AN AUTOMATION APPROACH FOR DATA AND INFORMATION MANIPULATION TO REDUCE KNOWLEDGE AND SKILL REQUIREMENTS IN CONSTRUCTION

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วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต
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พัศพันธน์ ชาญวสุนันท์ : การบริหารจัดการข้อมูลและสารสนเทศโดยกระบวนการอัตโนมัติเพื่อลดความต้องการความรู้และทักษะในงานก่อสร้าง. (AN AUTOMATION APPROACH FOR DATA AND INFORMATION MANIPULATION TO REDUCE KNOWLEDGE AND SKILL REQUIREMENTS IN CONSTRUCTION) อ.ที่ปรึกษาวิทยานิพนธ์หลัก : รศ.ดร.ธนิต ธงทอง, 242 หน้า.

ปัญหาการขาดแคลนบุคลากร โดยเฉพาะอย่างยิ่งบุคลากรที่มีความรู้และทักษะเป็นปัญหาที่มักพบในอุตสาหกรรมก่อสร้าง ผู้ที่เกี่ยวข้องตระหนักถึงปัญหาดังกล่าวเนื่องจากการขาดแคลนความรู้และทักษะส่งผลกระทบต่อผลลัพธ์ที่ได้จากการดำเนินงานก่อสร้างทั้งในด้านระยะเวลา ค่าใช้จ่าย และคุณภาพของงาน ดังนั้น การลดความต้องการความรู้และทักษะของบุคลากรจึงเป็นสิ่งสำคัญต่อการเพิ่มประสิทธิภาพการทำงาน เพิ่มจำนวนของบุคลากรที่มีคุณสมบัติในการทำงาน และเพิ่มโอกาสในการจัดหาบุคลากรเพื่อตอบสนองความต้องการของอุตสาหกรรมก่อสร้าง งานวิจัยนี้จึงมีวัตถุประสงค์เพื่อศึกษาแนวทางในการบริหารจัดการข้อมูลและสารสนเทศโดยกระบวนการอัตโนมัติ เพื่อลดความต้องการความรู้และทักษะในงานก่อสร้าง โดยใช้การติดตั้งชิ้นส่วนคอนกรีตสำเร็จรูปในโครงการก่อสร้างบ้านพักอาศัยเป็นกรณีศึกษา

ความต้องการความรู้และทักษะในงานก่อสร้างขึ้นอยู่กับรายละเอียดขั้นตอนการดำเนินงาน และบทบาทและหน้าที่ของบุคลากร นอกจากนี้ความต้องการความรู้และทักษะจะเพิ่มขึ้นเพื่อรับรู้และดำเนินการแก้ไขเมื่อมีการเปลี่ยนแปลงการทำงานที่แตกต่างจากที่วางแผนไว้ และเมื่อมีข้อผิดพลาดที่เกิดขึ้นก่อนและขณะดำเนินงานก่อสร้าง ดังนั้น การบริหารจัดการข้อมูลและสารสนเทศอัตโนมัติ โดยใช้เทคโนโลยีคอมพิวเตอร์และสารสนเทศร่วมกับระบบการชี้เฉพาะด้วยคลื่นความถี่วิทยุ จึงถูกนำเสนอในงานวิจัยนี้ ระบบการบริหารจัดการข้อมูลและสารสนเทศอัตโนมัติถูกพัฒนาขึ้นจากบทบาทหน้าที่ของบุคลากรและขั้นตอนหลักในการติดตั้งชิ้นส่วนคอนกรีตสำเร็จรูปทั้งสามขั้นตอน ได้แก่ ขั้นตอนการตรวจนับชิ้นส่วน ขั้นตอนการตัดสินใจในการดำเนินการติดตั้งชิ้นส่วน และขั้นตอนการติดตั้งชิ้นส่วน นอกจากนี้ ระบบยังถูกพัฒนาให้ครอบคลุมขั้นตอนเสริมอันได้แก่ ขั้นตอนการตรวจนับทรัพยากรที่มีอยู่ ขั้นตอนการเปรียบเทียบทรัพยากรที่มีอยู่และทรัพยากรที่ต้องการสำหรับการติดตั้งชิ้นส่วน ขั้นตอนการพิจารณาตำแหน่งการทำงานของเครื่องจักร และขั้นตอนการตรวจสอบคุณภาพการติดตั้งชิ้นส่วน ระบบดังกล่าวสนับสนุนบุคลากรในการเก็บข้อมูล การเข้าถึงสารสนเทศ และการจัดการข้อมูลและสารสนเทศโดยอัตโนมัติ รวมทั้งประมวลผลจากสภาพการทำงานที่เกิดขึ้นจริง ณ ปัจจุบันของการก่อสร้าง จากกระบวนการดังกล่าวทำให้บุคลากรสามารถรับรู้สภาพการทำงานที่เกิดขึ้นจริง และดำเนินการตามข้อมูลสารสนเทศที่ได้รับที่นำเสนอในรูปแบบของภาพ ส่งผลให้ความต้องการความรู้และทักษะของบุคลากรลดลง นอกจากนี้ความต้องการความรู้และทักษะของบุคลากรยังลดลงจากการลดขั้นตอนการทำงานโดยกระบวนการอัตโนมัติที่พัฒนาขึ้น ซึ่งส่งผลต่อระยะเวลาและคุณภาพของการดำเนินงาน

ภาควิชา วิศวกรรมโยธา ลายมือชื่อนิสิต ....

สาขาวิชา วิศวกรรมโยธา ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก ....

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PHATSAPHAN CHARNWASUNUNTH : AN AUTOMATION APPROACH FOR DATA AND INFORMATION MANIPULATION TO REDUCE KNOWLEDGE AND SKILL REQUIREMENTS IN CONSTRUCTION. ADVISOR : ASSOC. PROF. TANIT TONGTHONG, Ph.D., 242 pp.

The lack of personnel, especially knowledgeable and skilled personnel, always arises in the construction industry. This issue highly concerns the stakeholders and related personnel in the industry because it leads to prolonged construction, cost overrun, and lower quality of structure construction. Therefore, the reduction of knowledge and skill requirements is important in order to increase productivity, increase the number of qualified personnel, and supply personnel to the construction industry. Thus, this research aims to explore the automation approach for data and information manipulation to reduce knowledge and skill requirements in construction. The installation process of prefabricated members in residential projects was selected as a case study.

The knowledge and skill requirements depend on the construction processes and the roles and responsibilities of related personnel. In addition, the changes and mistakes increase the level of knowledge and skill requirements in the construction processes to perceive and select countermeasures. Thus, an automation approach for data and information manipulation, which is the integration of computer and information technology with Radio Frequency Identification (RFID), is proposed in this research. The approach was developed from the roles and responsibilities of related personnel and the three main steps of the installation process, specifically, checking the available prefabricated members, making a decision for an installation process, and installing the prefabricated members. Moreover, the approach covers four supplementary steps, which are checking the availability of other resources, comparing the required resources and the available resources, deciding the work location of the mobile crane, and inspection of installed prefabricated members. The approach offers support to personnel in collecting data, accessing information, and manipulating the data and information. In addition, the approach processes the data and information based on the current conditions. With this scheme, personnel perceive the actual conditions and perform the operation based on the provided information, which is displayed in graphical format. Some of the actions in an installation process were replaced using the processes of an automation approach. Thus, the knowledge and skill requirements of personnel can be reduced. This reduction affects the duration and quality of construction processes directly.

Department : Civil Engineering Student's Signature ....

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Chapter 1
Introduction

1.1 Introduction

In most countries, the construction industry is very large in terms of investment, capital expenditure, the number and size of firms, and the size of employment. Consequently, construction is one of the most influential industries affecting the national economy as a whole. Thus, investment and expenditure from construction activities have been used in many countries to recover from an economic crisis (Nixon, 2003). As part of the construction industry, most construction projects tend to have a high level of investment and employment; accordingly, inefficient processes in each project could considerably affect the large sum of money, the large number of human resources, and the company competitiveness.

Today, the business environment of the construction industry has become more and more competitive due to the increasing number of local and foreign construction firms, higher resource costs, demand for speedier construction and lower prices from the owner. All of these tendencies have influenced the construction firms respectively on the way of contract award, project delivery, profit making, and survival tactics. Therefore, almost all construction firms must augment the competitiveness by, for example, inventing new construction methods, creating new materials, adapting to better tools and equipment, improving productivity, and raising collaboration efficiency. However, these augmentations may not always give the expected results because human resources still plays a major role in the construction process and significantly affects the construction outcome.

1.2 Problem statements

1.2.1 The lack of human resources

Construction is a labour-intensive industry (Shehata and El-Gohary, 2011), in other words, an industry that requires a large number of workers, mainly depending on the economic conditions. Generally, in good economic times, the demand for the construction of buildings and facilities is high. Therefore, a considerable number of people working in construction activities are required (Lim and Alum, 1995). In contrast, during the recession period, the need of construction structures is decreased and the construction activities are restrained. Thus, the required number of human resource decreases. However, the construction sector is used for economic crisis recovery, particularly by allowing the circular flow of spending through construction activities. Both of the economic situations lead to the need of human resource in construction industry. Therefore, the lack of human resource always occurs in the construction industry. Moreover, labour availability was rated as the critical issue for builders and construction industry (Carliner, 1998).

The fluctuation of the required human resource does not depend only on the changing economic condition. In Thailand, the change in workforce depends also on the agricultural industry, i.e., some labours work in the agricultural sector during the certain time, and temporarily work in the construction industry for other periods. Thus, the supply of human resource especially labour drops in seedtime and harvest season.

1.2.2 The quality of human resource

The classification of construction industry is considered to fall between the manufacturing industry and service industry. Thus, the results of construction depend on the quality of personnel (Barrie and Paulson, 2003). In addition, construction is considered as a human-driven process. The quality of human resource directly affects the effectiveness and efficiency of the construction processes, which reflect on construction duration, cost, and quality. According to the embedded knowledge and intellectual ability in personnel, the personnel were referred as the greatest asset of any organisation (Carrillo, Anumba, Kamara, 2000). Generally, the quality of human resource is regarded in terms of knowledge, skills, and attitude.

The shortage of skilled workers are occurred from several factors, i.e., decreased real wages, transient nature of work, poor industry image, lack of training, and lack of a worker-oriented career path (Castañeda, Tucker, and Haas, 2005). The unskilled workers and supervisors tend to cause the undesired low productivity (Lim and Alum, 1995).

With regards to knowledge, it is an important part which is embedded in the personnel. Different types of knowledge and skill are required in different positions since each individual is assigned to different roles and responsibilities. The requirements of knowledge and skill are not only for the workers, who operate the construction tasks directly. The other positions such as foremen, machine operators, inspectors, and supervisors, also require the knowledge and skills for supporting their works.

Personnel with little or no knowledge and skill of the current construction methods will require some level of training in order to achieve the knowledge and skill requirements. However, the learning period has to be considered because these construction personnel cannot perform well during this period. Efficiency and effectiveness are directly affected by inadequate knowledge and skill, and mistakes tend to occur. Moreover, in case of on the job training, the quality of trainer is important because the quality of trainee depends on the knowledge, skills, attitude, and information that are transferred from the trainer. On the other hand, the training based mainly on the document may not cover all the scenarios that could occur at the real construction site.

1.2.3 Change in construction process

Changed condition is a condition that is different from the original plan created by the planner or the designer before execution. Such changes may occur due to various reasons, such as unavailable construction resources, inaccessible spaces, and different processes, etc. The changes affect the construction in terms of process, construction duration, resource usage, and construction result.

In order to deal with the changes in the current process, the knowledge and skills of personnel or the collaboration with the knowledgeable and skilled personnel are needed. Without the adequate knowledge and skills, the personnel cannot perceive the change and select the countermeasure properly in a timely manner. Therefore, the personnel cannot perform the efficient work consequently causing misunderstanding, low productivity, mistake occurrence, and problem solving inability.

The problem statements, i.e., the lack of human resource, the quality of human resource, and the change in any construction processes, could level up the importance of knowledge and skill reductions in the construction industry.

1.3 Motivation

The computer has been widely used in the construction industry. In the design stage, the computer is employed as Computer-Aided Design (CAD) and it is served as Computer-Aided Manufacturer (CAM) in the manufacturing process. In addition, the information technology and automation are also applied in the pre-construction processes. The examples are the automated manufacturing of construction materials and prefabricated members. The processes have changed from the handmade manner to semi-automatic or automatic process, which means the process mainly relies on the system. However, the construction processes at the site still depends on the labour and related personnel.

For knowledge requirements, the knowledge falls in the spectrum of tacit and explicit knowledge (Nonaka, Konno, and Toyama, 2000 cited in Pathirage, Amaratunga, and Haigh, 2007). Thus, the knowledge can be stated as the information provided to the related personnel. As a result, the integration and usage of computer, information technology, and automation approach are the motivation of this research in order to reduce the knowledge requirements.

1.4 Hypothesis

According to the problem statements and motivations, a hypothesis is created in this research as follows: “If the appropriate information is provided to the personnel, the requirements of personnel’s knowledge and skills can be reduced. The productivity and the number of mistakes in the construction process can then be improved.”

1.5 Research objectives

The main objective aims to propose an automation approach for data and information manipulation, which reduces the requirements of personnel’s knowledge and skills. The research includes sub-objectives as follows:

1) To investigate the data and information flows and the knowledge and skill requirements in construction processes
2) To propose the concepts and model for data and information manipulation to reduce the knowledge and skill requirements in construction processes

1.6 Scope of study

The prefabricated construction has become increasingly popular in Thailand and many other countries because of the high expectation in terms of construction period, cost, quality, or consistency of result. The prefabricated housing construction projects were selected as the case study because of the increasing number of usage, the repetitive work characteristic, the sequential work characteristic, the continuity of work, a number of related personnel, and the complication of work. The studied process in this research is only the prefabricated member installation process. The manufacturing and transportation of prefabricated members are not included in this research though. In addition, only the load bearing wall type of prefabrication is studied. Other systems of prefabricated members, such as columns and beams, and architectural prefabricated members, are excluded.

1.7 Limitation

The automation approach was developed based on the current practices of the installation process of prefabricated members in sample projects. Therefore, the data and information shown in the proposed automation approach may not be appropriate in other projects considering the different personnel roles and responsibilities, work processes, structural details, etc.

1.8 Research methodology

The research methodology in this research consists of the following eight major steps:

1) Survey construction projects for primary data and information that relate to the current practices and problems. The site observation and personnel interview were employed in this step. At the end of this step, the participants, work processes and problems in the installation process of the prefabricated members were identified.
2) Review the literatures, including the construction industry, the prefabricated construction, knowledge and skills in construction, and technology in the construction industry.
3) Collect the data using site observations, document reviews and interviews in six construction projects. The detailed data and information comprised of project details, personnel roles and responsibilities, working details and technical knowledge, resource requirements, quality assurance and control details, and current problems.
4) Analyse the current practices by breaking down the installation process to three main steps, and four supplementary steps. Each installation step was further broken down for the activities. Then, the action flow of each personnel in an activity was created.
5) Analyse the knowledge and skill requirements by considering the action flow of personnel in each step of the installation process. In each action, the physical action, including related data and information, were considered for knowledge and skill requirements. The requirements also considered the changes and the mistakes in the installation processes.
6) Develop the automation approach by using the knowledge and skill requirements of personnel and the current practices as the main skeleton. Therefore, the automation approach was developed based on the main and supplementary installation steps. The related resources in the approach include the personnel, materials, especially prefabricated members, tools, and equipment.
7) Evaluate the automation approach. There were three phases of evaluation, i.e., (1) evaluation by the prefabricated member models, (2) evaluation at the construction site, and (3) evaluation by the experts. Each of which have different objectives, advantages, and limitations.
8) Summarise and discuss the results of this research. Moreover, research contributions, adaptation for the other construction methods, and future works are also described.

1.9 Research contributions

From this research, the contributions are as follows:

1) Knowledge and skills, which are required in the installation process of prefabricated members. These requirements may be used for the training or the requirement reduction.
2) The automation approach, which aims to improve the productivity and reduce the number of mistakes. Both of them affect the efficiency and effectiveness of prefabricated construction.
3) The new idea for raising the automation degree in the construction process. For example, in the prefabricated construction, the production phase is using automation or semi-automation process while the construction at the site is still labour-intensive process. The automation approach reduces the dependency of personnel's knowledge and skills. In addition, the approach increases the automation degree in the construction process. Thus, the gap of automation degree between manufacturing process and construction process will be bridged.

Chapter 2
Literature reviews

2.1 Introduction

In this research, the related literatures were reviewed by studying journal articles, textbooks, conference proceedings, theses, dissertations, and related publications. The literatures are categorised into four groups as follows: (1) construction industry, (2) prefabricated construction, (3) knowledge and skills in construction, and (4) technology in the construction industry. The synopsis of each category is described as follows:

2.2 Construction industry

2.2.1 Overview of the construction industry

The construction industry is an important part of national economies. It plays a major role in sustaining the economic growth and helping the national economy recover by generating a major source of jobs, a large contribution to the Gross Domestic Product (GDP), and a major purchaser of manufactured products (Nixon, 2003).

Generally, the construction industry consists of four main construction types, namely residential, building, heavy engineering, and industrial, each of which has its own special needs, characteristics, participants, and clients. This research focuses on residential construction.

Residential construction in the Unites States averages 30-35% of construction expenditures in an average year. This type of construction requires low capital and modern low technology. Thus, residential construction is operated by a large number of very small firms and field labour-intensive construction methods. However, it has a slow growing trend towards industrialisation (Barrie and Paulson, 2003).

For the construction industry's characteristics, the industry is considered to be large, diverse, unique, and complex. Russell (2009) presented that the construction industry's characteristics involved transient nature, dynamic, lack of data, lack of standardisation, non-repetitive, and a large number of participants. In addition, the construction industry also has the following characteristics: low capital investment, instability, geographic dispersion, small size of firms, seasonal nature, low labour costs, labour unions, liability, lack of skills, and lack of resources (Haas et al., 2002). It is these characteristics that differentiate construction from other industries.

Compared to other industries, construction is said to be the gap between the manufacturing industry and the service industry, as some of its characteristics are similar to the manufacturing industry and some are similar to the service industry. An obvious example is personnel quality dependence, which is also indicative of the service industry. Personnel quality dependence means the quality of personnel that affects the success or failure of the work (Barrie and Paulson, 2003).

2.2.2 Industrialisation concept for the construction industry

Industrialisation aims to produce and supply quality products to a large number of people by process simplification. It leads to quality improvement and cost reduction. Even the construction processes are unlike the manufacturing processes; the construction industry tries to step up for the completed industrialisation to fit the large number of needed quality construction facilities. Industrialisation is divided into five degrees: (1) prefabrication, (2) mechanisation, (3) automation, (4) robotics, and (5) reproduction. These five degrees of industrialisation are summarised as shown below and in Figure 2.1.

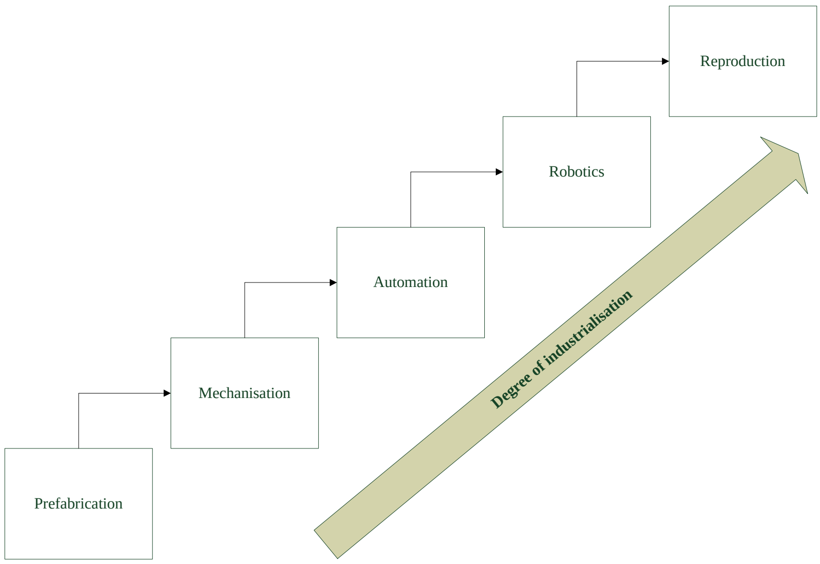


Figure 2.1 Five degrees of industrialisation (Richard, 2005)

Prefabrication refers to the method that some work or some parts are done in advance or elsewhere. Prefabrication normally employs the same process and materials as the conventional method. However, it has some advantages, such as the reduction of climate effects, improvement of quality control level, the continuation of production rate, use of semi-skilled labourers, and the procurement of large quantities of materials. On the other hand, the need for special tools or equipment is one of the disadvantages of prefabrication.

Mechanisation is the use of mechanical tools or equipment to simplify the work of personnel, such as a pneumatic hammer in the manufacturing process of precast concrete. In addition, prefabrication usually accompanies some mechanisation.

According to automation, the tasks of labour work are taken over by the automation system. However, the supervisor and engineers still work around this system.

The robotic system was developed to work with flexibility. It works for "mass customisation", in which individual products are created in mass production.

The reproduction system focuses on process simplification instead of technology investment. It is an innovation that creates a shortcut for repetitive operation (Richard, 2005).

One of the examples of using the industrialisation concept in the construction industry is the manufacturing of prefabricated members. The prefabricated members are made in a factory, with the application of the principles of mass production and mass customisation (Neelamkavil, 2009).

2.2.3 Problems in the construction industry

Many problems occurred in the construction industry. The lack of personnel as well as the lack of knowledge and skilled workers always arises. From the prediction by the Construction Institute of Thailand, the value of Thai construction in 2012 will be 930 billion baht, which is leveled up 15% from the previous year. The main problem at the moment is the lack of labour. The industry needs 80,000 to 100,000 more labourers, over 2.6 million labourers in the first quarter of 2012 (Matichon, 2012).

The lack of skilled personnel was of considerable concern to industry stakeholders (Castañeda, Tucker, and Haas, 2005). A shortage of skilled labour was stated in several countries, such as the United States (Carliner, 1998; Olsen and Tatum, 2012), Singapore (Lim and Alum, 1995), and South Africa (Makhene and Thwala, 2009).

The shortage of skilled labour in the North American industry was predicted in the early 1980's. This prediction was confirmed by a survey conducted by the Construction Users Roundtable (CURT) in 1996, which found that 60% of the respondents faced skilled labour shortages and 75% of the respondents also indicated that the shortage was worse than the last five years (Business Roundtable, 1997 cited in Wang et al., 2010).

Many reasons led the construction industry facing a shortage of skilled workers, namely low wages, the transient nature of work, poor industry image, lack of training, and lack of a worker-oriented career path (Castañeda, Tucker, and Haas, 2005). Makhene and Thwala (2009) studied the reasons for the skilled labour shortage in South Africa. The reasons include the retirement of personnel in the 1950s and 1960s and the fact that young people are not interested in working in the construction industry because of the work conditions, the hours of work, and the flexibility to travel. Another reason is because the workers did not get enough training and continual development because they were hired as temporary employees. The lack of training and development for personnel often leads to difficulty in closing the barrier between unskilled labour to skilled labour and between inexperienced labour to experienced labour. Inexperienced labour can lead to a prolonged construction schedule and improper installation of components (Koota, 2003), all of which could greatly affect the overall project performance.

2.3 Prefabricated construction

2.3.1 Prefabricated materials

Prefabricated materials or fabricated materials are one of the three categories of construction materials. The other two types of materials are bulk materials and manufactured standard materials. The example materials in each category are shown in Table 2.1. Bulk materials require little or no fabrication for a project, while manufacturing standard materials require some fabrication, and prefabricated materials are fabricated to the unique requirements of a project. According to prefabrication level, manufacturing standard materials and prefabricated materials must be installed at the location that is designed or stated in drawing with the suitable procedure and sequence (Halpin and Woodhead, 1998).

