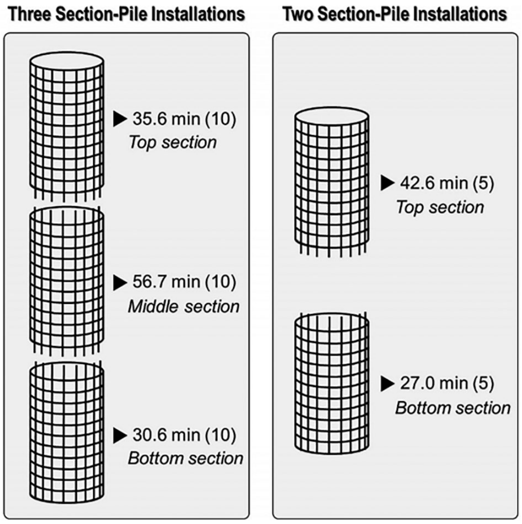

Figure 3. Installation time-spent for each section from two job configurations

The analysis also determined that one of the critical factors affecting the efficiency of the installation process was the location of the longest section in the sequence of the three-section configuration. It was determined that the location of the longest section of prefabricated steel pile cages is a critical factor in the efficiency of the installation. As can be seen in Table 9, it takes nine minutes longer to install the full prefabricated steel pile when the longest section is installed in the middle. The difference in the duration of the middle part installation was 21.8 minutes (= 61.2 – 39.4: total average from Table 8) on average for the total pile cases. When the longest section from the three-section configurations is planned as the middle of the entire three, it resulted in the longest workhour by 61.2 min for each pile installation.

The increased installation time can be attributed to the longer splicing time required when the steel reinforcement section is heavier and longer. The crane must hold the middle section up to allow the splicing to be completed, as seen in Figure 4, so it requires more time due to the extra weight. The longest section of steel reinforcement has been found to be a critical factor in the efficiency of the process of installation.

The data analysis found that there is no significant relationship between section weight/length and installation time for prefabricated steel reinforcement that is made up of two sections. As shown in Table 10, there is no discernible relationship between the section weight of the prefabricated steel reinforcement and the installation time. The installation minutes per ton do not show a pattern across both Section-1 and Section-2. This shows that the weight of the prefabricated steel reinforcement, in the case of the two-section configuration, does not affect the efficiency of the work crews installing the steel reinforcement.

To sum up, the three-section configuration of the prefabricated pile was vulnerable to work efficiency on site.

Figure 4. Lifting of one of the longest pile sections

Table 9. Data analysis of three-section prefabricated steel piles

	Longest section location	
	Bottom	Middle
Average total weight of steel (Tonnes)	11	8
Average total installation time (Mins)	152	161
Average total installation time – middle section (Mins)	45.6	61.2
Average percentage of installation time – middle section (%)	30	38

Table 10. Data analysis of two-section prefabricated steel

Parts		Section weight (tonne)	Section length (meter)	Installation duration (min)	Installation duration/Tonne
Pile 1	Section 1	4.78	15	38	7.95
	Section 2	3.65	10.7	47	12.88
Pile 2	Section 1	1.34	15	21	15.67
	Section 2	1.29	10.9	43	33.33
Pile 3	Section 1	3.06	15	26	8.5
	Section 2	1.68	13.12	46	27.38
Pile 4	Section 1	3.07	15	22	7.17
	Section 2	1.12	10.7	34	30.36
Pile 5	Section 1	2.21	12	28	12.67
	Section 2	1.33	7.45	43	32.33
Total		2.35	12.5	34.8	14.79

Notably, the longest section's location resulted in 21.8 minutes difference in the efficiency measurements. This extended work duration can be addressed by improved quality of the supply chain in a preventive mode. However, the two-section configuration did not show an evident pattern in the installation efficiencies. It can be concluded that the weight of the section does not have a strong causality with work efficiency when it is designed as a two-section installation. The operation is mostly supported by a crane, so it is assumed that the weight is not a critical factor in the work arrangement of one above the other, while the length was a crucial factor with the three-section configuration.

5. Research findings and discussion

This research paper presents a suggested method and describes a field study to demonstrate the concept of the method, proactive SCM. An offsite construction project was selected, and the work efficiency and its relevant causality during pile installation were investigated. The literature review and the initial site observations were able to point out the lack of proactiveness along the manufacturing-delivery-installation of a project. This recognition led the research team to focus on quantifying the sequential effect of the prefabricated piles on a series of processes. The research target stems from the limitation of literature reviews and aims to emphasize the critical factors in managing the offsite construction method.

One of the most significant findings in this research is the ability to discover unrecognized opportunities to further improve the current process. From the data in Table 7, it seems there is a high portion of "value-adding effort" and "contributory effort," but the following data analysis was able to determine the non-negligible effect of the work-sequence. The research findings in this paper also include that: (1) a gap regarding the change of quality recognition was identified between construction and general engineering fields; (2) the offsite construction method requires a higher level of supply-chain management, i.e., transformed definition and perception of the quality; (3) the field study confirms the unmanageable nature of the prefabricated rebar pile when it arrives at the site; (4) early-stage decision/design/planning is critical to the relevant on-site work efficiencies.

Conclusions and research limitation

It was observed that possible problems during an offsite construction stem from the lack of holistic consideration along the supply chain. With the traditional delivery method, most of the processes are carried out on-site, which allows room for possible defects or problems. However, since the offsite method tends to carry out a large portion of the workload from the factories, the room for error is limited. The field study and data analysis in this paper demonstrated this conclusion, with the quantified effect of different qualities on work efficiency.

The research paper concludes that there is a need to extend the managerial range to detect and maximize the expected benefits of offsite construction delivery. 21.8 minutes in the different configurations resulted from chained relations, but at the time of the installation, there was no chance to correct them. The culture of the "zero-sum game" decreases the effectiveness of the industries' effort to introduce offsite construction. During the field study in this paper, it was shown that the problem requires collaboration between supplier and construction site ahead of its execution. The longest section on site can only be re-planned before manufacturing.

Throughout the data collection in this research project, the comparison across projects was limited due to the lack of similar piling projects in construction at the time of data collection. As each work crew has a different experience with regards to the installation of the steel reinforcement for piles, the installation efficiencies might vary. As on a day-to-day basis on a project, the work crews change, and there is not an effective way to quantify these unexpected changes during the data collection. The differing work crews across the projects will affect the efficiency of the installation of the prefabricated steel reinforcement. Other factors, such as the site constraints, were not accounted for in this research study but can affect the efficiency of the installation process and the consistency of the results.

As each site is different in shape and space, the more room that the work crews have would influence the efficiency of the installation process. A relatively smaller and confined site can affect efficiency due to the need to double-handle equipment and materials more often and work at a slower pace. However, a site with more open space can allow work crews to work at a faster pace where damaging other pieces of equipment is less of a problem. Despite the confines of each site being a critical factor in overall efficiency, this factor was not taken into consideration in this research study.

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