Table 2.1 The examples of materials in each category (Halpin and Woodhead, 1998)

Bulk materials	**Manufacturing standard materials**	**Prefabricated materials**
- Paving material - Fill material - Form material – plywood, post shore, etc. - Ready mix concrete - Wire mesh	- Fencing material - Formwork system – metals and fiberglass pans, column forms, etc. - Waterproofing product - Metal-framed windows	- Fire alarm - Concrete reinforcement - Structural steel - Precast panels and decks - Sheet metal work - Hollow metal doors and frames - Wood and plastic laminated doors

2.3.2 Precast Construction

Precast construction is a type of prefabricated material as shown in Table 2.1. Precast construction has been widely used in residential construction because of its advantages. It was employed to improve productivity and quality, as well as reduce costs (Dawood, 1998). Several precast constructions were just-in-time concept implementations, large in panel size, and the increasing number of panel delivery (Ergen, Akinci, and Sacks, 2007). Not only are the advantages of prefabrication characteristics described above but the details of other advantages and disadvantages are also described in Table 2.2 and Table 2.3 respectively.

When focusing on the overall process, Cheng and Chen (2002) mentioned that the installation process is a major critical path for precast building construction. Construction conflict and project delay can be significantly reduced by an efficient lifting schedule and control plan. In addition, Dawood (1996) proposed that prefabrication and off-site manufacturing could increase the productivity and quality in construction. However, the processes are rather time consuming and need experts in design, manufacturing, and erection because of the high complexity, fragmentation, and manually intensive. The erection sequence is affected by structural factors, safety, production technology, and site conditions. Thus, an integrated intelligent planning approach is proposed in order to generate production plans, and simulate manufacturing processing and sequence. The approach includes the architectural and structural drawings, detailed erection, and production schedules between related parties.

2.3.3 Information in precast construction

Information flow in precast construction is different from material flow. In the process, material flow is unidirectional by transferring the materials from upstream to downstream. Meanwhile, information flow is bidirectional. The information in precast construction flows between an upstream supplier, manufacturer, erector or general contractor, and owner. Communication between an organisation uses paper documents, telephone, fax, and electronic data. Precast construction faces poor information flow problems, i.e., unavailable information and difficult access of information. The problems are divided into two approaches as follows: (1) the information is collected by different organisations. Thus, it makes more difficult and inconvenient for other organisations to access some of the information, and (2) the information is transferred to related organisations. The information is still in the creator’s format, which cannot be read or easy to access. Thus, the information is categorised into three groups: status information, shipping information, and handling information. The details of each group are as follows:

Table 2.2 Advantages of prefabrication (Gann and Senker, 1993; Tobarameekul, 1997; Rattanachai, 2000; Neelamkavil, 2003; Richard, 2005)

Advantages of prefabrication
Increase more cycle of formwork usage because of specific type and size of members
Reduce concrete waste in concrete transportation and pouring
Produce full size mock up, which enables to test and solve the problems
Improve the quality because the works are in the controlled environments
Reduce the impact of labour shortage problem by using technology and machine in manufacturing and erection processes
Reduce construction duration because manufacturing and installation processes can be done as parallel work
Reduce the operations and the store at the construction site
Reduce the architectural works. Precast member does not need plastering and can be painted after erection instantly.
Reduce of dust and noise pollution at the construction site
Reduce the usage of water and electricity at the construction site
Reduce energy consumption by the heat and noise insulator characteristics
Reduce the construction cost by less construction duration, waste, indirect cost, labour cost, and interest fee

Table 2.3 Disadvantages of prefabrication (Gann and Senker, 1993; Tobarameekul, 1997; Rattanachai, 2000; Neelamkavil, 2003; Richard, 2005)

Disadvantages of prefabrication
Limit the variation of structure
Require the up-front time for design and production
Need a high amount of investment in terms of factory, tools, and equipment
Need high skilled personnel for formwork process because the need of high precision panels
Limit in transportation by timing and weight of deliver truck
Find the contractor difficulty because of high investment and special technique requirements
Affected by the lack of material and lack of stocking area, which lead to erection problem, because precast construction is sequential construction
Affect the success of precast construction significantly by the lack of skilled labour
Need the training for installation process because the process is the sequential process
Need a high skill level of machine operator to cope with the high precision work
Require the space for installation
Modify the structure difficulty
Resist from the buyer, who has conservative mind

Status information: This involves the status of material, drawing and component, drawing status, material status, quality control results of component, and component status.

Shipping information: This consists of two main parts: material order and component delivery. Material order is the integration of daily concrete order, daily cement and aggregate order, rebar and hardware order and confirmation. While component delivery is the integration of erection sequence, load list, daily load list, daily delivery schedule, and the waybill.

Handling information: This consists of handling instructions, weight, quality control, and inspection result.

Information flow has six different actions, which include create, receive, update, transfer, access, and store. However, the information does not totally flow from the upstream supplier to the owner. The flow depends on the topic of information. Some information flows from the manufacturer to the owner, while some information flows between the upstream supplier and the manufacturer (Ergen and Akinci, 2008).

2.3.4 Knowledge in prefabricated construction

Based on the study of Dawood (1996), modular construction required data exchange between design, manufacturing, and the erection processes because the activities were highly complex, fragmented, time consuming, and demand expert personnel.

Charnwasununth (2006) proposed that recent documents prepared at the construction sites, such as the schedule, daily schedule, and construction drawings, are inadequate to transfer the information from planners to site supervisors or operators. And it can be one of the reasons why operations at construction sites may not reach the desired results as planned. Therefore, installation-based scheduling is proposed for prefabricated construction. The schedule composes of five components: (1) materials and tools, (2) installation sequence of prefabricated members, (3) activity and sub-activity schedule, (4) troubleshooting, and (5) integration schedule. For each activity and sub-activity, it covers activity and sub-activity, schedule and duration, labour and machine requirements, construction methods, activity cautions, working areas, and quality specifications. The information is shown in the graphical format, which can provide a better understanding to operators.

For the installation sequencing, there are many studies related to sequencing in construction processes. Echeverry, Ibbs, and Kim (1991) studied on the sequencing knowledge for construction scheduling. The four main factors related to sequencing in scheduling phases were revealed as (1) physical relationship among building components as shown in Table 2.4, (2) trade interaction as shown in Table 2.5, (3) path interference for the component to be installed and the equipment and personnel for transportation and installation, and (4) code regulation by the safety of workers and the general public as well as quality inspection of work.

Table 2.4 Physical relationship (Echeverry, Ibbs, and Kim, 1991)

Physical relationship	**Description**
Supported by	A component supports to another one directly in order to against gravity force.
Covered by	A component covers another component.
Embedded in, contributing to structural function	A component has to be inside another component for structural function.
Embedded in, noncontributing to structural function	A component is embedded into another but it is not for structural function.
Relative distance to support, with flexibility of installation	A component, which is closer to support, is installed first. After that, the flexibility of installation is determined.
Relative distance to access	If the component obstructs the access, the farthest component should be installed first and the closest component is installed in the last sequence.
Weather protected by	The protected component should be installed after the installation of protecting component.

Table 2.5 Interaction type (Echeverry, Ibbs, and Kim, 1991)

Interaction type	**Description**
Space competition	Two crews compete for same space.
Resource limitation	Two crews compete for same limited resource.
Unsafe environment effects	A work leads to unsafe environment effects.
Damaging of installed building components	A work might damage other works.
Requirement of service	A crew requires a service, such as the approval, test, and inspection.

Kähkönen (1993) was referred in Dawood (1996) for the factors, which affect the erection sequence of precast members. The details of the decisions and the affecting factors are shown in Table 2.6.

In addition, Kineesee (2006) proposed that personnel in prefabricated construction require additional skills from the conventional construction method. The erector is defined for the personnel, who install the prefabricated members. The additional skills include interpreting construction drawings, hand signal communication, installation sequencing skills, prefabricated member installation, and the operation skill for special equipment and tools.

Table 2.6 The details of decision and affecting factors (Kähkönen, 1993 cited in Dawood, 1996)

Decision	Affecting factors
Sequence of project locations	Contractual, and site conditions
Sequence of precast units	Structural, safety, erection technology, and site conditions
Overlap of erection	Erection equipment and resources, work area, and safety

2.4 Knowledge and skills in construction industry

Construction is a knowledge-based industry. The activities of the construction industry demand an increased level of knowledge, skills, and learning (Egbu and Robinson, 2005).

2.4.1 Knowledge

Carrillo, Anumba, and Kamara (2000) said that knowledge incorporated various definitions, such as much more than information, a dynamic human process of justifying personal belief towards the truth, know-why, know-how, and know-who, and an intangible economic resource from which future revenues will be derived.

Knowledge was defined and classified into formal (explicit) and tacit (expertise), foreground and background, personal, share, and public, practical and theoretical, hard and soft, or internal and external. The classification depends on the functional roles of knowledge within the organisation or the roles of knowledge for business relevance (Carrillo, Anumba, and Kamara, 2000; Pathirage, Amaratunga, and Haigh, 2007)

Tacit and explicit knowledge are the most common and practical ones. Tacit knowledge is based on the individual experience and expressed in human actions. Thus, it is difficult to articulate. For explicit knowledge, it can be stated in manuals, documents, or database. However, it is difficult to find the knowledge that is totally classified as tacit or explicit. Knowledge falls in the spectrum of tacit to explicit knowledge (Nonaka, Konno, and Toyama, 2000 cited in Pathirage, Amaratunga, and Haigh, 2007).

2.4.2 Skills

Felstead and Green (2008) studied the skills at work in Northern Ireland, in which 7,787 respondents were surveyed in 2006 in a questionnaire. The sample group worked in the production and service industries, both in the private and public sector. Skills were categorised into three types: broad skills, computer skills, and generic skills. Broad skills refer to the education level, training time and learning time.

Computer skills are used for computerised or automated equipment, essential computerised equipment, complex use of computers, and Internet use. The generic skills composed of literacy skills, physical skills, number skills, technical know-how, influence, planning, client communication, horizontal communication, problem solving, checking skills, aesthetic skills, emotional skills, and management skills, each of which are briefly described in Table 2.7.

Table 2.7 Generic skills (Felstead and Green, 2008)

Generic skills	Description
Literacy skills	Read and write forms, notices, memos, signs, letters, short and long documents, etc.
Physical skills	Use of physical strength and/or stamina; use one's hands
Number skills	Mathematic calculation
Technical know-how	Know how to use tools or equipment or machinery, know about products and services, use one's hands
Influence	Persuade or influence others, instruct, train or teach people, make speeches or presentations, write long reports, analyse complex problems in depth, and plan the activities of others
Planning	Plan the activities, organise the time, and think ahead
Client communication	Sell a product or service, counsel or care for customers or clients, deal with people, know about products and services
Horizontal communication	Work with a team of people, listen to colleagues carefully
Problem solving	Detect, diagnosis, analyse and resolve problems
Checking skills	Notice and check for errors
Aesthetic skills	Look and sound the part
Emotional skills	Manage own and handle other's feelings
Management skills	Motivate subordinate staff, control resources, coach, develop careers, make a decision

2.4.3 The effects of knowledge and skill

Nowadays, knowledge is a key role in the fast changing business environment. Knowledge also supports efforts towards a sustainable business (Pathirage, Amaratunga, and Haigh, 2007). Innovation and management of knowledge assets bring opportunities to business, i.e., increasing market share, and improving productivity and profitability. However, many challenges have developed from global competition, changing levels and patterns of the demands of clients, customers, and the society, as well as the changes in information and communication technologies (Egbu and Robinson, 2005).

Lim and Alum (1995) surveyed the issues that related to the Singapore construction productivity. The inefficient manpower deployment was caused by a shortage of skilled workers and supervisors, a large unskilled foreign workforce, and a weakening local workforce base. The most three concerned issues were (1) difficulty in the recruitment of supervisors, (2) difficulty in the recruitment of workers, and (3) a high rate of labour turnover.

The shortage of skilled workers tends to cause five categories of impact: (1) lower productivity, (2) higher project costs, (3) lower safety, (4) lower quality, and (5) higher supervision requirement (Olsen and Tatum, 2012).

Shehata and El-Gohary (2011) classified the factors that influenced labour productivity. These include (1) industry related factors, (2) management related factors, and (3) labour related factors. The details are shown in Table 2.8. It can be seen that the skill of labour is one of the important factors affecting productivity.

Table 2.8 Factors that influence labour productivity (Shehata and El-Gohary, 2011)

Source	**Factors**
Industry related factors	Design repetition, design complexity, building codes, construction technology, laws and regulations, job duration, size of the job, type of job, adverse, uncertain weather and seasonality, and site location
Management related factors	Planning and scheduling, leadership, motivations, communication, level of on-site management and coordination, job security, labour experience, workmen’s long-term pacing, delays, breaks in work, and the flow of men and materials.
Labour related factors	Labour skills, motives, and labour availability

2.5 Technology in construction industry

Technology plays a major role in everyday life and in the industry sectors. The examples of technology are computer technology and its applications, laser, Global Positioning System (GPS), and identification technology. In addition, the robotics or automation systems are advancing to operate the workload at the construction site, such as road lane painting robot (Woo et al., 2008), brick laying robot (Yu et al., 2008) and bridge inspection robot (Oh et al., 2009).

2.5.1 Computer technology

In the construction industry, personnel usually use sheets of paper to perform outdoor jobs. This approach creates a gap between the outdoor construction site and the indoor office in terms of duplex, lack and confusion of data, which could limit the efficiency of construction (Kimoto et al., 2005). Saidi, Haas, and Balli (2002) mentioned the usage of handheld computers in the construction industry. The accuracy and timeliness of the information is important for construction activities. Thus, the unavailable, inaccurate and outdated information could cause delay and unnecessary rework in construction activities.

Computer technology has been employed in construction in various aspects, such as decision support system (Shen et al., 2003), data collection, information providing, object identification, and data acquisition.

According to a study by Zhai et al. (2009), information technology (IT) positively affects construction labour productivity. The vision for future construction sites was proposed that job sites would become more intelligent and integrated. The use of IT helps deal with the shortage of skilled labour in the construction industry, although the labourers may not be the direct users of IT applications. Still, the labourers will benefit from the quality and timeliness of information.

Handheld computers can help and support information to be more accurate, reliable, timely, accessed at any location to reduce the time for supporting the work, and amount of idle time. The handheld computer was developed for six construction field activities: punch listing, material tracking, material safety datasheet access, request for information, drawing access, and quantity surveying (Saidi, Haas, and Balli, 2002).

The use of a mobile computing system offered benefits to construction management. In an experiment by Kimoto et al. (2005), the level of productivity improved thanks to the mobile computing system for the inspection process. The system consisted of four systems and two programs, including the inspection system, checklist and reference system, position check system, the progress monitoring system, data input program in personal digital assistant, and output program in personal computer. In the inspections of 30 dwelling units, the system improved the productivity of the inspection process, especially in marking instructions, the printing of instructions, and collection of data. However, this system required more time in the preparation stage as shown in Figure 2.2. The developed system could affect the mobility of information, the elimination of gap in time and space, the increase of productivity, and the linkage of existing computer-aided engineering (CAE) tools. The current personal digital assistant (PDA) technology meets the construction work's requirements, which are the mobility of hardware, durability of hardware, compatibility of hardware and operation system, compatibility of data between the mobile and personal computer, expressivity of display, stability of system, operability of user interface, processing speed, and continuous computing environment.

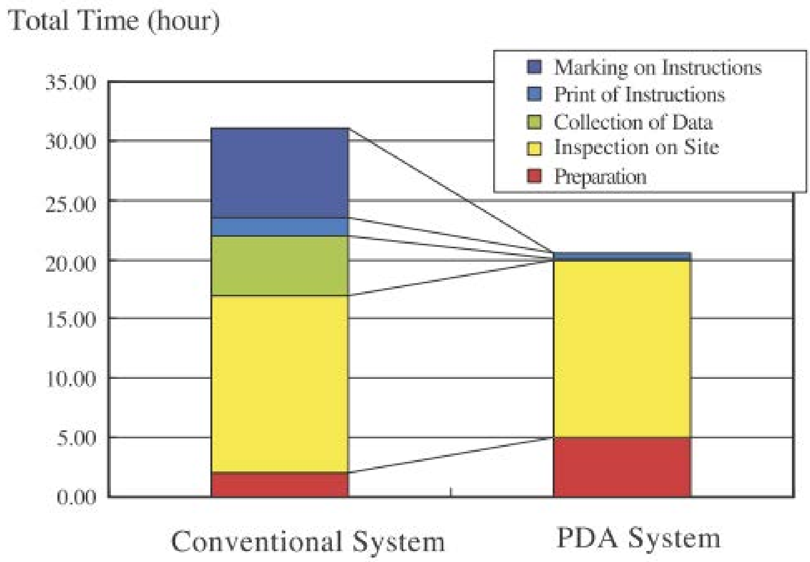


Figure 2.2 Comparison of process duration (Kimoto et al., 2005)

However, similar to the technology implementation in the construction industry, the implementation of handheld computers carries the barrier of technology limitation and the construction industry's characteristics, such as the specific nature of construction project, competitive bidding system, fragmentation and low risk tolerance, schedule pressures, conservatism, lack of information, human resistance to change, hierarchical organisational structure, and lack of information technology standards (Haas et al., 2002).

2.5.2 Automatic identification technology

There are many automatic identification technologies that have been employed in the industries and daily life. For instance, barcodes, smart cards, voice recognition, fingerprint scan, iris scan, Optical Character Recognition (OCR), touch probe, and Radio Frequency Identification (RFID). As for barcodes and RFIDs, both are widely used in the construction industry because of their advantages. The examples of barcode application in the construction industry are as follows:

In the beginning of the 1990s, barcode technology was used for tool management. However, barcodes suffer from very short read range, durability, line of sight requirement, and often unreadable when scratched or dirty (Wang, Lin, and Lin, 2007).

Stone, Pfeffer, and Furlani (2000) developed a web-based system for tracking, identifying and locating manufacturing components on a construction job site. The system composed of the barcode identification system, 3D long-range coordinate measurement technologies, portable/wearable computers, wireless communications, high-speed networking, temporal project database, web-based data analysis, and 3D user interface. This system uses coordinate measurement technologies to locate the position and calculate the orientation. Finally, the system also shows real-time site visualisation.

Cheng and Chen (2002) developed a real-time automated schedule monitoring system for steel erection process. The system integrated with Geographic Information System (GIS), barcode technology, wireless radio transmission technology, and voice recorder. Integration of GIS with the database management system is called the ArcShed system. This system displays the progress and sequence of erection, including video monitoring. Moreover, the detailed shop drawing and related tabular attributes are provided by the system.

Using barcode technology, data entry is automatic and data is in a searchable format. However, data collection is still manual carried out by a labour-intensive method. This scheme is expensive and insufficient since workers have to spend extra time collecting data, and it is prioritised as a secondary task. Thus, data collection is sometimes neglected or not fully performed, which commonly results in incomplete or inaccurate data (Ergen, Akinci, and Sacks, 2007).

Since RFID technology is a sister technology to barcode, the comparison between them is essential. Lu, Huang, and Li (2011) compared RFID and barcode technology as shown in Table 2.9. According to the comparison, RFID technology has some strength over barcodes. Moreover, a RFID tag is readable even if vision is blocked or the surface becomes dirty (Jaselskis et al., 1995). An RDIF tag is not damaged easily, it can be read in direct sunlight, and it can survive in harsh environments (Jaselskis and El-Misalami, 2003).

2.5.3 Overview of RFID technology

RFID stands for Radio Frequency Identification. It is the latest technology for identification and tracking objects. This technology has been identified as one of the

10 greatest contributory technologies of the 21st century, and has found to be a rapid growing market (Chao, Yang, and Jen, 2007). RFID technology can automatically identify the object. Normally, the RFID system consists of four main components: tag, antenna, interrogator, and host computer (Domdouzis, Kumar, and Anumba, 2007).

Table 2.9 A comparison of RFID, barcode, and magnetic strip (Lu, Huang, and Li, 2011)

	RFID technology	Barcode system	Magnetic strip
Read rate	Fastest	Slow	Medium
Storage capacity	Largest	Smallest	Modest
Ease of reproducing a "fake" one	Difficult	Easy	Difficult
Ease of positioning for sensing	Easy	Difficult	Easy
Cost of a tag	Cheap	Cheapest	Expensive
Ease of obtaining information	Difficult (if encryption is done)	Easy	Easy (use a reader)
Knowledge of items' exact position	Easy	Difficult	Difficult
Write	Possible	Impossible	Impossible

A tag in the RFID system communicates its identity when an interrogator transmits a signal to it. The tag's identity is also the identity of the attached object. The tag consists of an integrated circuit and antenna, and it can come in various shapes and designs, such as a disk or coin tag, smart label, or contactless smart card. The tag is divided into three main categories: passive tag, semi-passive tag, and active tag. Moreover, the tag is categorised in terms of memory classifications, which are read-only (RO), write-once read-many (WORM), and read-write (RW). Read-write tags are expensive but have more functionality, while read-only tags are more secure and easy to use.

Antennas are used to transmit and receive data between tags and interrogators. An interrogator or reader is used to activate the tag, receive information from the tag, and communicate information with a host computer or network device. The most common types of interrogators are handheld, fixed position, mobile mount, and interrogator/encoder. An interrogator/encoder or read/write interrogator can be modified from any kind of interrogator. And the type of interrogator can encode the data into the tag and interrogate that data as well.

Not only three main components have to be considered for the RFID system, the radio frequency has to also be determined due to several factors. Radio frequency is divided into four frequency ranges, namely low frequency, high frequency, ultrahigh frequency, and microwave frequency, each of which have their own pros and cons (Cooney, 2006).

2.5.4 The advantages of RFID technology

RFID technology has several advantages that make it popular in the construction industry. According to the studies conducted by Jaselskis et al. (1995), Jaselskis and El-Misalami (2003), and Chao, Yang, and Jen (2007), the outstanding advantages of RFID technology are shown below:

1. RFID does not need line of sight. A tag is readable even if vision is blocked.
2. RFID is capable of performing under a harsh environment, which is the common environment at a construction site.
3. RFID is readable under direct sunlight, dirt, dust and contaminants.
4. The system has the ability to scan items at a distance. Physical contact is not required for RFID tag reading, especially when compared to the magnetic strip technology.
5. The system has a high level of security because it is difficult to replicate tag information.
6. RDIF tags can store massive amounts of data.
7. RDIF tags can be read quickly.
8. The system can read multiple tags at once.
9. The system provides accurate processes.
10. RDIF tags are reusable.

2.5.5 The limitations of RFID technology

RFID technology, however, does not only have advantages. Jaselskis et al. (1995) mentioned the main limitations of RFID technology as follows:

1. Most RFID systems are closed systems, and tags from one supplier cannot be read by another supplier’s reader. It may cause a problem in material tracking and related processes, especially when the materials came from various suppliers with different RFID systems.
2. Physiological barriers occur within the workforce. The workforce feels that RFID is sophisticated, expensive, or time consuming. And they feel that RFID leads to increased monitoring levels, which affects their privacy and unrealistic productivity rate.
3. The cost of hardware for the RFID system is one of the obstacles for its popularity. The cost includes tag, reader, computer, network, software, and related technology.

4. RFID system may malfunction in certain conditions. For example, if RFID is attached to a metal object, or the RFID is working in another radio frequency range.

Finally, RFID is the later technology, which came later than barcode technology. It is difficult for an organization that is using barcode technology to implement RFID technology (Chao, Yang, and Jen, 2007).

2.5.6 Selecting the appropriate hardware for the RFID system

Compared to other industries, construction activities are performed under different environmental conditions. Thus, RFID specifications for construction projects are different in the reading distance and readability. Even for the same construction project, specifications depend on the processes that the RFID is applied to (Chin et al., 2005). In addition, Cooney (2006) stated the concerning topics to consider when selecting the appropriate interrogator. The considerations are as follows:

1. Operating frequency
2. Supported RFID tag protocols
3. RF output power
4. Number of antennas that can be used with it
5. Interrogator communication protocol
6. Configuration software availability
7. Upgrade availability

The use of RFID leads to automatic identification. However, the distance between the tag and reader must be within the reading range. The reading range composes of the minimum reading range and the maximum reading range. The minimum reading range is the distance between the tag and reader at the optimum location while do the process this range leads to a smooth process. The maximum reading range is the distance that prevents multiple simultaneous tag reading (Ergen, Akinci, and Sacks, 2007).

2.5.7 RFID in the industries

RFID technology has been widely used in many industries. The contributions of RFID in managerial perspective and opportunities for enterprises were categorised into four categories: (1) identification of objects and persons, (2) tracking process flow, (3) authentication, authorisation and security, and (4) financial record keeping (Chao, Yang, and Jen, 2007).

In addition, Jaselskis et al. (1995) divided RFID application into three main applications as follows: (1) reading tag as an object passes a fixed scanner to record the movement of the object, (2) writing the information on the tag that can be retrieved later, and (3) retrieving the information from the tag by mobile scanner.

According to the research of Chao, Yang, and Jen (2007), RFIDs are widely used in various industries, as in the following examples:

1. Health care: RFID is used for fighting drug counterfeiting, tracking blood products, and tracking medical goods, operation, and treatment.
2. Airlines: RFID is employed for luggage handling process.
3. Military: US Army uses RFID for inventory management.

2.5.8 RFID in the construction industry

RFID has been developed and implemented for construction processes. Jaselskis et al. (1995) discussed the potential applications of RFID in the construction industry. The RFID applications were proposed for concrete processing and handling, cost coding for labour and equipment, and material control. Jaselskis and El-Misalami (2003) categorised RFID applications in the construction industry into four groups, which are engineering and design, material management, maintenance, and field operation.

For engineering and design, Wang, Lin, and Lin (2007) mentioned that RFID provided cost savings through the increased speed and accuracy of data entry. Thus, mobile construction RFID-based dynamic supply chain management (M-ConRDSCM) was developed to reduce construction conflicts and project delays. The system consists of RFID, mobile device, and a web portal.

Lu, Huang, and Li (2011) described the case scenarios of applying RFID technology in construction project management. The scenarios were the management of materials, men, and machinery (m^3). For materials, RFID technology was used for logistic and supply chain management, inventory management, quality assurance, and waste management. Access control and staff attendance records, as well as the safety of men were the RFID scenarios used in men management. The RFID was used for machinery management by tracking machines and tools, machine operation and record, and machine maintenance record.

For material management, an automated system to track and locate precast concrete components with no or minimum worker input by integrating RFID with GPS technology was proposed by Ergen, Akinci, and Sacks (2007). An RFID reader captures the identification of each component, while the location is located by the GPS receiver.

For maintenance, Yabuki, Shimada, and Tomita (2002) developed an on-site inspection system for building construction, operation, and maintenance processes. The system aims to improve the inspection by a junior inspector and improve knowledge transfer. RFID technology, PDA, cellular phone, local area network, Internet, voice input and output, and digital camera were integrated into the system in order to support the inspectors for document and related information acquisition. Inspectors can input and transfer the recent inspection data of each member, such as measured data, notice, sound, or photograph for inspection purposes. Moreover, the junior inspector can receive advice, teachings, and warning from the senior inspector as a knowledge system through this system. Using VoiceXML, this system leads to hands-free and eye-free capability while communicating with the computer. In this system, the hybrid method was used to contain the data for the most suitable practical purposes. The type of data and information that can be stored on RFID tags, PDAs, and local servers are shown below in Table 2.10.

Table 2.10 Data and information in an on-site inspection system (Yabuki, Shimada, and Tomita, 2002)

Container	Data and Information
RFID tags	ID, main feature, specification, inspection procedures, latest measured data, latest inspection notes, etc.
PDA	Measured data, digital photographs, digital sounds, information about information routes, etc.
Local server	All the inspected data, document and drawing files

For field operation, Chin et al. (2005) presented the progress management system, which integrates 4D CAD with RFID technology. The 4D CAD is 3D CAD and scheduling. The system aims to manage the logistics and the progress control of structural steelwork by focusing on the critical part elements of high-rise building construction.

2.6 Discussions and conclusion

In this chapter, four topics are reviewed, specifically the construction industry, prefabricated construction, knowledge and skills in construction, and technology in the construction industry.

The construction industry has its own characteristics. These characteristics cause personnel dependence in terms of quantity and quality. At the moment, the lack of labour, especially knowledgeable and skilled workers is of concern to stakeholders and other related personnel in the construction industry. Knowledge plays a key role in the fast changing business environment. It supports efforts towards a sustainable business and brings new opportunities to the business for productivity, market share, and profit. Lack of knowledgeable and skilled personnel, however, results in lower productivity, which expands to construction costs, duration, quality, and safety.

Residential construction is an important part of the construction industry. The demand for structures and construction leads the construction industry to industrialisation. One example is prefabricated construction, which is the case study of this research. When focusing on prefabricated construction, the gap between the manufacturing process and construction process was found. In the manufacturing process, the degree of industrialisation reached the automation level. Meanwhile, the erection process at construction sites is only at the mechanisation level. In addition, the characteristics and features of prefabricated construction require additional knowledge and skills of related personnel in the construction process.

New technologies have been employed in the construction industry to support the work and improve construction productivity. Some examples include the use of GPS technology to locate the location, using a handheld computer to collect the data and provide information, using a computer to process the data, and using the identification technology to identify the related components. The use of handheld computers positively affects construction productivity by providing quality and timeliness information. As for the identification technology, RFID is the latest technology that has its advantages in the construction industry. It is employed in construction for various purposes, such as engineering and design, material management, maintenance, and field operation. However, these recent technologies do have their limitations, which must be considered when applied to the construction process.

Chapter 3
Research methodology

3.1 Introduction

The research employed eight steps of methodology as follows: (1) primary site survey, (2) literature reviews, (3) data collection, (4) current practice analysis, (5) analysis of knowledge and skill requirements, (6) automation approach development, (7) evaluation, and (8) research summarisation and discussion. The brief details of each step are described in the following chapters below.

3.2 Research methodology

3.2.1 Primary site survey

In order to design and develop the research methodology, the primary information related to the current practice and problems is needed. Thus, a project of prefabricated housing construction was selected for this primary survey. A selected project was the construction site of one-storey and two-storey houses. In this stage, site observation and interviewing were employed. Site observation aimed to explore working processes, personnel roles and responsibilities, as well as problems. The personnel, who participated in the installation process of prefabricated members, were interviewed on the following topics: project overview, process workflow, personnel roles and responsibilities, working details and current problems. Therefore, the participants, rough working process, and problems in the installation process of prefabricated members are identified at the end of this step.

3.2.2 Literature reviews

The journal articles, textbooks, conference proceedings, theses, dissertations, and related publications were reviewed in the second step. The literatures were categorised into four groups: (1) construction industry, (2) prefabricated construction, (3) knowledge and skills in construction, and (4) technology in the construction industry.

3.2.3 Data collection

This step employed site observations, document reviews, and personnel interviews within the six prefabricated construction projects to get the following data and information: project details, personnel roles and responsibilities, working details and technical knowledge, resource requirements, quality assurance and control details, and current problems. The details of each data collection approach are described below.

The site observation aimed to survey the overview of the project, the working processes, the roles and responsibilities of each staff in the installation process, and the current problems. The data and information, especially physical actions in the installation process, were also collected using photographs. This approach led to the actual occurrence in construction processes. Thus, some of the following problems were discovered by this approach; the problems that were concealed by the interviewees, the problems that were missed from the interviews, and the problems that were not important in the participants' point of view.

Because the documents were concrete evidences, which represented the desired operation of the construction project and its processes, the documents were reviewed. Nevertheless, the actual operation usually differed from the statement in documents. Then, both of them were considered and collected as the data in this research. In this approach, the document reviews focused on general documents and specific documents. The general documents, which were applied to every construction unit in the project, include project summary detail, site layout, organisation chart, project main schedule, personnel work assignment sheet, working procedures or quality manual, personnel job specifications and descriptions, and working evaluation sheet. The specific documents, which are varied in the construction types or units, include construction drawings, planned installation sequence, resource requirements and specifications, and quality checklists, were reviewed.

The personnel related to the installation process were interviewed. The issues were personnel data, personnel roles and responsibilities, process workflow, working details and technical knowledge, data and information flow, and current problems.

3.2.4 Current practice analysis

From the investigations, the current practices were analysed. The related personnel in the installation process were summarised, including the roles and responsibilities of each staff member. And because the same roles and responsibilities of the staff were assigned to the various positions in different projects, the personnel were categorised instead by their functions, namely worker, foreman, mobile crane operator, inspector, and supervisor. The roles and responsibilities of each category are shown in Table 3.1.

The installation process of prefabricated members was broken down into three main steps and four supplementary steps. The three main steps of installation include (1) checking the available prefabricated members, (2) making a decision for an installation process, and (3) installing the prefabricated members. While the four supplementary steps include (A) checking the availability of resources, (B) comparing the required resources and the available resources, (C) deciding the working location of a mobile crane, and (D) inspection of the installed prefabricated members. Each installation step was further broken down based on the current practice. After that, the action flow of each person in each step was created for current practice analysis.

Table 3.1 Function of personnel

Position	**Function**
Worker	The person who uses workforce for installation and related processes.
Foreman	The person who supervises the installation, manages the related resources, and provides the technical knowledge.
Mobile crane operator	The person who operates the mobile crane to support the installation and related process.
Inspector	The person who inspects the quality of installation.
Supervisor	The person who manages the resources and supervise the works in the project.

3.2.5 Analysis of knowledge and skill requirements

As the installation group plays a major role in installation process of prefabricated members, the requirements of knowledge and skill for personnel are of main focus. This analysis consists of two parts. Firstly, the three main steps and four supplementary steps of installation and its action flow were analysed. The analysis of knowledge and skill requirements was based on the requirement of each person by considering the physical actions and related data and information. Secondly, the changes and obstacles, which usually occurred in current practice, were analysed using the cause and effect diagram to find out the sources of each problem. The sources, related to personnel knowledge and skills, were extracted and further analysed to identify the knowledge and skill requirements to prevent and solve that problem.

3.2.6 Automation approach development

The automation approach was developed based on the main and supplementary steps of installation and the requirements of knowledge and skill. The automation approach was scoped to cover the steps of installation.

In the development, the hardware and technologies were considered based on the working characteristics of each person and the actual environment of the construction site. Then, the system architecture was designed. After that, the automation approach was developed based on the designed system architecture.

3.2.7 Evaluation

The evaluation was employed in three phases: evaluation by the prefabricated member model, evaluation at the construction site, and evaluation by the experts, each of which have different objectives and limitations, as shown in Table 3.2.

For the evaluation by the prefabricated member model, 10 samplers installed the prefabricated member model. Each sampler performed three rounds of installation. A round of installation consisted of an installation by the conventional method and an installation by the automation approach. The situation in each round was originated randomly to simulate the changed condition in the installation process. While the samplers were installing the model, video was recorded. The reduction of knowledge and skill requirements was analysed by the playback of the installation video. The installation duration and installation mistakes in each round of each sampler were observed. Then the duration and mistakes were analysed to find out the results of using the automation approach.

For the evaluation at the construction site, the installation processes of the first floor wall in five houses were selected. The installations by the conventional method and automation approach were observed. The total number of observations was 56 members out of 78 members, of which 34 members utilised the installation process of the conventional method while 22 members employed the automation approach. The installation duration per panel was recorded, including the duration of swing back, find and hook, swing, and installation of a prefabricated member. Finally, the working durations by both the conventional method and automation approach were compared in order to find out the results of using the automation approach. In addition, the implementation at the actual construction site revealed improvement issues for future development of the automation approach.

In the last phase of evaluation, six experts, who have at least three years experience in prefabricated construction, evaluated the automation approach. The evaluation was in terms of the suitability of work breakdown structure, the importance of each step in the installation process, the completeness of knowledge and skill requirements in each step, the importance of knowledge and skill for each person in each step, the relaxation of knowledge and skill using the automation approach, and the evaluation of automation approach. The Likert scale was employed in this evaluation.

3.2.8 Research summarisation and discussion

Finally, the results from the research were summarised and discussed. The summary included the requirements of knowledge and skill of each person in each step and the details of the developed automation approach. The contributions of research, adaptation for other constructions, and future works for this research also were discussed in this part.

Table 3.2 Details of evaluations

Evaluations	Objectives	Limitations
By the prefabricated member models	- Evaluate the automation approach with the controlled factors	- The installations are not affected by the huge size of prefabricated members
At construction site	- Evaluate the automation approach in the actual installation process - Evaluate the workability of the automation approach of the real construction environment	- The evaluation cannot control the related factors while the prefabricated members are being installed
By the experts	- Evaluate the overall of automation approach by using the expertise in prefabricated construction	- The installation of prefabricated members cannot be performed in order to get the feedback from the experts

3.3 The overview of sample projects

The samples in this research were six residential construction projects, which were located in the Bangkok Metropolitan and nearby areas. These six projects were selected because of the use of prefabricated construction. The projects consisted of single houses or townhouses with area from 150 to 250 square meters. Both one-storey and two-storey houses were constructed in Project A. Project B, Project C and Project E constructed only two-storey houses while only one-storey houses were constructed in Project D. In Project F, only three-storey houses were constructed.

From the details of each project, as shown in Table 3.3, all of the sample projects experienced long project duration and had a large number of construction units. Moreover, many types of houses were assigned in each project. However, the numbers of house types were not included in the effect of house mirror, which doubled the number of house types by duplicating the house in the left type and the right type, as shown in Figure 3.1. In addition, the townhouse construction in Project

F caused an increasing number of prefabricated member variation due to its characteristics and limitations.

Table 3.3 The details of sample projects

Detail		**Project**					
		A	**B**	**C**	**D**	**E**	**F**
Project duration (year)		3.5	More than 4	4	1	7	1.5
Construction unit (unit)		486	Around 1,000	600	29	1,198	99
Construction type (type)		3	7	2	2	4	3
Type of product	One-storey house	✓	-	-	✓	-	-
	Two-storey house	✓	✓	✓	-	✓	-
	Three-storey house	-	-	-	-	-	✓

Figure 3.1 Mirror houses

The sample projects had a wide range of prefabrication use. In project A, project B, and project F, all structures were prefabricated members. Only slabs and walls were prefabricated for project C. In project D, only the walls were prefabricated members. The conventional method was used in the construction of the first floor beam in Project E. The slab, wall, and second floor beam were prefabricated members. The details of prefabrication in each project are shown below in Table 3.4.

Table 3.4 The details of prefabrication in each project

Structure	Project					
	A	B	C	D	E	F
The 1st floor beam	✓	✓	-	-	-	✓
The 1st floor slab	✓	✓	✓	-	✓	✓
The 1st floor wall	✓	✓	✓	✓	✓	✓
The 2nd floor beam	✓	✓	-	N/A*	✓	✓
The 2nd floor slab	✓	✓	✓	N/A*	✓	✓
The 2nd floor wall	✓	✓	✓	N/A*	✓	✓
The 3rd floor beam	N/A*	N/A*	N/A*	N/A*	N/A*	✓
The 3rd floor slab	N/A*	N/A*	N/A*	N/A*	N/A*	✓
The 3rd floor wall	N/A*	N/A*	N/A*	N/A*	N/A*	✓

* N/A means not available

Figure 3.2 The house in project A

Figure 3.3 The house in project D

3.4 Conclusion

The eight steps of methodology were employed in this research as follows: (1) primary site survey, (2) literature reviews, (3) data collection, (4) current practice analysis, (5) analysis of knowledge and skill requirements, (6) automation approach development, (7) evaluation, and (8) research summarisation and discussion. The data was collected from the installation processes of prefabricated members at six construction projects, which performed the prefabricated housing construction.

Chapter 4
Current practice

4.1 Introduction

The current practices and related information of the installation process in the sample projects were investigated in this stage by site observation, document review, and interviewing. For the current practice, the roles and responsibilities of personnel and the installation process of prefabricated members are mainly focused. In addition, the changes and mistakes in the prefabricated member installation were also analysed in order to find out the knowledge and skill requirements later.

Therefore, this chapter includes the personnel roles and responsibilities, the prefabricated constructions, the documents in the installation process, the changes in prefabricated member installation, and the mistakes in the prefabricated member installation.

4.2 Personnel roles and responsibilities

From the investigations, the installation processes of prefabricated members were performed by a group, which consisted of workers, a mobile crane operator, and a foreman. The number of workers in a group varied from two to five workers. The inspector and supervisor were also involved to the installation process, although both of them did not supervise the installation of prefabricated members directly. The inspector investigated the quality of the installed member after the installation step was completed, while the supervisor planned and managed the installation process and other related resources. Figure 4.1 shows the organisation chart of an installation group. The supervisor, inspector, and foreman might operate with more than one group during the installation. The personnel were assigned to perform the work based on the different roles and responsibilities, which are summarised below.

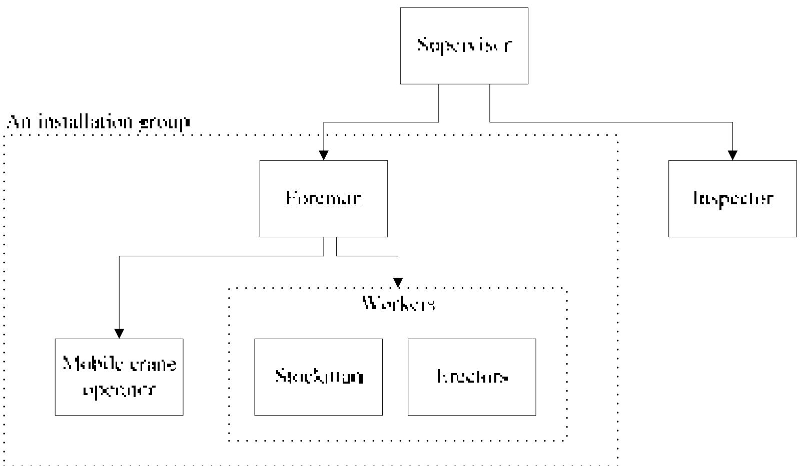


Figure 4.1 Organisation chart of an installation group

4.2.1 Worker

Normally, more than one worker performed in the installation group. The workers were employed to install the prefabricated members using their workforce, under the supervision of the foreman and the cooperation of a mobile crane operator. The roles and responsibilities divided the workers in the installation process into two categories based on the work locations as follows:

(1) Worker at stock, or stockman: This person worked at the stock location or on the delivery truck to find and hook a prefabricated member, which was the current installation sequence. While the mobile crane was operating at the stock location or the delivery truck, the stockman communicated with the mobile crane operator using hand signals. The illustrations of the stockman's work are shown in Figure 4.2.

Figure 4.2 Stockman's work

(2) Workers at installed location, or erectors: These personnel used their workforce to handle and install a prefabricated member, which was being lifted and moved by machine. The work included the installation process at the desired location. After installing a prefabricated member, the erectors temporarily and continually shored the prefabricated member. The work process is shown in Figure 4.3. At least one person in this group communicated with the mobile crane operator using hand signals while the work was being performed.

In addition, after the installation process, some of the workers may be assigned to make the joints between the prefabricated members or between a prefabricated member and another structure. The joints were either wet joints or dry joints depending on the specification and design. Workers did the wet joints by pouring cement paste or specified material into the opening or the formwork. For the dry joints, workers welded the plates or fastened bolts.

However, the roles and responsibilities of each worker described above were merged or separated based on the assignment by the foreman or supervisor. Welding and bolt fastening might be assigned to the erectors, or a stockman might support and operate the erector's work in his idle time.

Figure 4.3 Erectors' works

Figure 4.4 Wet joint

Figure 4.5 Weld joint

Figure 4.6 Bolt fastening joint

4.2.2 Mobile crane operator

This person was employed to operate the mobile crane for prefabricated member lifting, moving and installation, as well as any support work under the supervision of the foreman as shown in Figure 4.7. One example of support work is the moving of the stock rack as shown in Figure 4.8. Before performing this operation, the mobile crane operator would first check the required resources and consider the work location before setting up the machine. The operation of a mobile crane must be safe and efficient.

Figure 4.7 Prefabricated member lifting, moving, and installation

Figure 4.8 Stock rack moving

4.2.3 Foreman

The foreman supervised the installation process by following the schedule, construction drawing or any documents that were provided by the planner or designer before the installation process began. However, the current condition might differ from what was planned, so the foreman has to recognise the actual current condition, perceive the change, and select the proper countermeasures in a timely manner. The foreman also managed the resources and provided technical knowledge to the installation group. Also, some of the work assigned to the foreman was assigned to a headman in some construction projects.

4.2.4 Inspector

This person inspected the quality of the prefabricated member installation and related works by following the checklist or specification. The main inspections of installed members included the level, alignment, and inclination. The inspector recorded the results of the inspection in a document or form, and provided guidance to the installation group in order to correct any possible disqualification of an installed prefabricated member.

4.2.5 Supervisor

The supervisor planned and managed the construction schedule and the production line. The work criteria included the assignments of personnel, resource management, and control of the construction process to meet the expectations of prefabricated construction, specifically in terms of time, cost, quality and safety.

4.3 Prefabricated construction

Prefabrication has been employed in many projects, which have a large number of construction units or a large number of structural members. One of the reasons is that prefabrication needs a large amount of investment for production facilities and equipment. This investment is worthwhile in that it allows for using facilities repetitively to produce a large number of prefabricated members.

According to the characteristics of prefabrication, the working scheme, especially its installation process, is repetitive work. Hence, work is affected by the volume of construction, the limitations and conflicts of space, as well as the complications of resource requirements. The effects largely influence not only the current working unit but also the rest of the project. Thus, an improvement in efficiency and effectiveness can be advantageous for a large number of construction units or structural members, where these results also expand to the project level.

The installation process of prefabricated members is one of the most important processes in the construction state because it is always on a critical path. The installed prefabricated structure is the crucial skeleton of the building and most of the successive activities will be operated on this structure. Thus, the unexpected results, such as undesired productivity and mistakes, in prefabrication activities continually affect to the construction process.

After the prefabricated members arrived at the construction site, the members were transferred to the stock rack or were left on the truck. These alternatives were selected based on the policy and management principle of the construction supervisor. If the just-in-time concept was applied in the project, the members were left on the truck and directly installed at the location without transferring to the rack. Or else, the members were transferred and stocked at the rack.

The installation process started out by checking the available prefabricated members. After that, a decision was made based on the current condition of the installation process on whether to postpone or continue the operation. In the case of continuing the installation, the sequence was made. Then, the prefabricated members were installed based on the selected installation sequence. All of these were the main steps, which are always operated in the installation process of prefabricated members.

In addition, the supplementary steps might be performed in the installation process as follows: the available resources were checked for availability; the available resources and required resources were compared in the next step to perceive the unavailable resources and prefabricated members; the work location of the mobile crane was considered; and the installed members were inspected. These supplementary steps may or may not be operated based on the practice of the particular foreman and the installation group.

According to the working scheme above, stocking the members at the rack was assigned as the pre-installation step because some projects skipped this step. The installation process was broken down into three main steps and four supplementary steps as shown in Figure 4.9. The details of each step are described below.

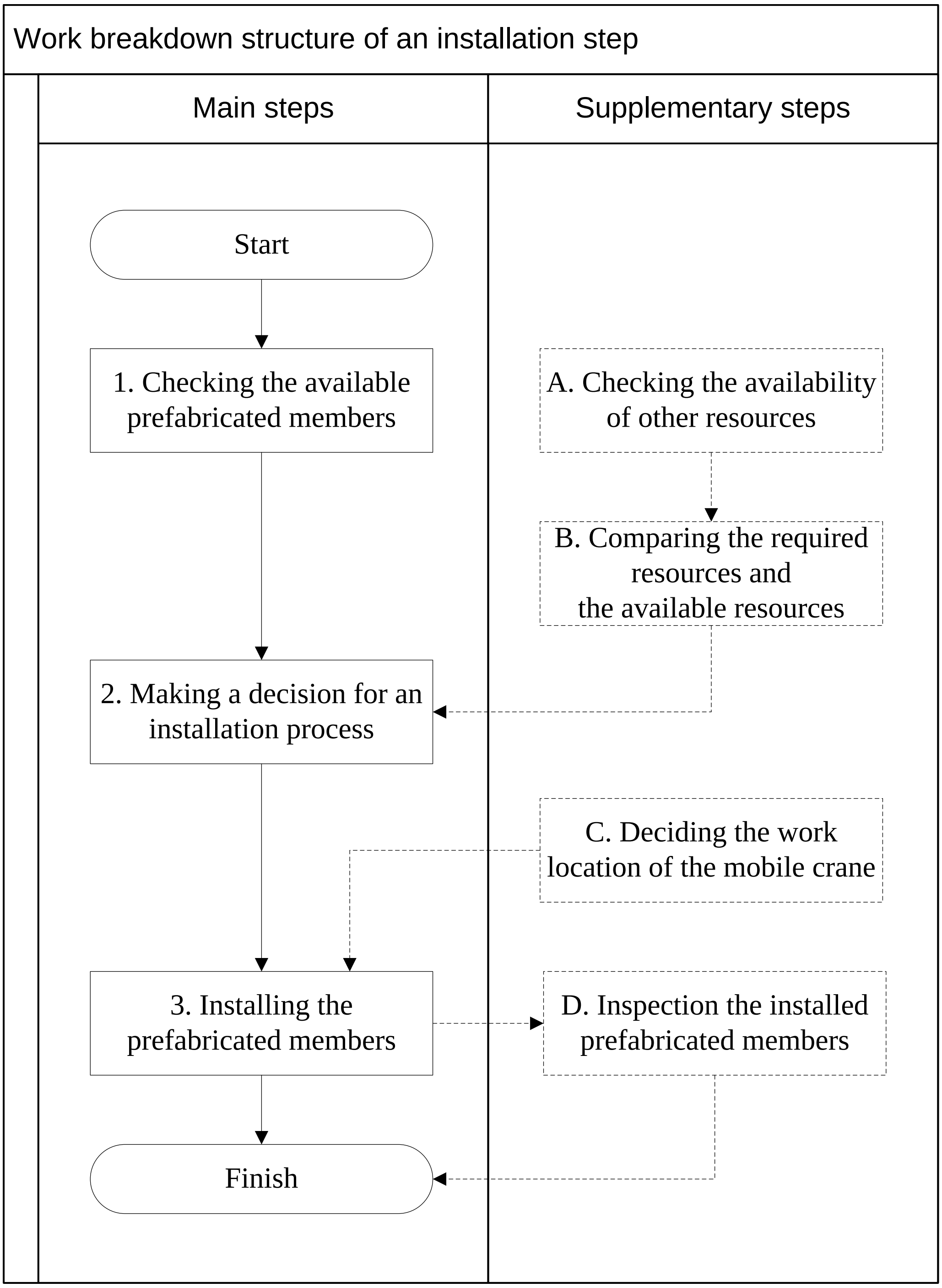


Figure 4.9 Work breakdown structure of an installation process

4.3.1 Checking the available prefabricated members

Whether the prefabricated members were stocked in the rack or left on the truck, the foreman checked the delivered prefabricated members and identified each member. Verifying the available prefabricated members for the installation process was the main goal of this step.

In the beginning, the foreman considered the available prefabricated members and decided the target of the installation. At the rack or on the delivery truck, the foreman looked at each prefabricated member and identified every member. The identification is determined by the prefabricated member's appearance or marking based on knowledge and skills. After the identification activity, the available prefabricated members were perceived. Then, the foreman will make the decision to stop checking in the case that all the prefabricated members were checked or could not find the prefabricated members any more. The work breakdown structure of Step 1 is summarised and shown in Figure 4.10.

In current practices, the markings were made using colour spray, ink, sticker tags, or barcode tags to indicate the prefabricated member code and other information as shown in Figure 4.11. The marking or code can be interpreted with the detailed information such as project name, house number, structure type, member number, etc. The foreman also obtained the information of available prefabricated members by considering the document from transportation process. The document showed the list of prefabricated members in each delivery trip as shown in Figure 4.12.

However, the work breakdown structure in Figure 4.10 had further actions and details. In order to consider the prefabricated members, the target group of installation was identified and the list of prefabricated members in the target group was considered. The reason for this target group identification was that the structural types or housing units were stocked at the same stock rack or on the same delivery truck. After getting the target group, the list of prefabricated members in a target group was perceived. This list helped the foreman to scope the prefabricated member checks.

The identification by other methods was also performed in case of uncertain or doubtful situations. The identification was done by measurement or examination with the construction drawing. After each prefabricated member was identified, the foreman wrote this down on the document or simply remembered the available member. Recording to accumulation must be done to perceive the list of available prefabricated members.

The checking of prefabricated members is finished when the members in the target group are complete or another prefabricated member could not be found. Otherwise, the foreman will search another member by redoing 1.2 or search at other possible locations.

Finally, the foreman perceived the available prefabricated members in the target group at the end of this step. The action flow of this step from the above operations is summarised and shown in Figure 4.13.

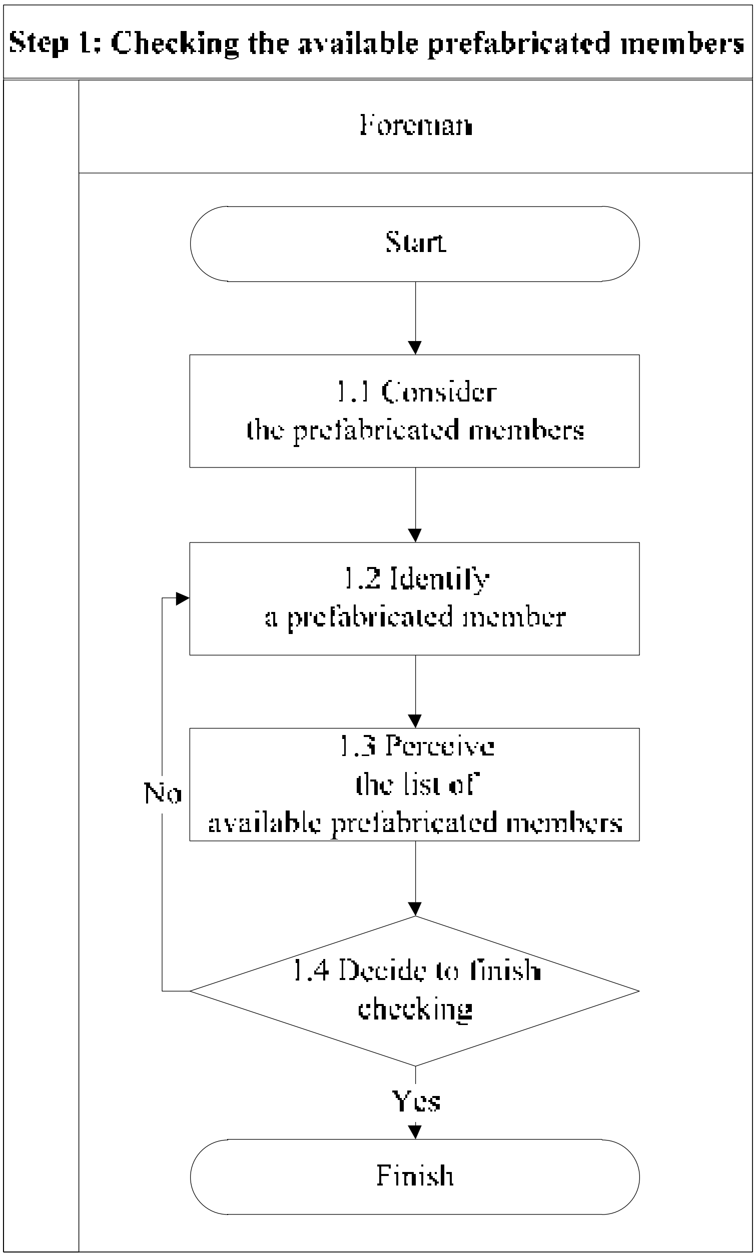
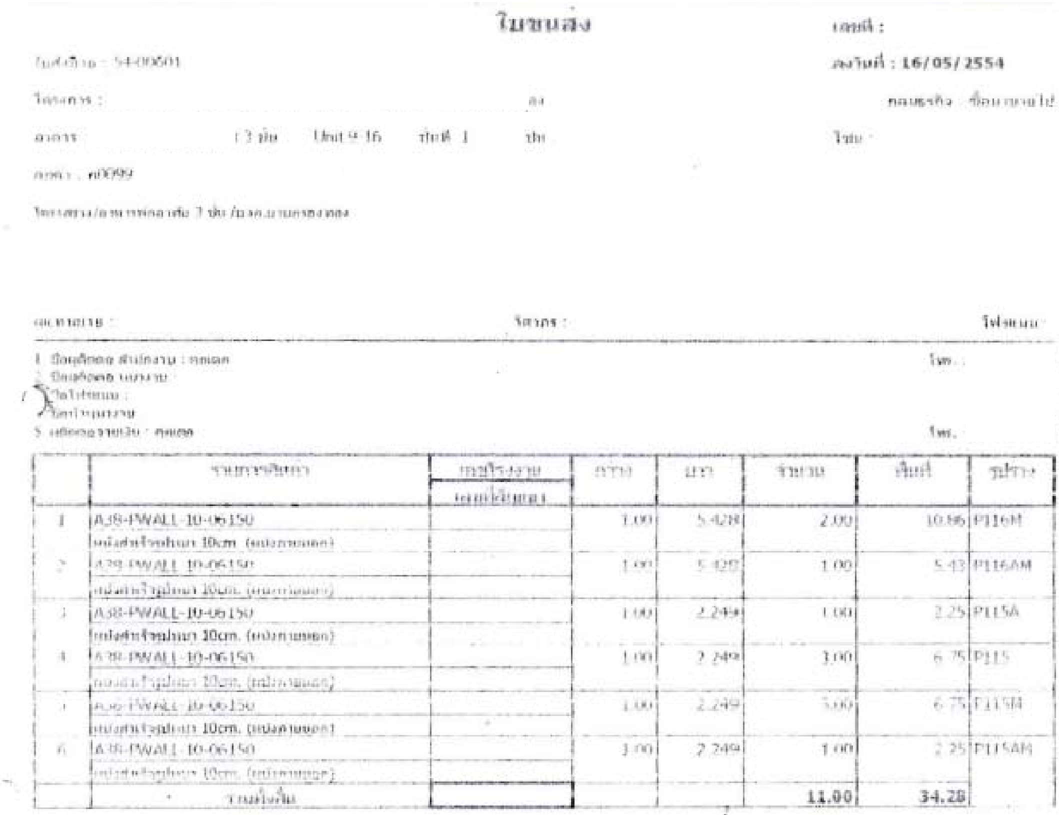


Figure 4.10 Checking the available prefabricated members

Figure 4.11 Prefabricated member marking



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	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1	A38-PWALL-10-06150 [illegible] 10cm. [illegible]		1.00	5.428	2.00	10.86	P116M
2	A38-PWALL-10-06150 [illegible] 10cm. [illegible]		1.00	5.428	1.00	5.43	P116AM
3	A38-PWALL-10-06150 [illegible] 10cm. [illegible]		1.00	2.249	1.00	2.25	P115A
4	A38-PWALL-10-06150 [illegible] 10cm. [illegible]		1.00	2.249	3.00	6.75	P115
5	A38-PWALL-10-06150 [illegible] 10cm. [illegible]		1.00	2.249	3.00	6.75	P115M
6	A38-PWALL-10-06150 [illegible] 10cm. [illegible]		1.00	2.249	1.00	2.25	P115AM
	[illegible]				11.00	34.28	

Figure 4.12 Document from transportation process

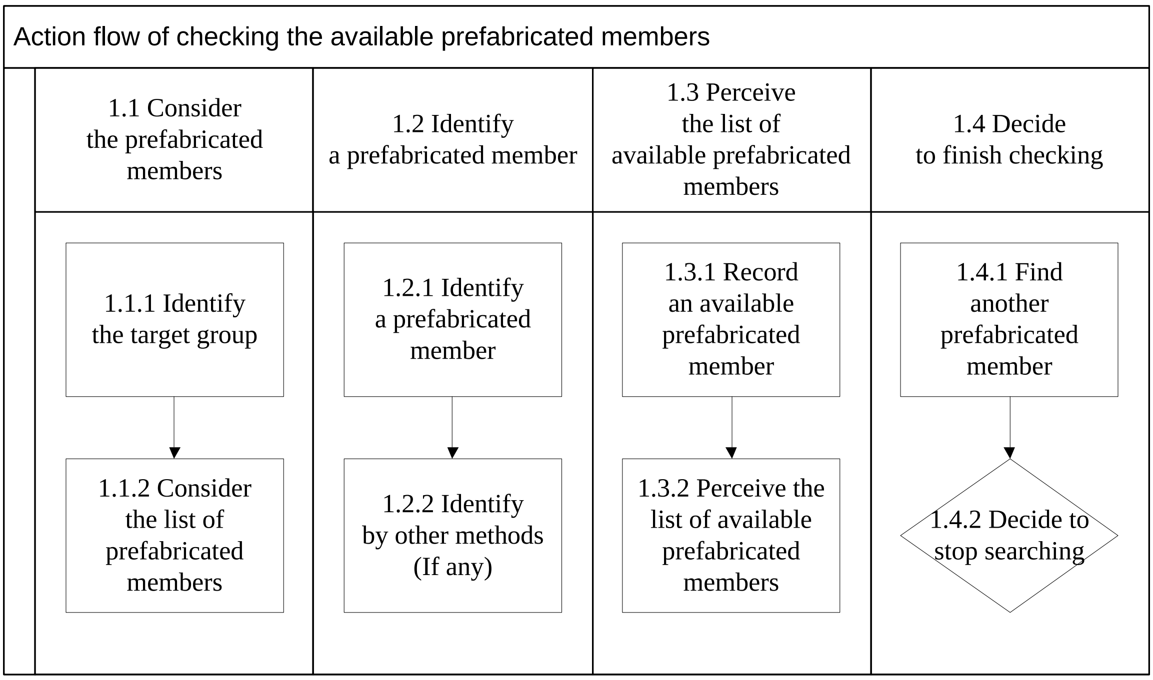

Figure 4.13 Action flow of checking the available prefabricated members

4.3.2 Making a decision for an installation process

After discerning the list of unavailable resources, the foreman will make a decision for the installation process. The decision is whether to postpone or continue the process. The process is postponed if the unavailable resources significantly affect the installation process, or the resources could be moved for more ready installations. If the installation process continues, the foreman considers other related factors that could affect the installation sequence. Finally, the installation sequence is generated by the foreman, which is shown in Figure 4.14.

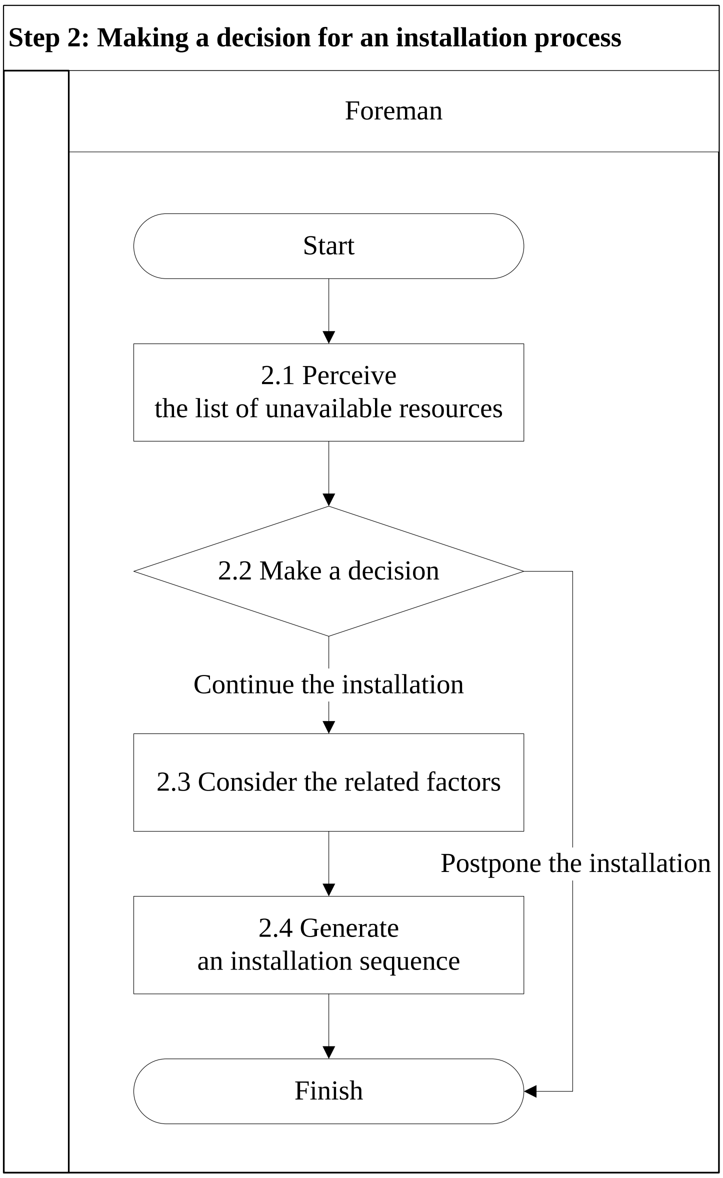

Figure 4.14 Making a decision for an installation process

The actions in this step started by recalling the list of unavailable resources from the previous step. Then, the unavailable prefabricated members and the lack of resources were considered. In the case of incomplete prefabricated members, the installation might be postponed to avoid the double moving of resources, the line-of-sight blocking, or the installation between prefabricated members. In the case of unavailable resources, some resources could negatively affect the installation significantly. The installation cannot be performed without the all the required resources, such as a mobile crane or driller. From the current practice, the related resources were categorised into two types: the fixed and the variable resource. The required quantity of fixed resource was constant and did not depend on the installation number of prefabricated members. On the other hand, the required quantity of variable resource depended on the installation number of prefabricated members. The unavailability of resources caused two schemes of installation, i.e., (1) the installation was postponed, and (2) the installation was started but the installation sequence was shortened.

Then, a decision was made whether to postpone or to continue the installation process. The installation was postponed in case the required materials were not complete, or a group of personnel, including resources, could be moved for use at another installation that was more prepared and ready. If the resources are completely available or the work could be accomplished by shortening the sequence, the foreman makes the decision to continue the process. The related factors will be considered: (1) the location of the mobile crane, house, and stock, (2) the unavailable prefabricated members, and (3) the unavailable resources. Finally, the installation sequence is generated after considering the effects from related factors as shown in Table 4.1 in order to avoid line-of-sight blocking and the installation between prefabricated members. The flow of above actions is summarised as stated in Figure 4.18.

Table 4.1 Factors and its effects in the installation sequence

Factors	**Effects**
The related location of house, mobile crane, and stock.	The installation sequence was considered by starting at the outermost corner from the stock to avoid line-of-sight blocking. The examples are shown in Figure 4.15. Both of the illustrations were the installations of the same structure (the second floor wall). On the left hand side, the stock was on the left. Thus, the installation sequence started from the outermost right corner. On the other hand, the stock was on the right. The sequence started from the outermost left corner.

Table 4.1 Factors and its effects in the installation sequence (Cont.)

Factors	Effects
The unavailable prefabricated member	The parts of installation sequence were skipped due to the unavailability of prefabricated members. The foreman considered an installation sequence in order to avoid the line-of-sight blocking as shown in Figure 4.16 and the installation between prefabricated members as shown in Figure 4.17. The installation with line-of-sight blocking or between prefabricated members caused the difficult installation, prolonged the installation duration, and raised the chance of damage or accident.
The unavailable resources	Due to the lack of required resources, the installation process was not performed or the installation sequence was shortened. For example, the lack of cable and hook canceled the installation process or the inadequate props shortened the installation sequence.

Figure 4.15 Different installation sequences

Figure 4.16 Line-of-sight blocking

Figure 4.17 Installation between prefabricated members

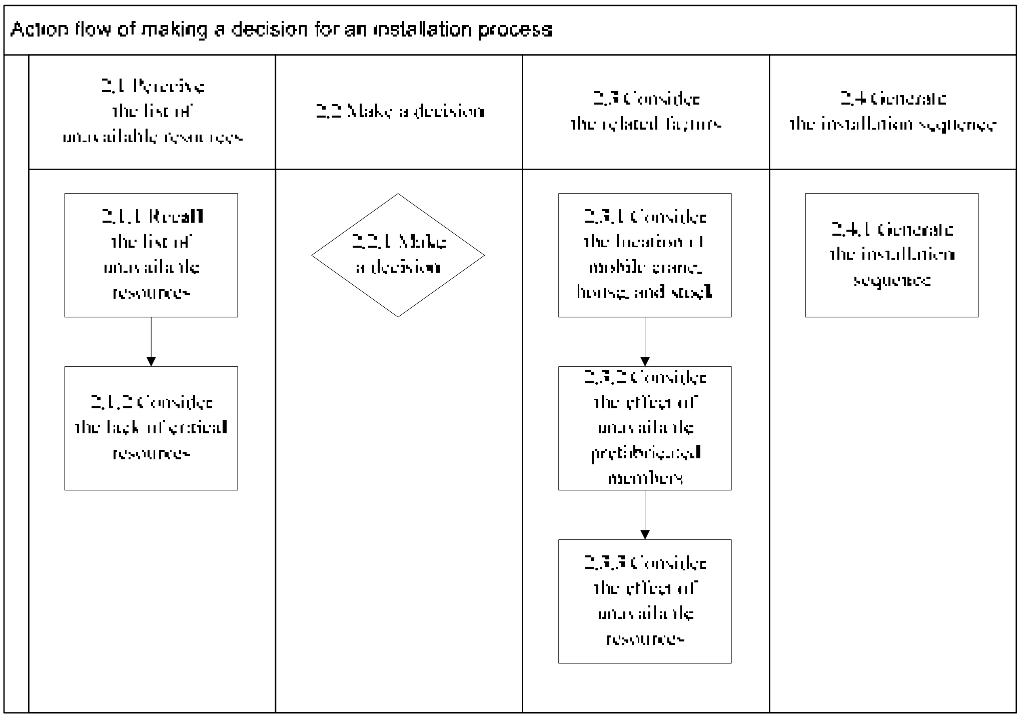

Figure 4.18 Action flow of making a decision for an installation process

4.3.3 Installing the prefabricated members

Firstly, the foreman recalls the installation sequence. Then, the foreman supervises the process, while the prefabricated members are being installed. The process in this step is a repetitive loop along with the cooperation of the mobile crane operator, stockman and erectors. The mobile crane operator operates the machine to lift, move, and install the prefabricated members. The stockman hooks a prefabricated member in the rack or on the truck and then lifted and moved to the desired location to be installed. Next, the prefabricated member is installed and shored by erectors. Finally, erectors unhook the prefabricated member before starting the whole process again. All the personnel in this step communicate and cooperate with each other throughout the work being performed. This step can be summarised as shown in Figure 4.19.

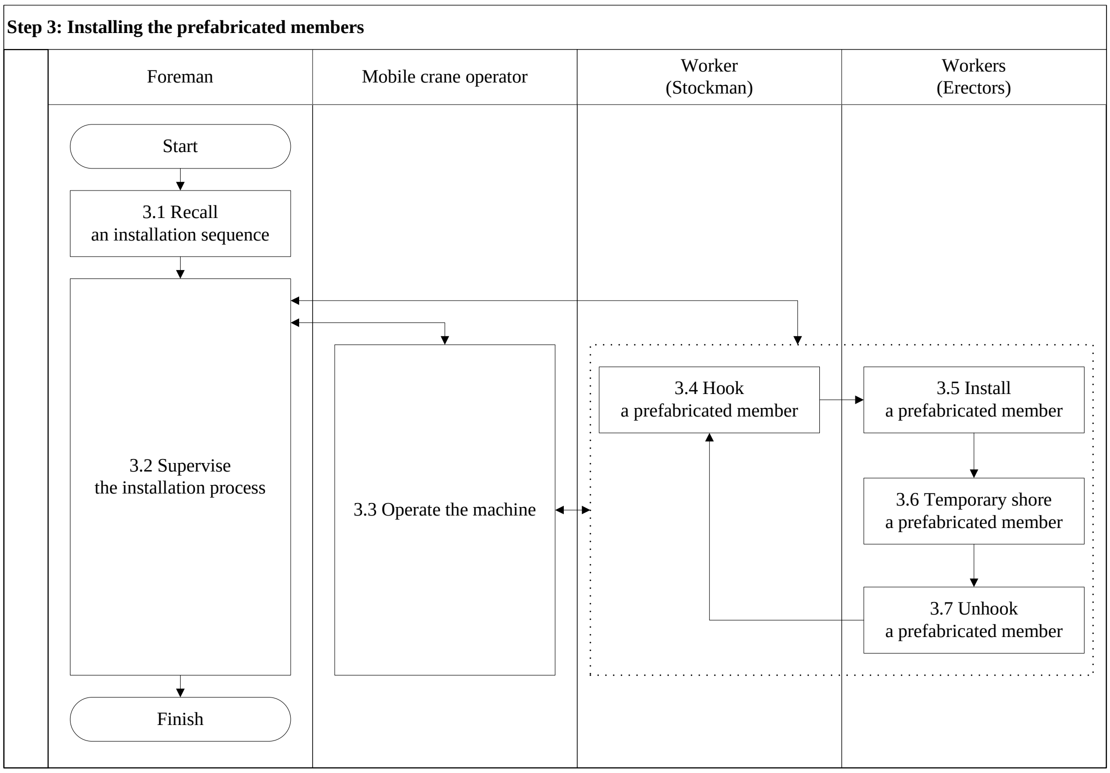

Figure 4.19 Installing a prefabricated member

For the action flow, the foreman started by recalling an installation sequence from the previous step. Then, the foreman performed the supervision procedures until all prefabricated members were installed. The actions included the operation by following an installation sequence, providing information for stockman to hook a prefabricated member, providing information for erectors to install a prefabricated member, and supervision and cooperation with personnel in the installation group.

In this installation step, a mobile crane operator supported the operation by lifting and moving the prefabricated members. The operator also controlled the machine to move between stock location and the house, controlled the machine to hook, lift, install, and unhook a prefabricated member, and cooperated with the personnel in the installation group.

Stockman performed the actions to find a prefabricated member and hook a member. Stockman cooperated with the personnel in the installation group while the actions were being performed.

When a prefabricated member was lifted and moved to the proper location, erectors handled the member and installed it, and then the shoring step began. Erectors performed the shoring and the adjustments respectively. The shoring generally used props to support the member. The erectors adjusted the member in terms of level, alignment, and inclination. After shoring, the erectors unhooked the member and started the process again with a new member. The erectors cooperated with the personnel in the installation group throughout the process. The action flow of this step is shown in Figure 4.20.

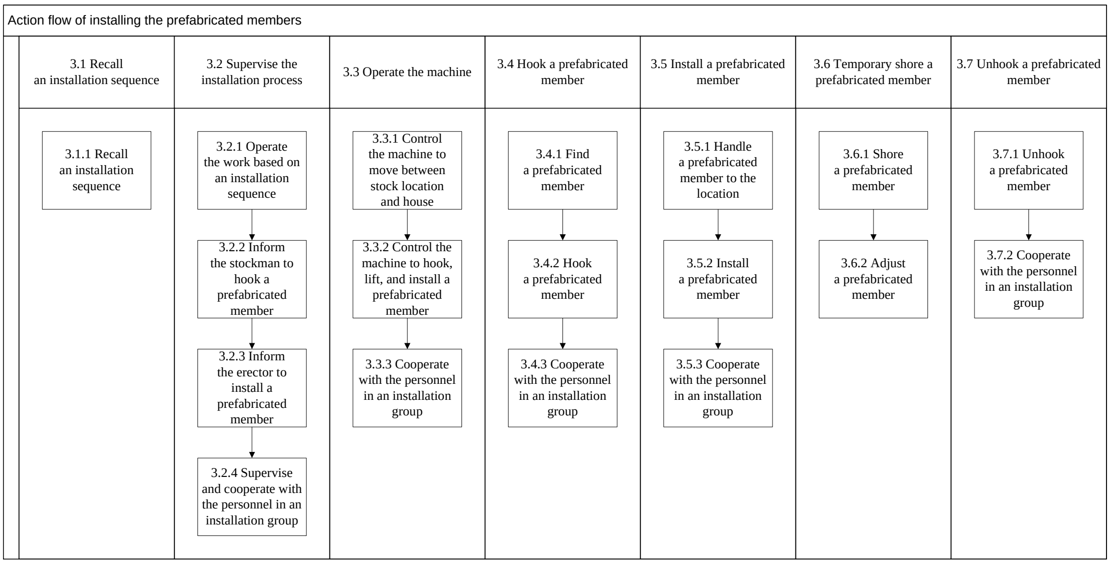

Figure 4.20 Action flow of installing the prefabricated members

4.3.4 Checking the availability of other resources

The foreman operates this step as the supplementary step by considering the resource requirements, identifying the resources, perceiving the list of available resources, and deciding whether to finish checking as shown in Figure 4.21. The resources in this step cover the personnel, materials, tools, and equipment. The function and illustration of sample materials, tools, and equipment are described in this part and shown in Table 4.2, Table 4.3, and Table 4.4 respectively.

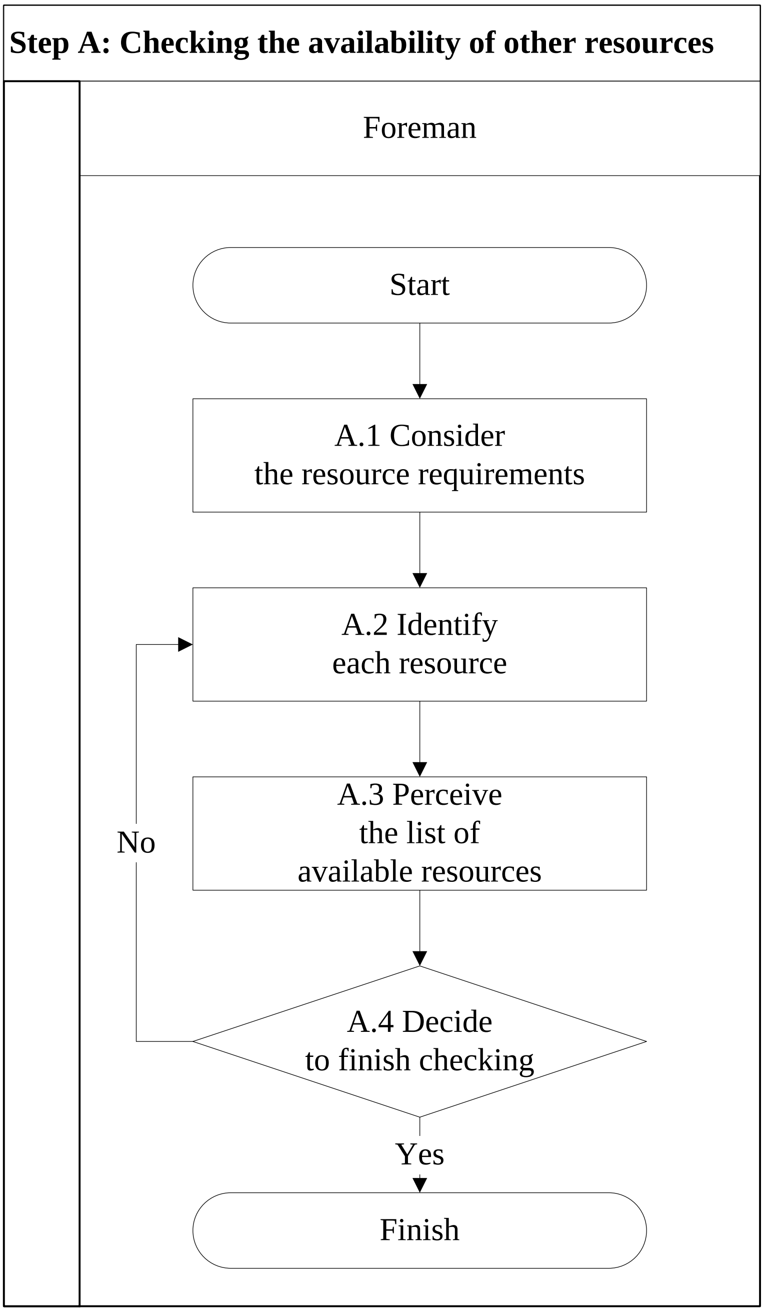

Figure 4.21 Checking the availability of other resources

Table 4.2 Functions and illustrations of materials

Materials	**Functions**	**Illustrations**
Adjusting bolt	- Adjust the level of prefabricated member	
Dowel	- Transfer the load from the prefabricated member to another structure	 
Epoxy	- Bond the dowel to another structure such as prefabricated beam or wall	
Shimplate	- Raise the level of prefabricated member in case of the highest level of adjusting bolt is not enough	
Bolt	- Connect the prefabricated member to another tool or structure	

Table 4.2 Functions and illustrations of materials (Cont.)

Materials	Functions	Illustrations
Backing rod	- Fill the gap between a prefabricated member and another member or between a prefabricated member and another structure before using the polyurethane to conceal the gap	
Polyurethane	- Conceal the gap - Prevent the water leak - Conceal the crack, which may occur, by its elastic feature	

Table 4.3 Functions and illustrations of tools

Tools	Functions	Illustrations
Stock rack	- Store the prefabricated members	
Machine base plate	- Increase the stability of machine by distributing the machine load - Increase the accessibility for the poor ground condition - Reduce the ground damage from the machine point load	

Table 4.3 Functions and illustrations of tools (Cont.)

Tools	**Functions**	**Illustrations**
Cable, shackles, and hooks	- Link the mobile crane and the lifted object in lifting, moving, or installation	 
Driller	- Drill the structure to insert dowel or bolt	
Hammer	- Drive the dowel or bolt in to the hole	
Crowbar	- Lever and move a prefabricated member to a desired position - Lever a prefabricated member to insert the shimplate	
Wrench	- Tight the bolt in the shoring process and other processes	

Table 4.3 Functions and illustrations of tools (Cont.)

Tools	**Functions**	**Illustrations**
Prop	- Shore the prefabricated member - Adjust the inclination of prefabricated member	 
Leveling tool	- Measure the inclination and level of prefabricated member	
Plumb	- Measure the inclination of prefabricated member	
Steel tape	- Measure the dimension of prefabricated member, the distance from offset line, and the dimension and location of structure	

Table 4.4 Functions and illustrations of equipment

Equipment	**Functions**	**Illustrations**
Mobile crane	- Lift and move the prefabricated members in the installation process - Lift or move other related materials and tools	

The actions in this step were similar to the actions of checking the available prefabricated members. At the start, the foreman recalls the target group of an installation process from the previous step. Thus, the list of required resources based on the installation of prefabricated members in the target group is considered. This list helps the foreman to scope and carry out resource checks. Then, the foreman looks at and identifies each resource by its appearance using his knowledge and skills.

After identifying each resource, the foreman records or remembers the availability of the resources. The list of available resources is perceived by accumulating the available resources and their quantity. The foreman decided to stop searching when resource requirements were complete or could not find the resource any more. Otherwise, the foreman searched for the resources by redoing step A.2 or searched at other possible locations. Finally, the foreman perceived the list of available resources at the end of this step. All actions in this step are illustrated in Figure 4.22.

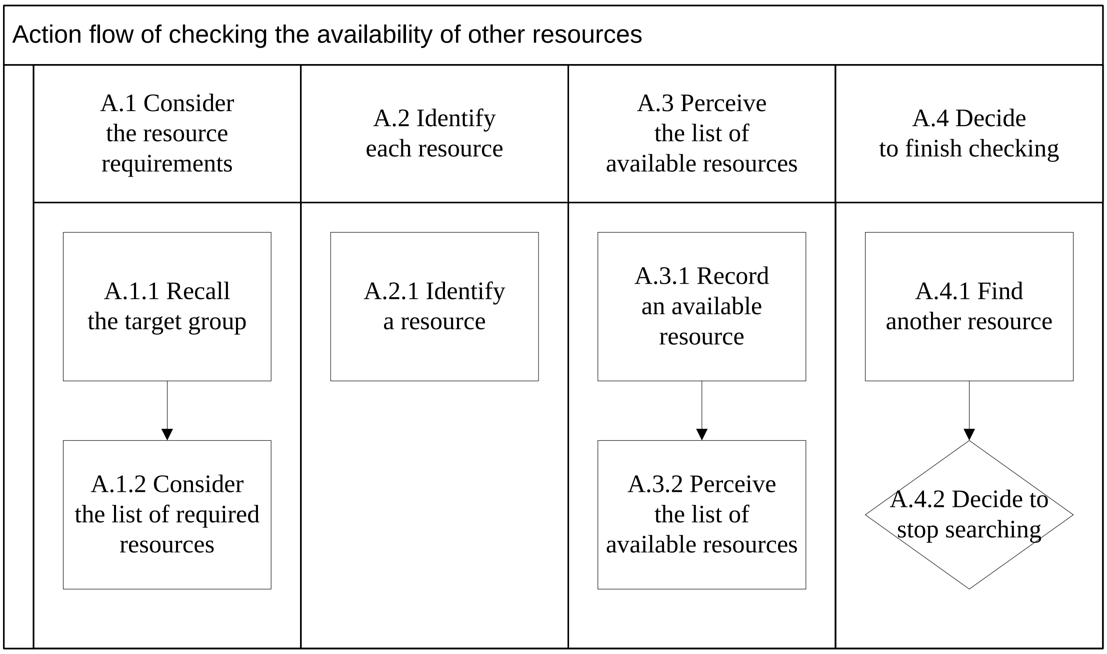

Figure 4.22 Action flow of checking the availability of other resources

4.3.5 Comparing the required resources and the available resources

In this step, the resource requirements and the available resources were recalled and compared to perceive the list of unavailable resources as shown in Figure 4.23. The resources included the prefabricated members, materials, personnel, tools, and equipment. This comparison is a supplementary step for making a decision for the installation step.

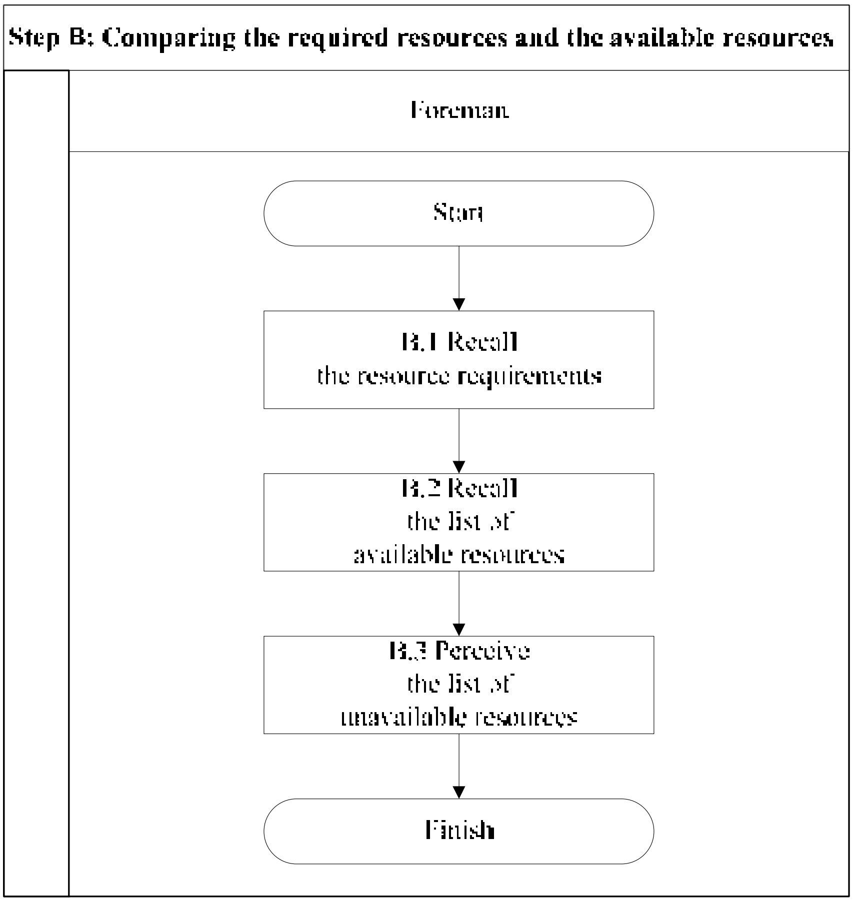

Figure 4.23 Comparing the required resources and the available resources

The process started from the recall of resource requirements. These requirements included the list of resource requirements based on the installation of members in the target group. The members in the target group were interpreted as prefabricated member requirements. Then, the available resources were recalled. In this step, the list of available resources and the list of available prefabricated members were separately acted on. Finally, the required resources and the available resources were compared, and the list of unavailable resources was perceived. The action flow of this step is shown in Figure 4.24.

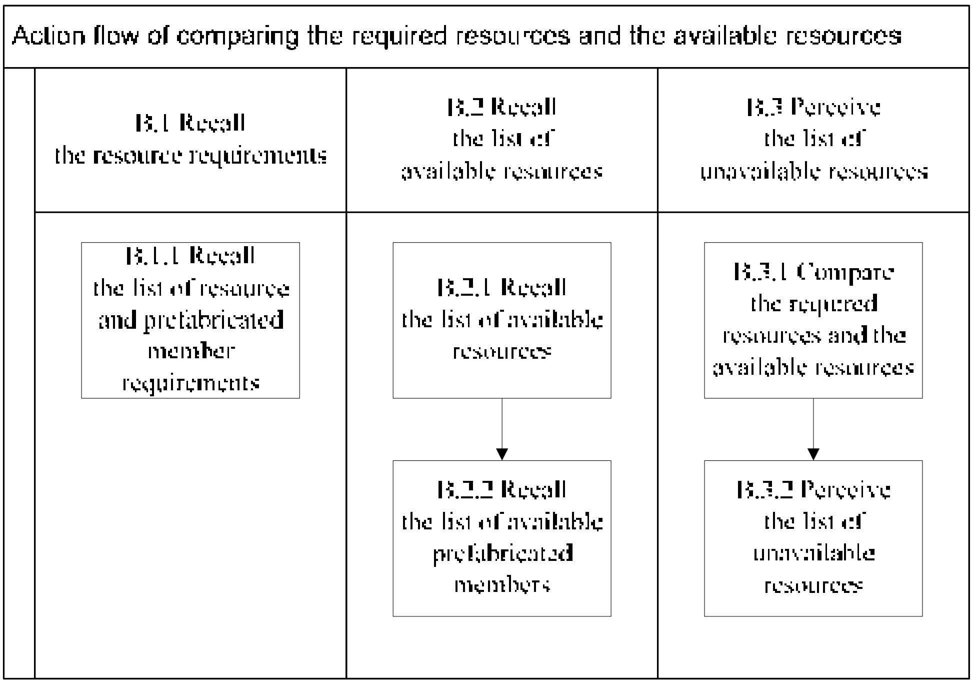

Figure 4.24 Action flow of comparing the required resources and the available resources

4.3.6 Deciding the work location of the mobile crane

The related personnel in this step include a mobile crane operator and related workers. The mobile crane operator plays a major role in this step and is the person who considers the suitable work location, perceives the list of available resources, reconsiders the work location, and sets up the machine. The workers support the work duties by preparing and handling the resources at the location, including setting up the machine. The work breakdown structure of this step is shown in Figure 4.25.

Considering the work location is the first action in this step. The target group of installation and the list of prefabricated members are recalled by the mobile crane operator. Then, the working range of the machine is considered, along with the prefabricated member weight and location. The location pertains to both stock location and installed location. Next, the conditions of the ground at the work site is analysed by the mobile crane operator in terms of accessibility and the possible bearing load of the machine. Then, the mobile crane operator arrives at a suitable work location. The work location involves not only the distance from the house but also the alignment of the mobile crane as shown in Figure 4.26.

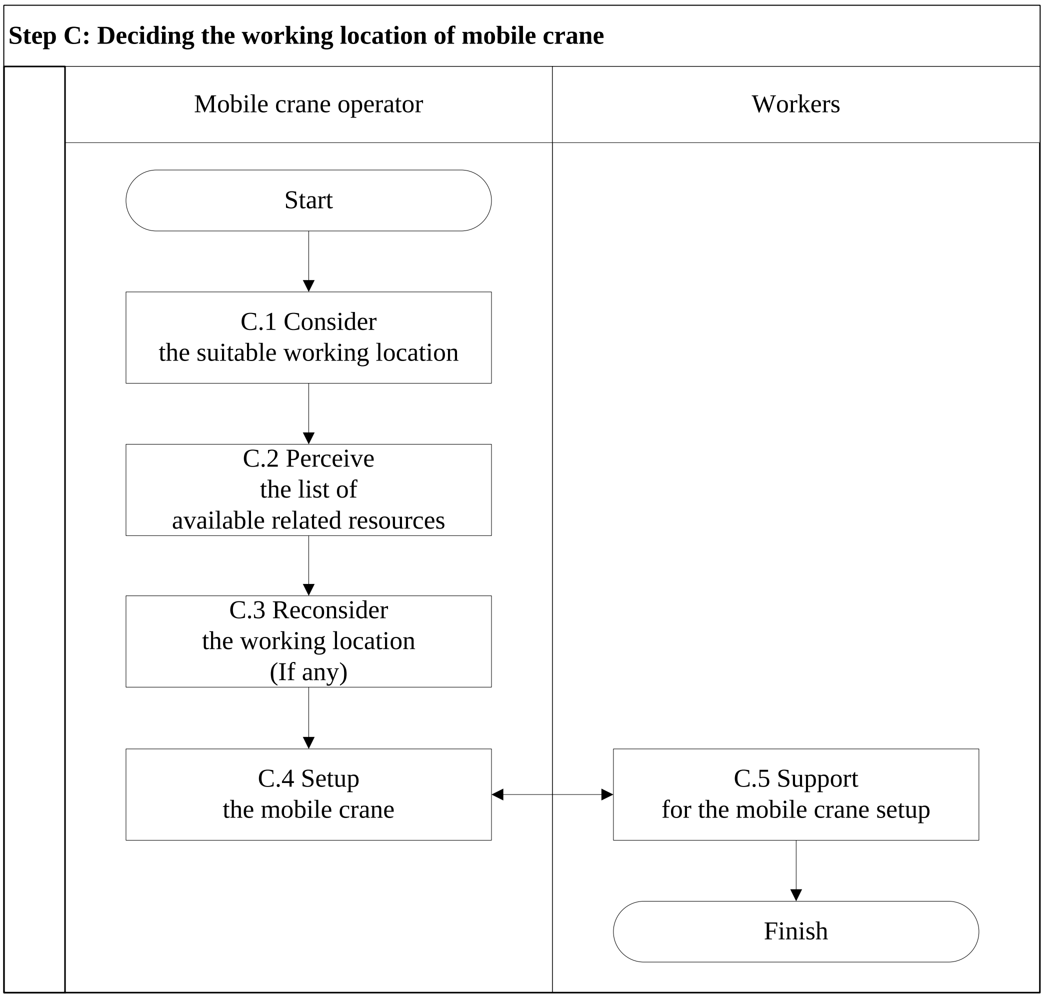

Figure 4.25 Deciding the work location of the mobile crane

The available resources were recalled in the next step. The required resources were also considered to find out the requirements based on the actual conditions. One of the most important resources in this step was the machine base plate. These plates varied in size, from large, medium to small. The number and size requirements of machine base plates depended on the work location of the mobile crane and the condition of the ground.

In the case of incomplete machine base plates, the required resources were searched and prepared in order to set up the machine at a suitable location. Otherwise, the required resources and the available resources, especially the machine base plates, would be compared and the work location reconsidered.

After agreeing to the work location, the related resources were moved to the location and the mobile crane was set up with the cooperation of the mobile crane operator and workers as shown in Figure 4.27. The action flow of deciding the work location of the mobile crane is shown in Figure 4.28.

Figure 4.26 Different alignments of mobile crane

Figure 4.27 Set up the mobile crane and support from workers

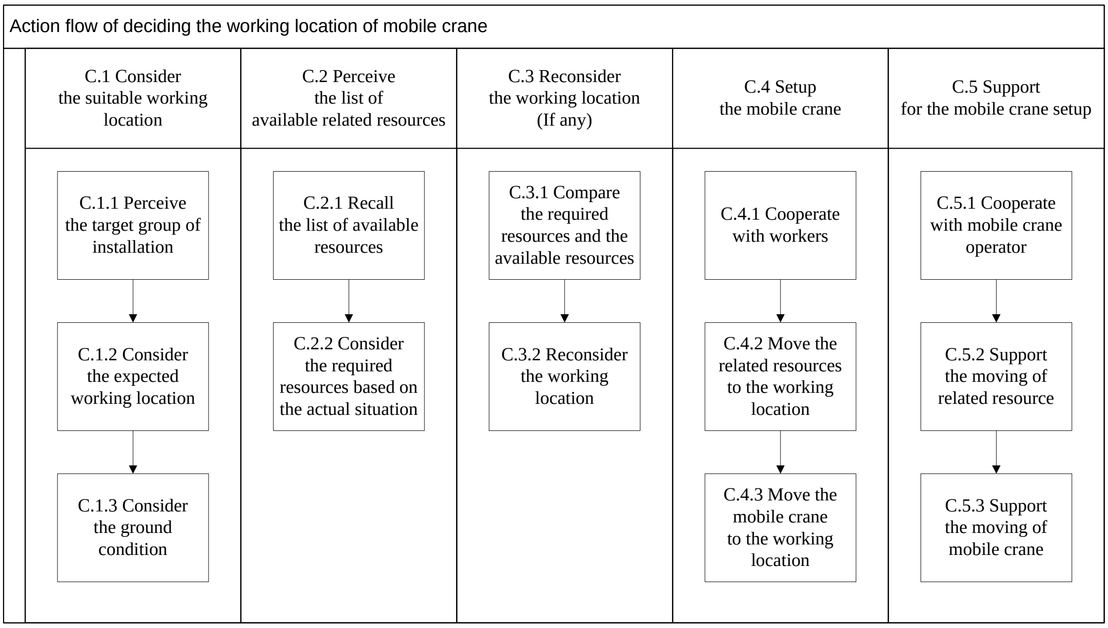

Figure 4.28 Action flow of deciding the work location of the mobile crane

4.3.7 Inspection the installed prefabricated members

After the prefabricated members were installed, the inspector inspected the quality of installation by checking the list of prefabricated members, identifying each prefabricated member, and inspecting each prefabricated member as shown in Figure 4.29. The work was repeated until all installed members were inspected.

The inspector started by perceiving the list of prefabricated members. The list of prefabricated members in a structure and scope of work was checked by the inspector. Then, the inspector identified each prefabricated member by its appearance or marking. Perceiving the quality terms of each prefabricated member was the next action. The terms of quality were indicated under specifications or on checklists. Finally, the member was inspected and the results from the inspection were recorded. The decision to stop was made in the case that all the installed members were inspected. Otherwise, the inspector performed the above actions for another prefabricated member as part of a repetitive loop. The action flow and details are shown in Figure 4.30.

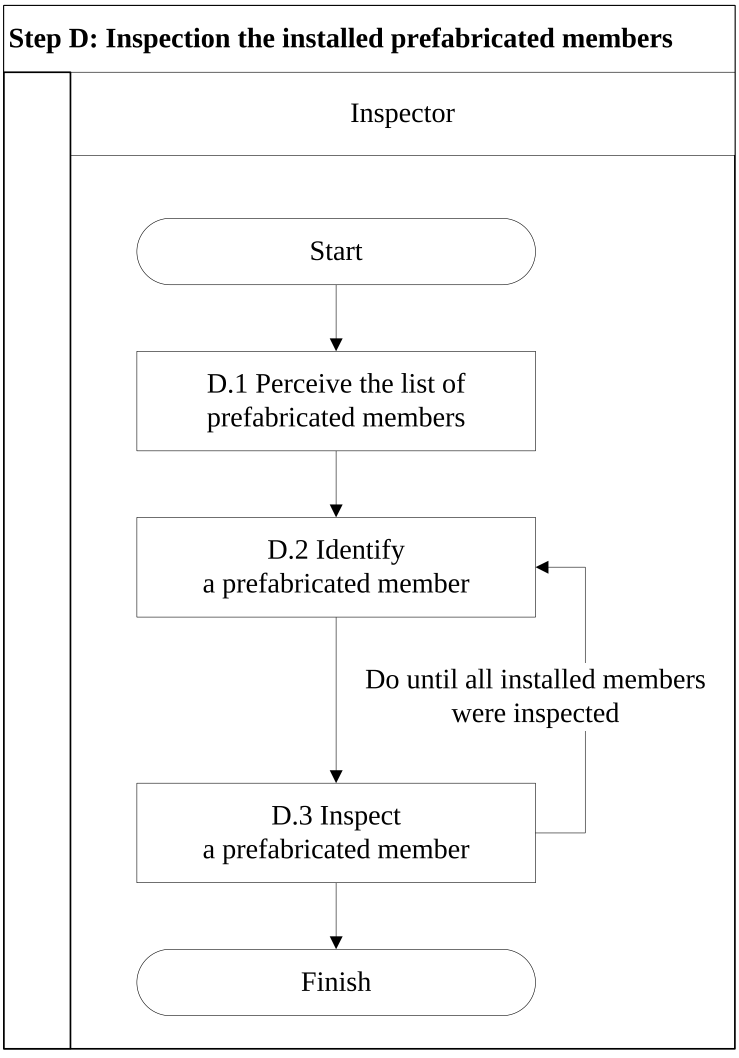

Figure 4.29 Inspection on the installed prefabricated member

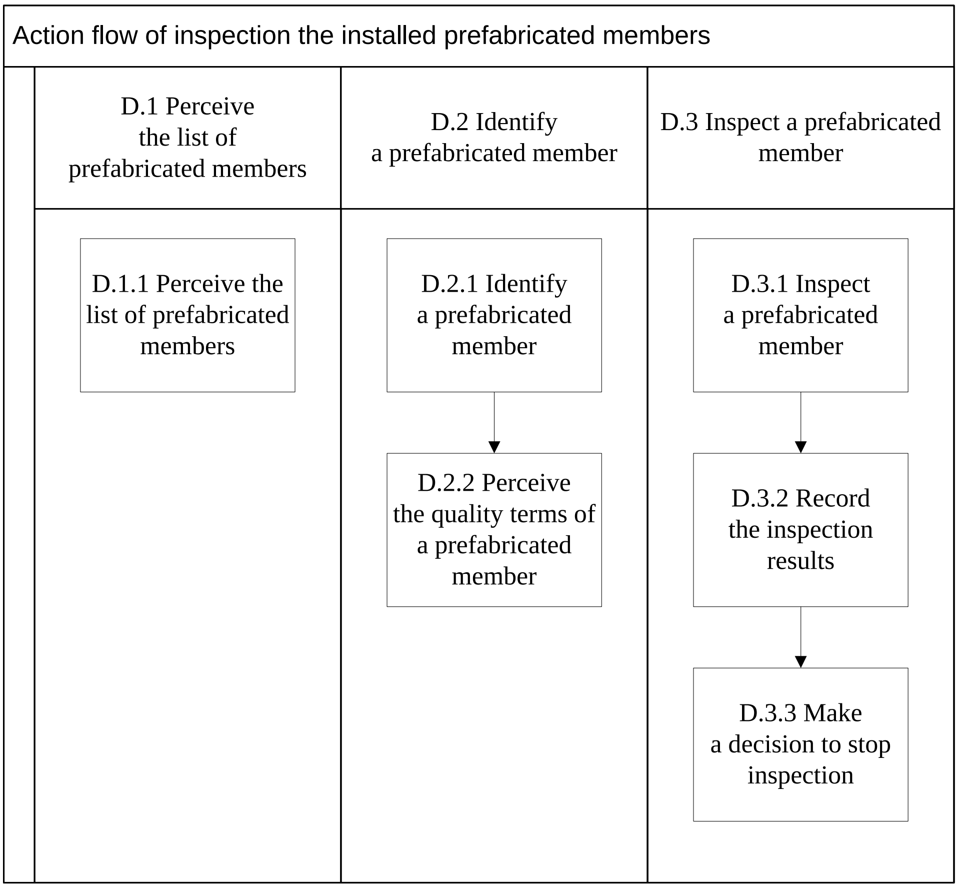

Figure 4.30 Action flow of inspection on the installed prefabricated members

4.4 Documents in the installation process

Although many documents were created or used for the construction project, some documents were used by an installation group, which is shown in Table 4.5. From the investigations, only the construction schedule and construction drawing were used in the installation process. Further details, such as installation sequence or work procedure, were unavailable for the installation group.

The information in the construction schedule did not focus on the installation process. The main information in the schedule was activities and planned operation date. The information of sub-activity, duration, activity relationship, labour, equipment, work procedure, and inspection activity were indicated in the schedule of some of the projects. In the construction drawing, the floor plan and views of each prefabricated member were the main information for the installation process. The information was interpreted for the list of members in a structure, the appearance of each prefabricated member, and the installed location of each prefabricated member. The examples of a construction drawing are shown in Figure 4.31. In addition, the transportation document was also found at the construction sites. It showed the list of delivered prefabricated members for each delivery trip. The list was used for checking the prefabricated member but the availability and location of each prefabricated member had to be rechecked with the actual stock.

Table 4.5 Documents in the installation process

Document	Project					
	A	B	C	D	E	F
Construction schedule	✓	✓	✓	✓	✓	✓
Construction drawing	✓	✓	✓	✓	✓	✓
Work procedure	-	-	-	-	-	-
Installation manual	-	-	-	-	-	-

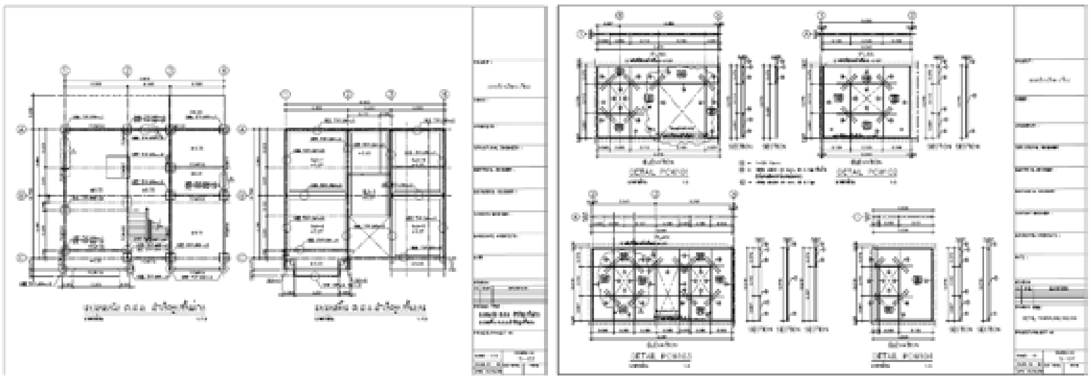

Figure 4.31 Examples of construction drawing

4.5 Changes in the prefabricated member installation

From the investigations, many changes occurred in the installation process. Any changes mean that the current condition at the construction site varies from the planned condition indicated by the designer or planner before the installation process. The foreman had the responsibility of detecting the changes and selecting the proper countermeasure in a timely manner. The changes are described as follows:

4.5.1 Unavailability of prefabricated members

Normally, the prefabricated members are assumed complete before the installation process begins. However, the unavailability of prefabricated members always arises during the actual installation process and affects the installation process significantly. From the investigations, the unavailability of prefabricated members occurs for various reasons, as shown in Figure 4.32.

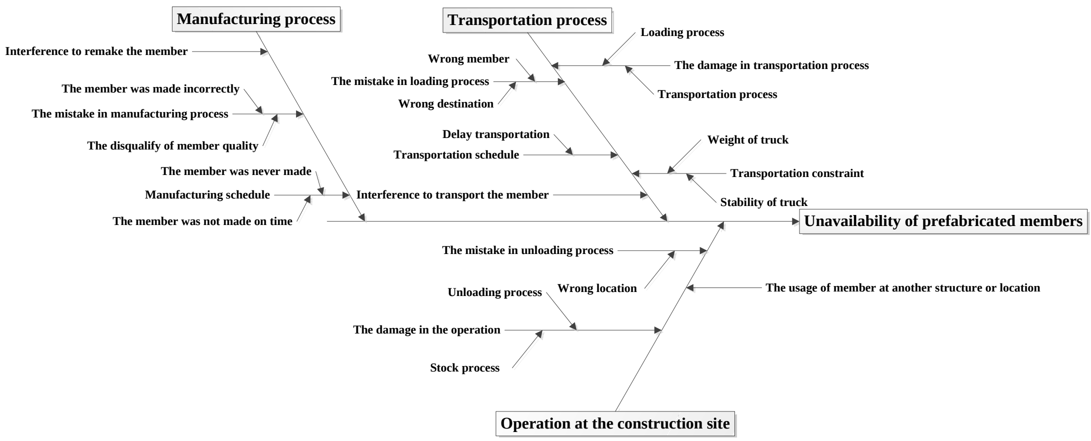

Figure 4.32 Causes of the unavailability of prefabricated members

According to the constraints and mistakes in the manufacturing and transportation process, the delivered prefabricated members always had the chance of incomplete installation. In addition, the prefabricated members that were transported by each delivery truck were inconsistent. The reasons for this were the manufacturing schedule, the quality control of manufacturing process, the transportation schedule, the limitation of transportation weight, and the stability of the trucks. The damage incurred to the prefabricated members was another reason why damaged members were sent back to the manufacturer, after which the damaged members are repaired or replaced and sent back to the project. Thus, the list of delivered members was interfered and inconsistent. Therefore, the unavailability of a prefabricated member tended to occur in the construction project.

Based on the unavailability of a prefabricated member, the installation process was decided whether to postpone or continue. The installation was postponed to prevent the double moving of resources and to operate at the structure, which had more ready resources. If the installation process was allowed to continue, the installation sequence was considered to avoid the line-of-sight blocking and the installation between prefabricated members.

4.5.2 Random location of prefabricated members in the rack

At the construction site, the location of each prefabricated member in the stock rack was changed randomly because the stock process of prefabricated members did not have a fixed location and procedure. The unloading and stock sequence of prefabricated members depended on the delivery schedule, the order of delivery trucks, the stability of the delivery trucks, the overlap of prefabricated members on the truck, and the stability of the stock rack, as shown in Figure 4.33, Figure 4.34, and Figure 4.35. The unloading started with the first arriving truck and the outer prefabricated member. The stock process started at the middle of the rack and alternated between the left and right side to balance and ensure the stability of the stock rack.

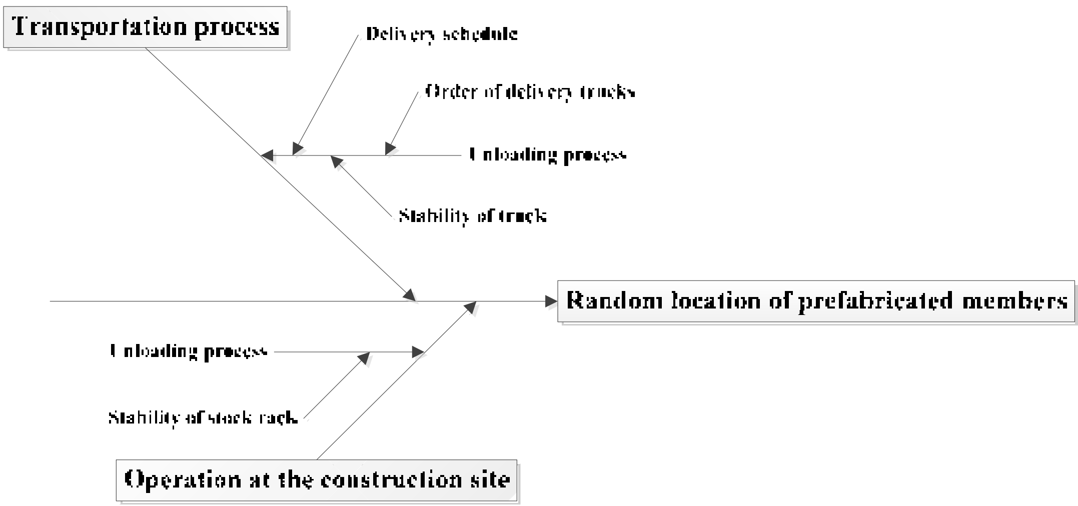

Figure 4.33 Causes of the random location of prefabricated members

Figure 4.34 Order of delivery trucks at a construction site

Figure 4.35 Back view and side view of prefabricated member overlapping

The random location of prefabricated members in a rack in turn changed the conditions of the installation process. It was difficult to fix or plan the stock location of each prefabricated member in the rack. The foreman had to check the availability of prefabricated members and consider the necessary members for the desired installation step. The stockman had to find the desired prefabricated member based on the shuffle in location. These mistakes and prolonged installation time may occur with this working scheme.

4.5.3 Excess prefabricated member in the rack

In the current practices, the stock rack was used for all prefabricated members in a house, such as the first floor wall and the second floor wall. Therefore, it was possible that a stock rack contained more than one prefabricated member structure. In addition, the rack was always located between two houses to reduce the number of rack transportation. Thus, the prefabricated members of another house might be stored in the rack for a moment. The causes of excess prefabricated members are shown in Figure 4.36. All this depended on the management in manufacturing, transportation, and installation process. Therefore, the prefabricated members in a rack might be in excess for the current installation. The foreman, therefore, has to check the excess prefabricated member to prevent a mistake in the installation process.

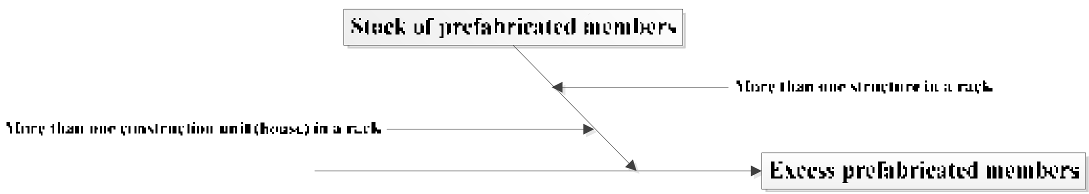

Figure 4.36 Causes of the excess prefabricated members in the rack

4.5.4 Unavailability of installation resources

As mentioned earlier, the installation process requires resources for the operation, such as personnel, materials, tools and equipment. From the investigations, the unavailability of materials and the unavailability of tools always arose in the installation process. The lack of materials occurred from a material shortage at the construction site. The lack of tools occurred from the management of an installation group, except the loss or damage of tools, because the tools were prepared and employed repeatedly. Thus, an installation group had to prepare and bring the tools from the previous installation site.

The installation process could not be operated or was shortened due to the unavailability of resources. The foreman has to detect the unavailability of resources and select the right countermeasures. Otherwise, the installation process is stopped before the process is complete, which results in precious time, money, and effort wasted.

4.5.5 Relative location between house, mobile crane, and stock

As mentioned in Table 4.1, the relative location between house, mobile crane, and stock affected the installation sequence of prefabricated members. The sequence was considered to avoid the line-of-sight blocking and the installation between prefabricated members. At the construction site, the stock location was not fixed due to the use of space and accessibility at that moment. Thus, the installation sequence was always varied based on the relative location between house, mobile crane, and stock.

4.6 Mistakes in the prefabricated member installation

From the investigations, the obstacles in prefabricated member installation were found. The mistakes are described below.

4.6.1 Mistakes in prefabricated member marking

At the construction sites, the mistakes in prefabricated marking were found. The mistakes were damaged markings, missing markings, and incorrect markings. The prefabricated member identification, which used only the marking, tended to be incorrect. With incorrect identification, the chance of wrong installations increased.

4.6.2 Mistakes in the prefabricated member installation

From the investigations, mistakes in the prefabricated member installation were found. The mistakes caused from the manufacturing, transportation, or installation process. The knowledge and skills were required to perceive and correct the mistakes.

However, the mistakes from the manufacturing process could not be prevented and corrected immediately because the prefabricated members were produced in advance. The mistakes were still found continuously and the correction was done later until the backlog of prefabricated members were installed or corrected. The foreman and an installation group needed the knowledge and skills to point out and correct the mistakes. Figure 4.37 shows the mistake from the opening work in the manufacturing process, while Figure 4.38 shows the correction of a dowel in the case where the dowel sleeve in the prefabricated member was too short.

Figure 4.37 The mistake from manufacturing process

Figure 4.38 Dowel correction

4.7 Summary

From the investigations and analysis, the current practices of the prefabricated member installation were summarised in this chapter. The chapter mentioned the personnel's roles and responsibilities, the prefabricated constructions, the documents in the installation process, the changes in the prefabricated member installation, and the mistakes in the prefabricated member installation.

Personnel in the installation process of prefabricated members consisted of an installation group, inspector, and supervisor. The group composed of two to five workers, a mobile crane operator, and a foreman, each of which had different roles and responsibilities to perform during the installation process. In some projects, the work of the foreman was assigned to the headman.

The installation process was broken down into three main steps and four supplementary steps. The three main steps are (1) checking the available prefabricated members, (2) making a decision for an installation process, and (3) installing the prefabricated members. While the four supplementary steps include (A) checking the availability of available resources, (B) comparing the required resources and the available resources, (C) deciding the work location of the mobile crane, and (D) inspection of the installed prefabricated members. These steps were broken down for activities and the action flows were created to analyse the knowledge and skill requirements.

The documents in the installation process were investigated. From the sample projects, only the construction schedule and construction drawing were used in the installation process. The information contained in documents was interpreted for the list of members in a structure, the appearance of each prefabricated member, and the installed location of each prefabricated member using the knowledge and skills of personnel. However, these documents did not have further information about the installation, i.e., installation sequence.

In addition, the changes and mistakes in the installation process were revealed from the investigations. The changes were the unavailability of prefabricated members, the random location of prefabricated members in the rack, the excess prefabricated member in the rack, the unavailability of installation resources, and the relative location between house, mobile crane, and stock. The mistakes in the prefabricated member installation were the mistakes in prefabricated member marking, and the mistakes in the prefabricated member installation. Both the changes and mistakes adversely affected the installation duration and installation quality.

Chapter 5
Knowledge and skill requirements

5.1 Introduction

The current practices of the installation steps are analysed in this chapter. The analysis aims to gather the knowledge and skill requirements of each person in each installation step. The results from this analysis will be used for automation approach development in order to reduce knowledge and skill requirements in the next step.

5.2 Analysis of knowledge and skill requirements

The knowledge and skill requirements were analysed based on the roles and responsibilities of each person, and the installation process of the prefabricated member. Moreover, the changes and mistakes in the installation process were also considered for analysis of knowledge and skill requirements as shown in Figure 5.1. The installation process was broken down into installation steps, activities, and actions respectively. The knowledge and skill requirements in each action were captured from two parts: (1) the physical work or movements, and (2) the related data and information. In addition, the requirements were revealed from the interviews of personnel, who were involved in each step of the installation process.

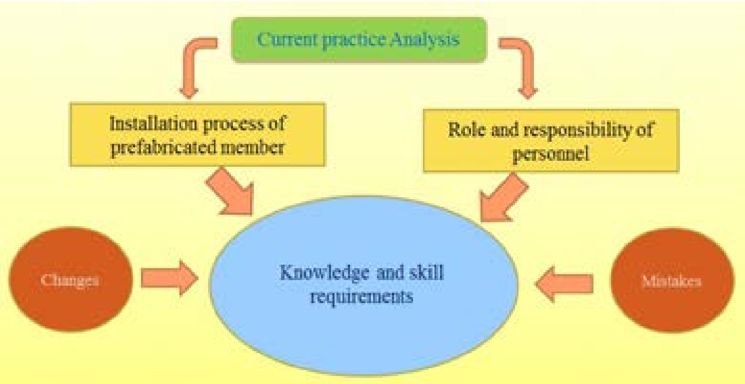

Figure 5.1 Analysis of knowledge and skill requirements

5.2.1 Checking the available prefabricated members

In this step, the knowledge and skill requirements were analysed from the combination of physical work and related data and information using the actions in work breakdown structure as shown in Figure 5.2. In addition, the interviewees revealed the requirements as well.

For <u>1.1.1 Identify the target group of installation,</u> the target group of installation was considered from the construction schedule in general. However, the number of available prefabricated members in the target group was also considered.

Thus, knowledge of the combination of prefabricated members in each structure and knowledge and skill of prefabricated member identification were required to consider and select the target group of installation. The majority group of available prefabricated members or the readiest group was considered to install as the target. The combination was perceived by the personnel’s knowledge and skill or considered based on the floor plan of the structure as shown in Figure 5.3. The floor plan always shows many details and information related to the prefabricated member. In Figure 5.3, the prefabricated members in the structure of the first floor wall were indicated as “PCW1XX”, such as PCW101. In this example, there are 19 prefabricated members in the structure of the first floor wall, which were indicated as PCW101 to PCW119 in the drawings. Thus, the foreman required the proper knowledge and skill to interpret the construction drawings, identify of the prefabricated members, perceive the prefabricated members or combination in each structure, and make a decision in this action.

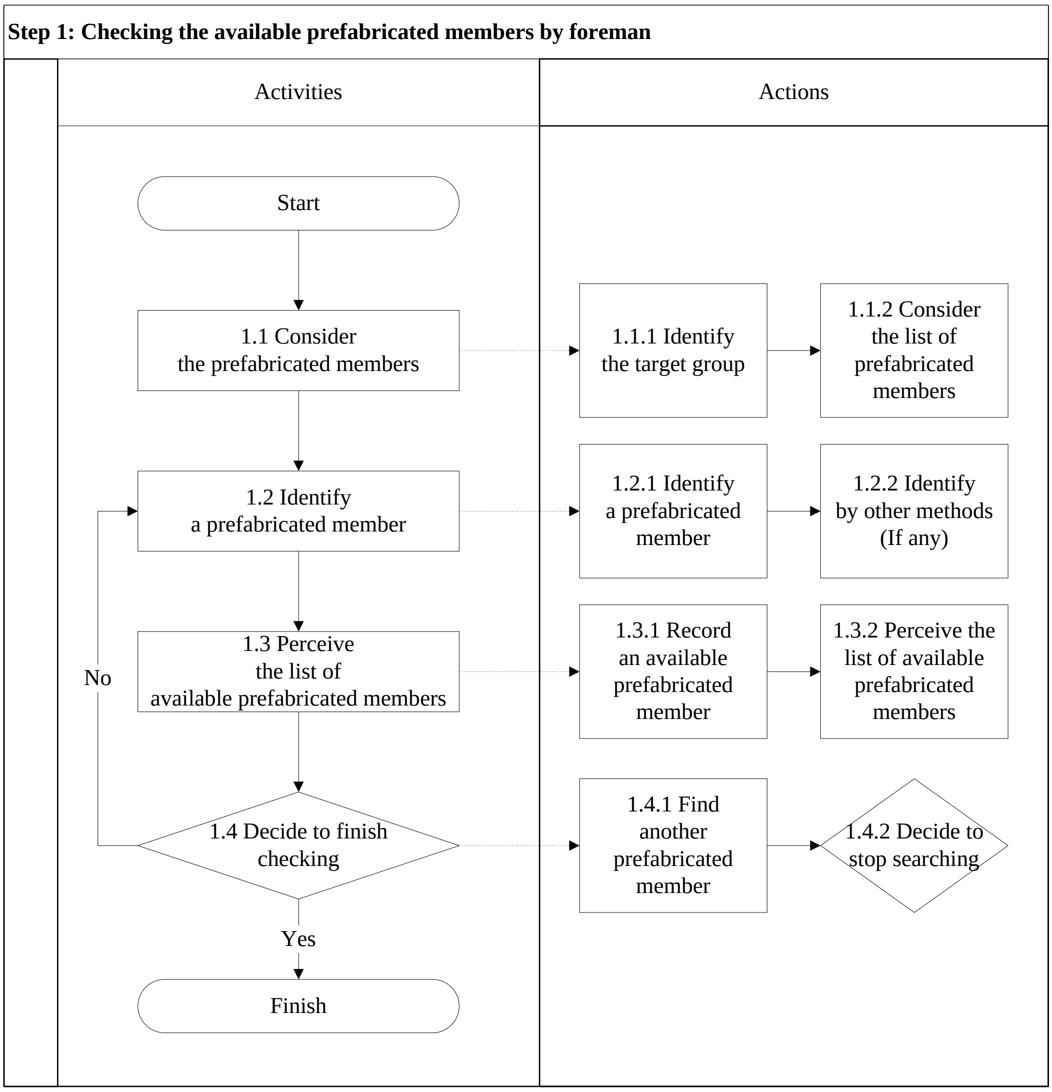

Figure 5.2 Work breakdown structure and actions of foreman in step 1

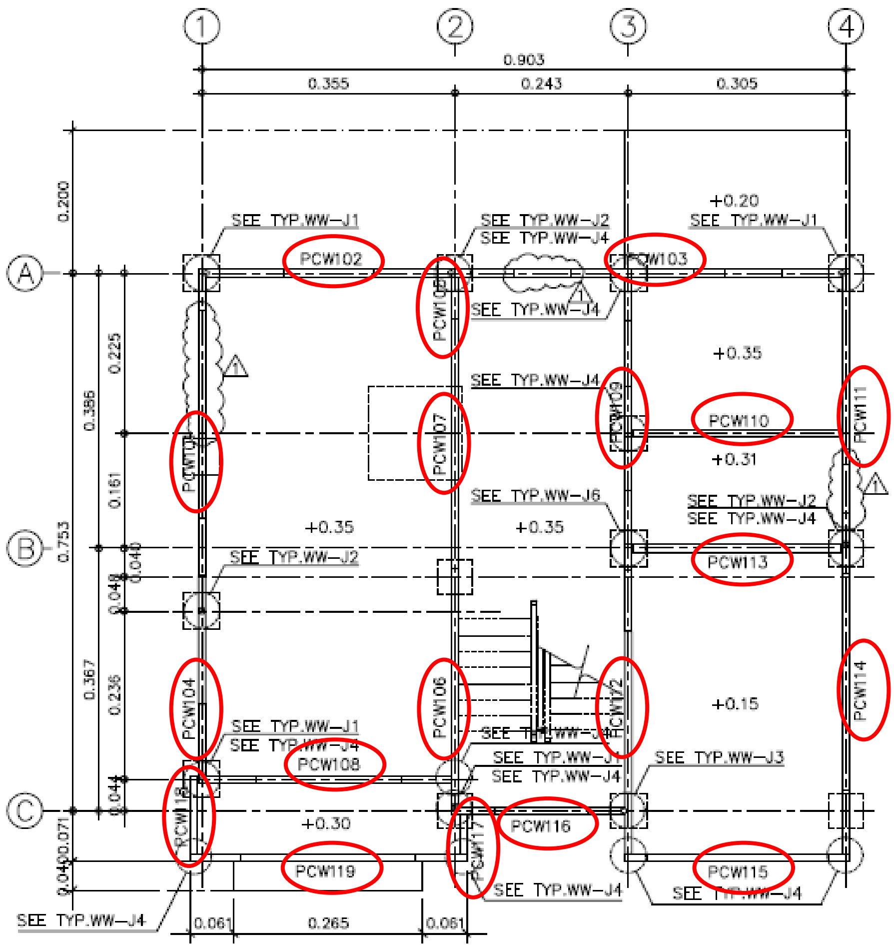

Figure 5.3 Floor plan in the construction drawing

After the target group was identified, the list of prefabricated members in the target group was considered, as stated in 1.1.2 Consider the list of prefabricated members. In order to perform this action, the foreman required the information of prefabricated members or combination in the target group by using his knowledge. The knowledge and skill for interpretation was also required in order to get the required information from the construction drawings.

For 1.2.1 Identify a prefabricated member, the foreman identified the prefabricated member at the stock rack or on the truck. The identification was done by prefabricated member appearance, markings, or any documents. For the identification by member appearance or marking, it was increasingly more difficult when the prefabricated members were placed closely together because the line-of-sight was limited, as shown in Figure 5.4. The identification could be supported by the section views in the construction drawing, as shown in Figure 5.5. However, due to the harsh environment of a construction site, the marking might be lost or damaged. Moreover, the marking might be incorrect due to possible mistakes in the previous processes.

Figure 5.4 Appearance of prefabricated members from side view

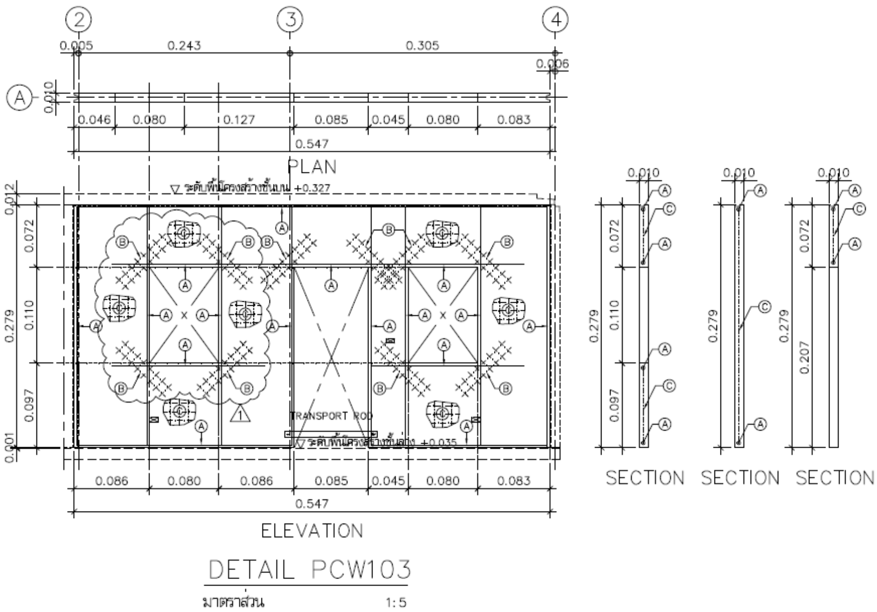

Figure 5.5 Section views of prefabricated member

The transportation document might be used for prefabricated member identification by obtaining the list of transported prefabricated members. However, this document does not guarantee that these members were actually stocked or located at the current location. The foreman must identify the prefabricated members in order to truly confirm the available prefabricated members. Thus, the knowledge and skill for prefabricated member identification is rather important for personnel who worked in this step of installation. In addition, the interpretation of construction drawings was used to support the work, especially in the consideration of section views as shown in Figure 5.5.

However, in an uncertain situation, the foreman identified a prefabricated member by using other methods as stated in 1.2.2 Identify a prefabricated member by other methods, such as measurement. The measurement was always performed to identify the prefabricated member. In this case, the use of measurement tools was necessary for measuring the dimensions of the prefabricated member and its related distance, and comparing the section views in the construction drawings. Thus, the use of measurement tools and the interpretation of construction drawings are critical for this action.

After identifying a prefabricated member, the foreman performed 1.3.1 Record an available prefabricated member. The foreman performed this action to record an available prefabricated member in a document or remembered the available member. Then, the foreman continually recorded and perceived the list of available prefabricated members as stated in 1.3.2 Perceive the list of available prefabricated members. The perception of available prefabricated members was originated by accumulating the available prefabricated members. Therefore, knowledge and skill for data collection were required in both actions.

However, if the members in the target group were incomplete, then 1.4.1 Find another prefabricated member by redoing activity 1.2 was performed to search another prefabricated member in the stock location or the foreman tried to search the member at other possible locations. In order to do this, the information of the prefabricated member combination in each structure was required to check the completeness of the prefabricated members in the target group. If the additional member was found, the knowledge and skill, which were required in 1.2 Identify a prefabricated member and 1.3 Perceive the list of available prefabricated members, was essential for further operations. In the case where the members in a target group were complete or the foreman could not find the prefabricated member, 1.4.2 Decide to stop searching was determined by the foreman. Thus, the foreman has the decision of whether to stop searching for the prefabricated member. The knowledge and skill requirements in this step were summarised in Table 5.1.

Table 5.1 Knowledge and skill requirements for checking the available prefabricated members

Activities / Actions	**Knowledge and skill requirements**
1.1 Consider the prefabricated members 1.1.1 Identify the target group of installation because more than one houses or structural types might be stored together at the same stock rack or on the same delivery truck	- (K&S) The interpretation of construction drawings - (K&S) The prefabricated member identification - (K) The perception of prefabricated members or combination in each structure - (K) The consideration of target group in the installation process
1.1.2 Consider the list of prefabricated members in a target group to scope the checking	- (K) The perception of prefabricated members or combination in target structure - (K&S) The interpretation of construction drawings
1.2 Identify a prefabricated member 1.2.1 Identify a prefabricated member by using knowledge. A prefabricated member can be identify by its appearance or marking	- (K&S) The prefabricated member identification - (K&S) The interpretation of construction drawings
1.2.2 In the uncertain or doubtful situation, identify a prefabricated member by other methods such as measurement or examination the construction drawings	- (K&S) The use of measurement tools - (K&S) The interpretation of construction drawings
1.3 Perceive the list of available prefabricated members 1.3.1 Record an available prefabricated member	- (K&S) The data collection
1.3.2 Perceive the list of available prefabricated members	- (K&S) The data collection

Table 5.1 Knowledge and skill requirements for checking the available prefabricated members (Cont.)

Activities / Actions	**Knowledge and skill requirements**
1.4 Decide to finish checking 1.4.1 If the members in the target group are not complete, find another prefabricated member by redoing activity 1.2 or try to search at other possible locations.	- (K) The perception of prefabricated members or combination in target structure (All knowledge requirements, which were required in activity 1.2 and 1.3)
1.4.2 Decide to stop searching in case of complete target group or cannot find the prefabricated member anymore	- (K) The decision making to stop searching

5.2.2 Making a decision for an installation process

The work breakdown structure and actions of the foreman in this step is shown in Figure 5.6. The work in this step is the non-physical work. Before making a decision, the foreman must have the information of unavailable resources as stated in 2.1.1 Recall the list of unavailable resources. Then 2.1.2 Consider the lack of critical resources was performed by considering the effects of unavailable resources. As mentioned earlier, some resources significantly affected the installation process. If these resources were unavailable, the installation process could not be performed and had to be postponed. For example, an unavailable mobile crane, mobile crane operator, or driller obstructed the installation process. However, where the unavailability of some resources affected the installation process but the process could still be performed also exists, such as the incomplete number of required props. This unavailability shortens the installation process. Thus, the foreman requires the knowledge to appropriately consider the effects of resource unavailability. After that, 2.2.1 Make a decision is performed. The foreman decides whether to postpone or continue the installation process using his knowledge and skill. If the foreman decides to postpone the process, the installation of this target group is cancelled.

In the case of continued installation, the foreman considers the related factors, which affect the installation process significantly, for example, the relative location of the mobile crane, stock, and house, the unavailable prefabricated members, and the unavailable resources, as stated in 2.3.1 Consider the location of the mobile crane, house, and stock, 2.3.2 Consider the effect of unavailable prefabricated members, and 2.3.3 Consider the effect of unavailable resources respectively. Thus, the foreman requires the applicable knowledge to consider the effects from these factors. Finally, the foreman generates the installation sequence as stated in 2.4.1 Generate the installation sequence. The foreman requires the proper knowledge and skill to generate the installation sequence of members in the target group based on the effects of related factors. However, the sequence must avoid the line-of-sight blocking and installation between prefabricated members. The examples of installation sequence in the case of the complete prefabricated members and resources are shown in Figure 5.7 and Figure 5.8. These two sequences are the installation of the same structure but with the only difference being the location of stocks. The sequence in Figure 5.7 is the installation when the member stock is on the left side, while Figure 5.8 shows the installation when the member stock is on the right side. The knowledge and skill requirements in this step are summarised in Table 5.2.

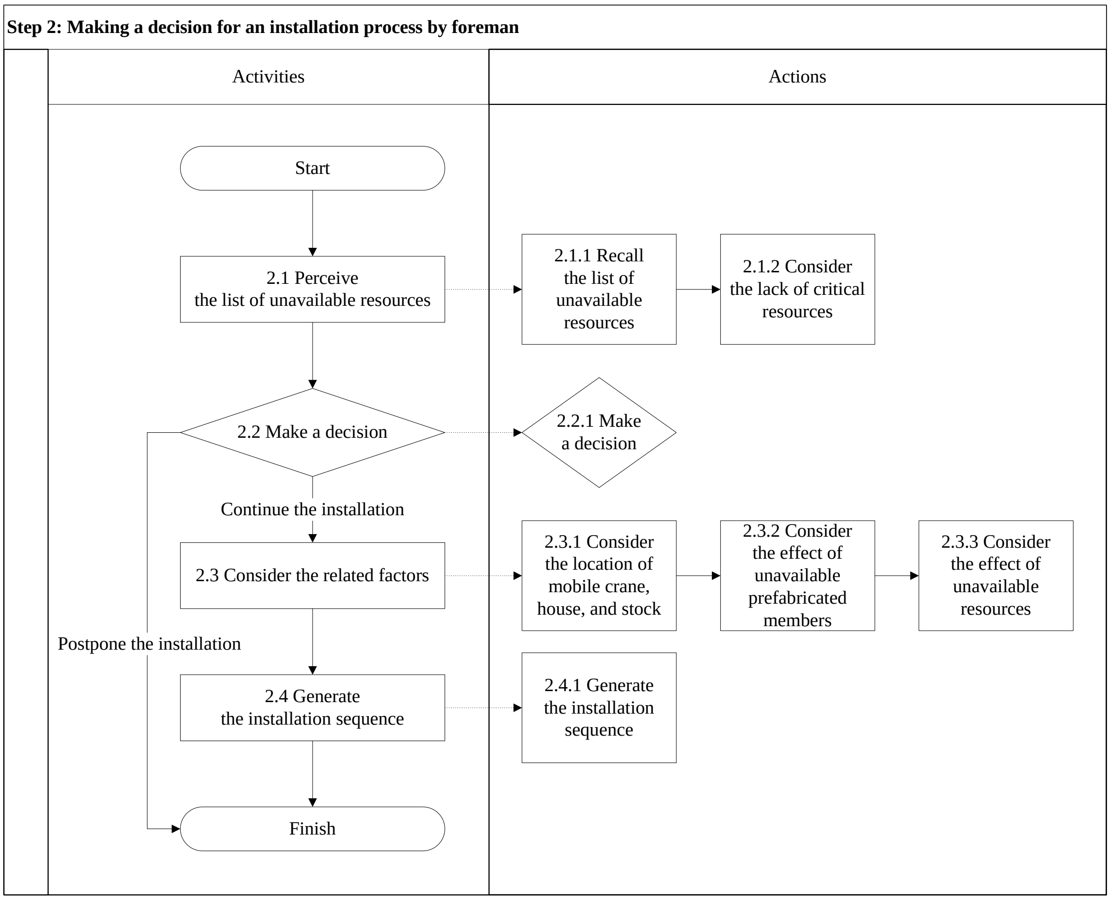

Figure 5.6 Work breakdown structure and actions of the foreman in Step 2

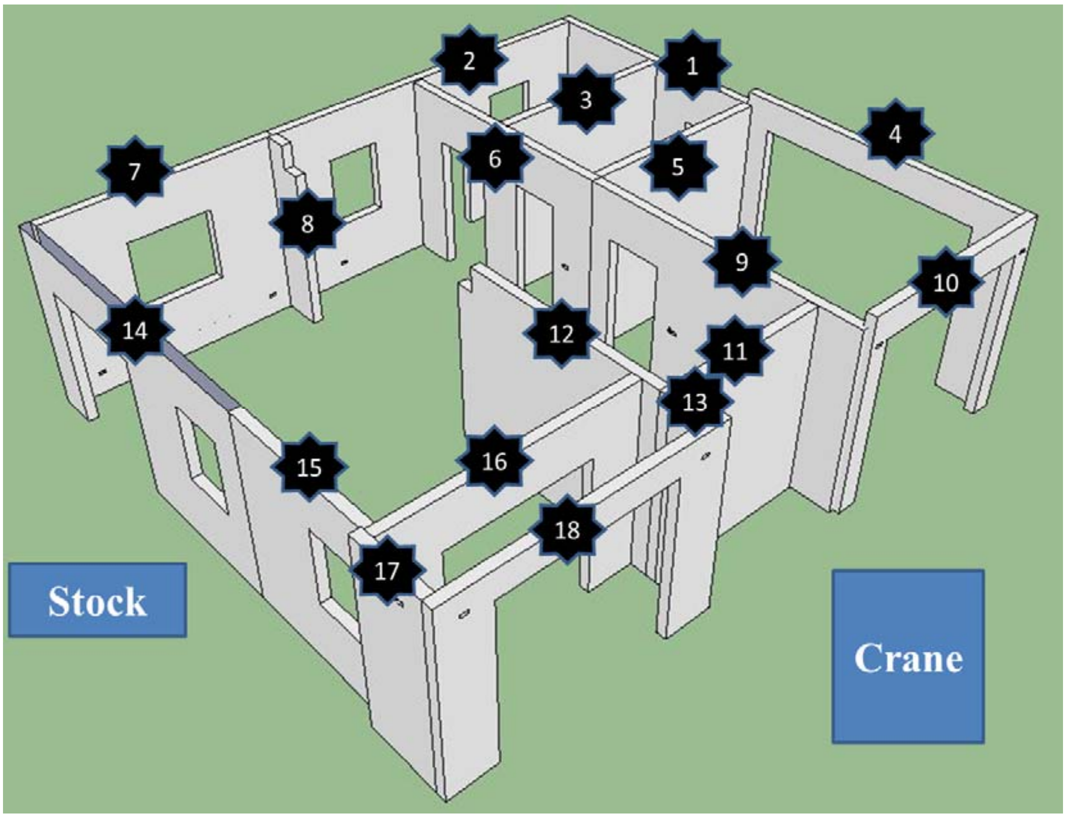

Figure 5.7 Installation sequence in the case of where the stock is on the left-hand side

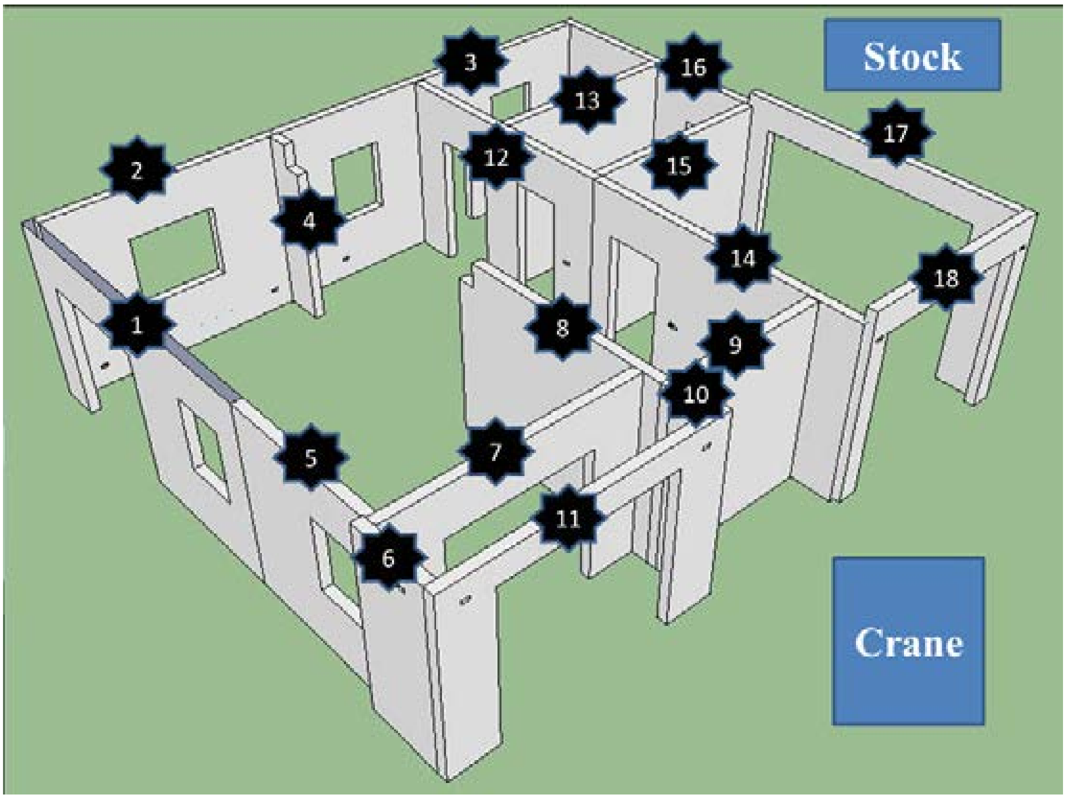

Figure 5.8 Installation sequence in the case of where the stock is on the right-hand side

Table 5.2 Knowledge and skill requirements for making a decision for an installation process

Activities / Actions	**Knowledge and skill requirements**
2.1 Perceive the list of unavailable resources 2.1.1 Recall the list of unavailable resources	- (K) The perception of unavailable resources
2.1.2 Consider the lack of resources especially the resources that affect to the installation significantly. The installation could not be performed without the complete of some resources such as mobile crane or driller.	- (K) The consideration of the effects from resource unavailability to the installation process
2.2 Make a decision 2.2.1 Make a decision whether to postpone or continue the installation process	- (K&S) The decision making to postpone or continue the installation process
2.3 Consider the related factors 2.3.1 Consider the location of house, mobile crane, and stock	- (K) The consideration of the effects from the house, mobile crane, and stock location to the installation sequence
2.3.2 Consider the effect of unavailable prefabricated members	- (K) The consideration of the effects from unavailable prefabricated members to the installation sequence
2.3.3 Consider the effect of unavailable resources	- (K) The consideration of the effects from resource unavailability to the installation sequence
2.4 Generate the installation sequence 2.4.1 Generate the installation sequence	- (K&S) The installation sequence generation

5.2.3 Installing the prefabricated members

In this step, the work involved the combination of physical work and non-physical work. The work was a cooperation between the foreman, mobile crane operator, stockman, and erectors. The work breakdown structure and actions of each person is shown in Figure 5.9 to Figure 5.12.

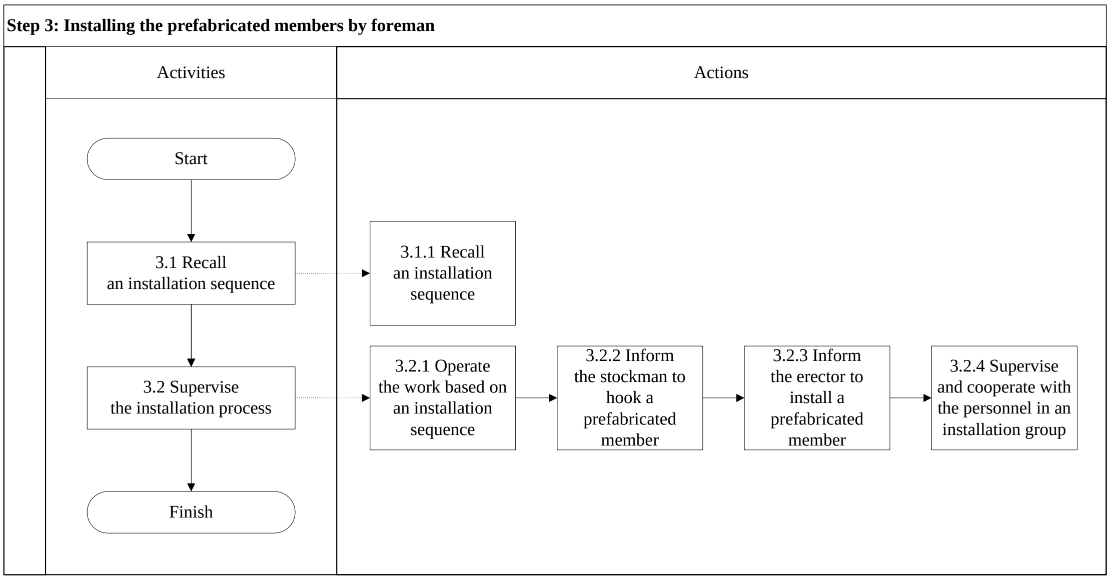

Figure 5.9 Work breakdown structure and actions of the foreman in Step 3

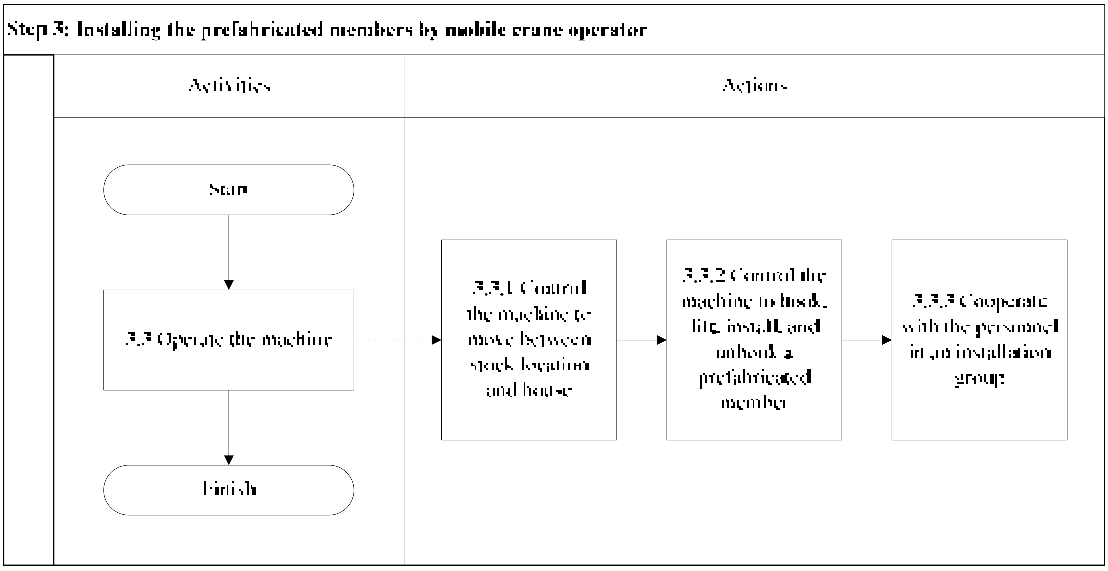

Figure 5.10 Work breakdown structure and actions of the mobile crane operator in Step 3

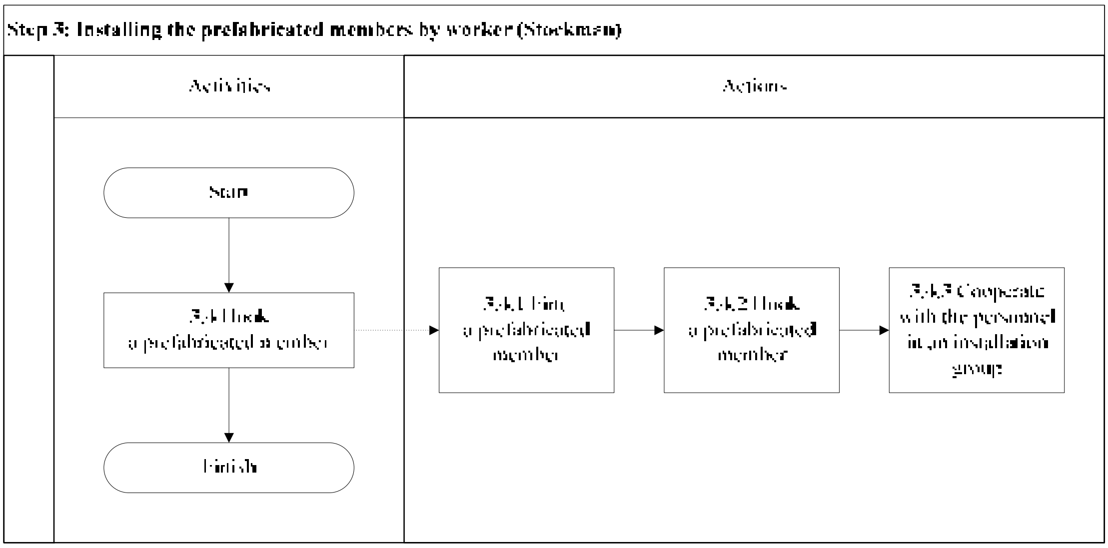

Figure 5.11 Work breakdown structure and actions of a worker (Stockman) in Step 3

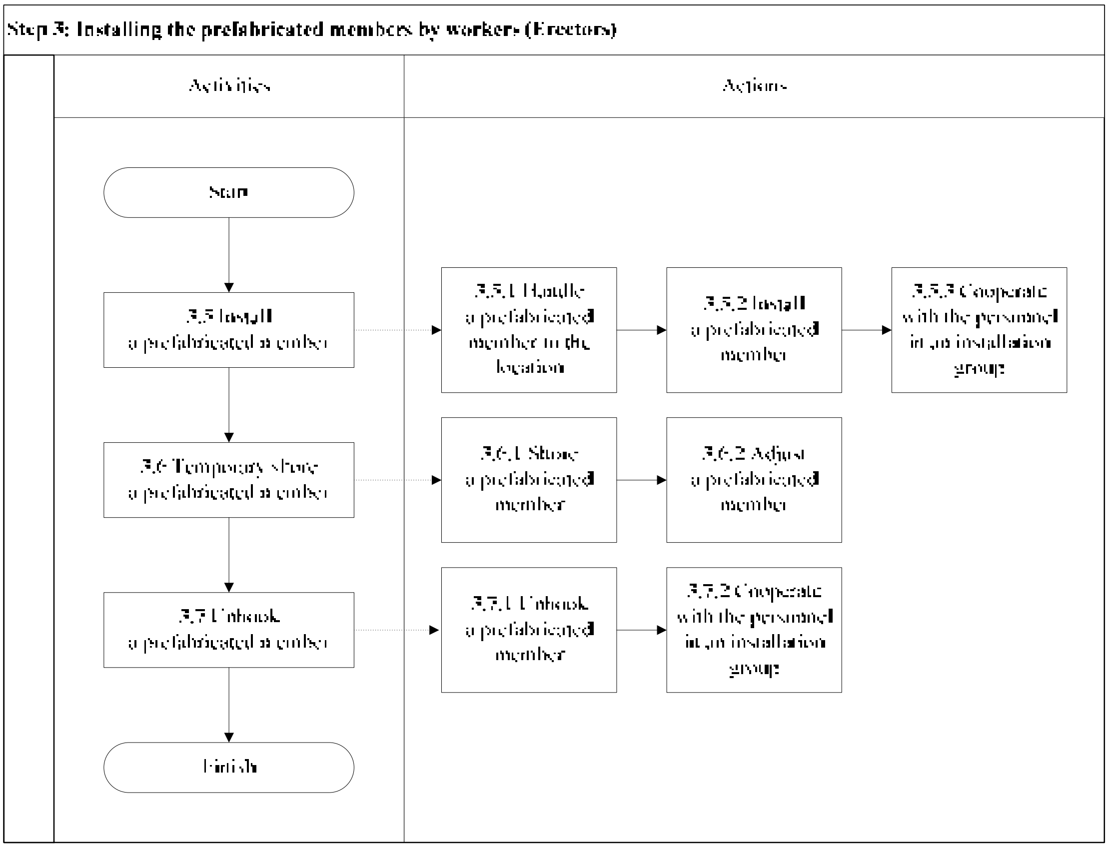

Figure 5.12 Work breakdown structure and action flow of workers (Erectors) in Step 3

This step starts with 3.1.1 Recall a selected installation sequence, in which the foreman requires the information of selected installation sequence from the step of making a decision for an installation process. The foreman is assigned to supervise the process while the prefabricated members are being installed. Thus, the foreman needs information about the details of a selected installation sequence, as stated in 3.2.1 Operate the work based on an installation sequence, by perceiving the list of members and the installation sequence. Then 3.2.2 Inform the stockman to hook a prefabricated member, in which the foreman informs a stockman to hook a desired prefabricated member. Thus, the foreman requires information on the current prefabricated member, which needs to be lifted and installed. 3.2.3 Inform the erector to install a prefabricated member is the next step. The foreman informs the erectors of the location where the prefabricated member needs to be installed. Therefore, the foreman must have the knowledge related to the location where the prefabricated members will be installed. Then 3.2.4 Supervise and cooperate with the personnel in an installation group, the foreman supervises the installation process in order to get the expected results. The assignments require the cooperation between the mobile crane operator, stockman, and erector. Thus, the work in this action requires the perception of the installation procedure, the perception of the installation specification, the interpretation of the construction drawings, prefabricated member identification, resource identification, the use of materials, the use of tools, the use of measurement tools, the use of cable, shackles, and hooks for resource hooking and unhooking, an understanding of hand signals, and use hand signals for communication.

For the mobile crane operator, the actions are shown in Figure 5.10. The main operations include 3.3.1 Control the machine to move between stock location and house and 3.3.2 Control the machine to hook, lift, install, and unhook a prefabricated member. The working scheme of a mobile crane operator can be illustrated as shown in Figure 5.13. Thus, the operator must have knowledge and skill to operate the machine to swing between the stock rack and house and to hook, lift, install, and unhook a prefabricated member. As mentioned earlier, while the mobile crane operator is controlling the machine, communication with the installation group is necessary. The popular method for communicating is using hand signals, as shown the examples in Figure 5.14. Thus, the operator must have knowledge and skill to understand hand signals in activity 3.3.3 Cooperate with the personnel in an installation group.

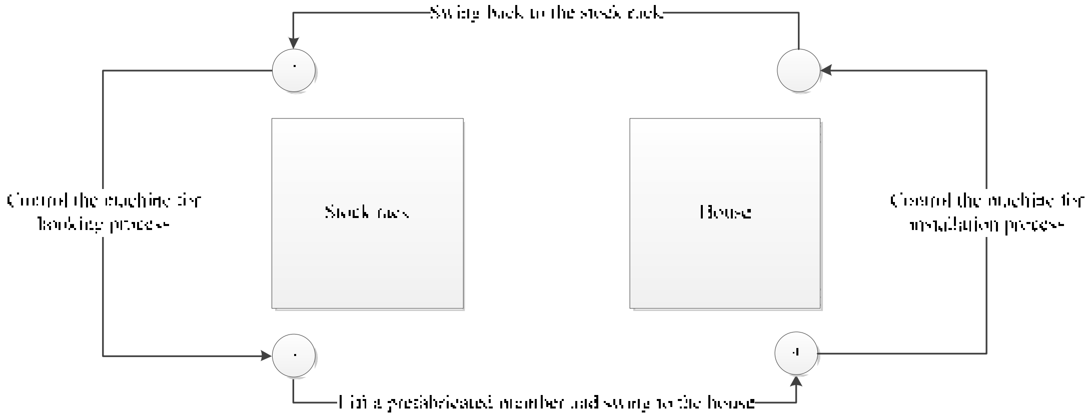

Figure 5.13 Working scheme of a mobile crane operator

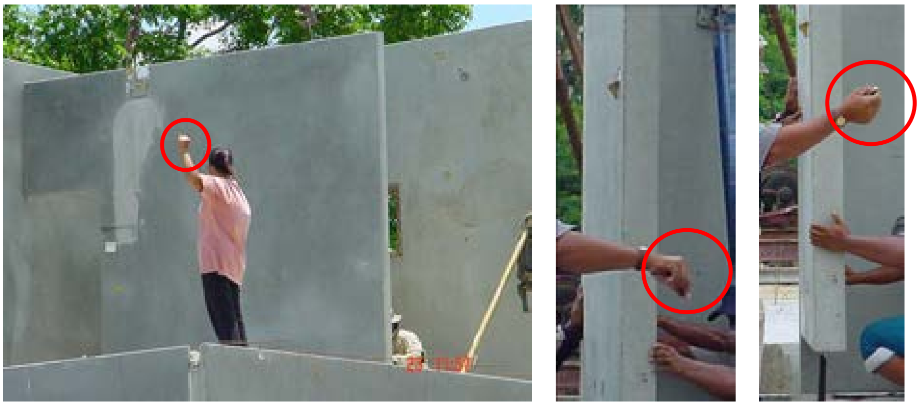

Figure 5.14 Examples of hand signals

The stockman's duty in this sequence is to hook a prefabricated member by 3.4.1 Finding a prefabricated member and 3.4.2 Hooking a prefabricated member. After gathering the required information about the prefabricated member from the foreman, a stockman performs the finding process for the required member at the stock rack or on the truck. Figure 5.15 shows the finding of a prefabricated member by a stockman at the stock rack. In order to do this, a stockman must be able to identify the prefabricated member and perceive the location of the required member. Then, a stockman must climb to the top of the prefabricated member and hook it as shown in Figure 5.16. Thus, working at a great height required and use of cable, shackles, and hooks were also required by a stockman for this action. In addition, a stockman communicates with the mobile crane operator to guide the mobile crane movement, such as when swinging to the installed location and lifting the prefabricated member as shown in Figure 5.17. Therefore, a stockman needs knowledge and skill how to communicate using hand signals.

Figure 5.15 Stockman finds a prefabricated member

Figure 5.16 Stockman hooks a prefabricated member

Figure 5.17 Stockman communicates with the mobile crane operator

After the prefabricated member was lifted and moved to the house, erectors had to handle the member to the desired location as stated in 3.5.1 Handle a prefabricated member to the location. In order to do this, the location, where the member had to be installed, needed to be known. Then, the erectors handled the member to the location by using the workforce along with the cooperation of the mobile crane operator. Figure 5.18 illustrates the action of the erectors. Therefore, the erectors require the knowledge of installed location and the knowledge and skill of handling the prefabricated member.

Then, 3.5.2 Install a prefabricated member is performed. The erectors require the knowledge of the installation procedure and specification. The installation procedure is required in this action because some additional tasks are required in this operation. An example is shown in Figure 5.19, in which the erectors bend the steel loops for this type of prefabricated member before installation. Erectors require the specification in order to properly install a prefabricated member as it is specified, for example, the member must be placed on two adjusting bolts, or two dowels must be inserted in the dowel sleeves, as shown in Figure 5.20. In addition, these actions require materials, tools and measurement tools to support this operation. Therefore, knowledge and skills about all the materials, tools and measurement tools used are required by the erectors.

Figure 5.18 Erectors handle a prefabricated member at the location

Figure 5.19 Erectors bend the steel loops

Figure 5.20 Two dowels must be inserted in the two dowel sleeves

However, while the erectors were working, an installation group cooperated with each other as stated in 3.5.3 Cooperate with the personnel in an installation group. The cooperation with mobile crane operator was communicated using hand signals as shown in Figure 5.14. Thus, having knowledge and skill of hand signal communication was vital for the erectors. The erectors communicated with the rest of the installation group through words.

The next action was 3.6.1 Shore a prefabricated member. The erectors drilled the slab or prefabricated member and fastened the bolts for shoring the member as shown in Figure 5.21 to Figure 5.23. Figure 5.23 shows the main tools in this action, including bolts, props, drills and wrenches; electricity is also needed for this operation. Therefore, knowledge and skills for material usage, use of tools, and shoring were required for this action. After that, the prefabricated member was adjusted as stated in 3.6.2 Adjust a prefabricated member. The erectors adjusted the member in terms of inclination, level, and alignment. The inclination was adjusted by turning the prop as shown in Figure 5.24. Crowbars and shimplates were employed for level adjusting as shown in Figure 5.25. The alignment was measured and compared with the house gridline. The gridline indicates the prefabricated member outline and the offset line. The alignment of a member was adjusted using a crowbar as shown in Figure 5.26. While the prefabricated member was adjusted, the personnel measured the related distance and position as shown in Figure 5.27. Therefore, knowledge and skill for inclination, level, and alignment adjustment using materials, tools, and workforce are required for this operation. In addition, the use of measurement tools is included in the list of requirements.

Figure 5.21 Shoring a prefabricated member

Figure 5.22 Fastening a bolt

Figure 5.23 The use of bolt, prop, wrench, and drill for shoring

Figure 5.24 Inclination adjustment

Figure 5.25 Level adjustment

Figure 5.26 Alignment adjustment

Figure 5.27 Measurement in the adjustment action

After the prefabricated member was installed, shored, and adjusted at the desired location, the member was unhooked as stated in 3.7.1 Unhook a prefabricated member. The erector performed this action by climbing to the top and unhooking the member as shown in Figure 5.28. Therefore, having knowledge and skills related to working at height and unhooking a prefabricated member was required by the erector for this action. After unhooking the member, the erector cooperated with the mobile crane operator as stated in 3.7.2 Cooperate with the personnel in an installation group. The erector gives the hand signals to the mobile crane operator to lift up and swing the cable for the next action. Thus, having knowledge and skill of hand signal communication is vital for erectors.

As mentioned above, the foreman, mobile crane operator, stockman, and erectors performed the step of installing the prefabricated members based on their different roles and responsibilities. The knowledge and skill requirements for each position in each action are summarised below in Table 5.3.

Figure 5.28 Unhook a prefabricated member

Table 5.3 Knowledge and skill requirements for installing the prefabricated members

Activities / Actions	**Knowledge and skill requirements**
3.1 Recall an installation sequence by foreman 3.1.1 Recall a selected installation sequence from the previous step	- (K) The perception of selected installation sequence
3.2 Supervise the installation process by foreman 3.2.1 Operate the work based on an installation sequence	- (K) The perception of details in a selected installation sequence
3.2.2 Inform the stockman to hook a prefabricated member	- (K) The perception of a prefabricated member, which will be lifted and installed
3.2.3 Inform the erector to install a prefabricated member	- (K) The perception of location, where a prefabricated member has to be installed

Table 5.3 Knowledge and skill requirements for installing the prefabricated members (Cont.)

Activities / Actions	**Knowledge and skill requirements**
3.2.4 Supervise and cooperate with the personnel in an installation group	- (K) The perception of the installation procedure - (K) The perception of the installation specification - (K&S) The interpretation of construction drawings - (K&S) The prefabricated member identification - (K&S) The resource identification - (K&S) The use of materials - (K&S) The use of tools - (K&S) The use of measurement tools - (K&S) The use of cable, shackles, and hooks for resource hooking and unhooking - (K&S) The communication using hand signals
3.3 Operate the machine 3.3.1 Control the machine to move between stock location and house	- (K&S) The operation of the mobile crane to swing between the stock rack and house
3.3.2 Control the machine to hook, lift, install, and unhook a prefabricated member	- (K&S) The operation of the mobile crane to hook, lift, install, and unhook a prefabricated member
3.3.3 Cooperate with the personnel in an installation group	- (K&S) The communication using hand signals
3.4 Hook a prefabricated member 3.4.1 Find a prefabricated member	- (K&S) The prefabricated member identification - (K) The perception of the prefabricated member location
3.4.2 Hook a prefabricated member	- (K&S) The work at height - (K&S) The use of cable, shackles, and hooks for resource hooking and unhooking

Table 5.3 Knowledge and skill requirements for installing the prefabricated members (Cont.)

Activities / Actions	**Knowledge and skill requirements**
3.4.3 Cooperate with the personnel in an installation group	- (K&S) The communication using hand signals
3.5 Install a prefabricated member 3.5.1 Handle a prefabricated member to the location	 - (K) The perception of the location, where a prefabricated member has to be installed - (K&S) The handling of prefabricated member
3.5.2 Install a prefabricated member	- (K&S) The perception of the installation procedure - (K&S) The perception of the installation specification - (K&S) The use of materials - (K&S) The use of tools - (K&S) The use of measurement tools
3.5.3 Cooperate with the personnel in an installation group	- (K&S) The communication using hand signals
3.6 Temporary shore a prefabricated member 3.6.1 Shore a prefabricated member	 - (K&S) The use of materials - (K&S) The use of tools - (K&S) The shoring of prefabricated member
3.6.2 Adjust a prefabricated member	- (K&S) The use of materials - (K&S) The use of measurement tools - (K&S) The prefabricated member adjustment for inclination, leveling, and alignment using material, tools, and workforce

Table 5.3 Knowledge and skill requirements for installing the prefabricated members (Cont.)

Activities / Actions	**Knowledge and skill requirements**
3.7 Unhook a prefabricated member 3.7.1 Unhook a prefabricated member	- (K&S) The work at height - (K&S) The use of cable, shackles, and hooks for resource hooking and unhooking
3.7.2 Cooperate with an installation group	- (K&S) The communication using hand signals

5.2.4 Checking the availability of other resources

According to Figure 5.29, the details of checking the availability of other resources were revealed in the work breakdown structure and actions. Similar to the step of checking the prefabricated members, the actions in this step were the combination of physical and non-physical work. First, A.1.1 Recall the target group of installation process was initiated. The foreman requires the information of the target group of installation and the list of prefabricated members in the target group. Then A.1.2 Consider the list of required resources, in which the foreman considers the resource requirements based on the installation of members in the target group. The resources include personnel, materials, tools, and equipment. From the investigations, the resources were categorised into two categories: (1) fixed quantity resources, and (2) variable quantity resources. The required quantity of fixed quantity resources was constant. Although the number of installing the prefabricated member was raised or changed, the required quantity of the variable quantity resources varied by the number of the installing prefabricated member. The higher the number of installing members resulted in the higher required quantity of resources. Thus, the foreman required the information of the target group and its members. Then, the foreman considered the fixed resources and the variable resources with the list of members in the target group to perceive the required resources and its quantity using his knowledge.

The next step was A.2.1 Identify a resource. As shown in the previous chapter, many resources were employed in the installation process. Some of the resources differed from the resources in conventional construction. Thus, the personnel required the knowledge and skill to identify the resources by their appearance only. The examples of resources at the installation location are shown in Figure 5.30.

After each resource was identified, A.3.1 Record an available resource including its cumulative quantity and A.3.2 Perceive the list of all available resources and its quantity were performed respectively. These operations required knowledge and skill for data collection, especially to accumulate the quantity of available resources. If the required resources were incomplete, A.4.1 Find another resource by redoing activity A.2 or trying to search at other possible locations was implemented. In order to do this, having the knowledge related to resource requirements for each structural type and each prefabricated member is necessary for the search scope. When the resource requirements were complete or the foreman could not find the resource, the foreman will make the decision to stop searching as stated in A.4.2 Decide to stop searching. The knowledge and skill requirements in this step are summarised in Table 5.4.

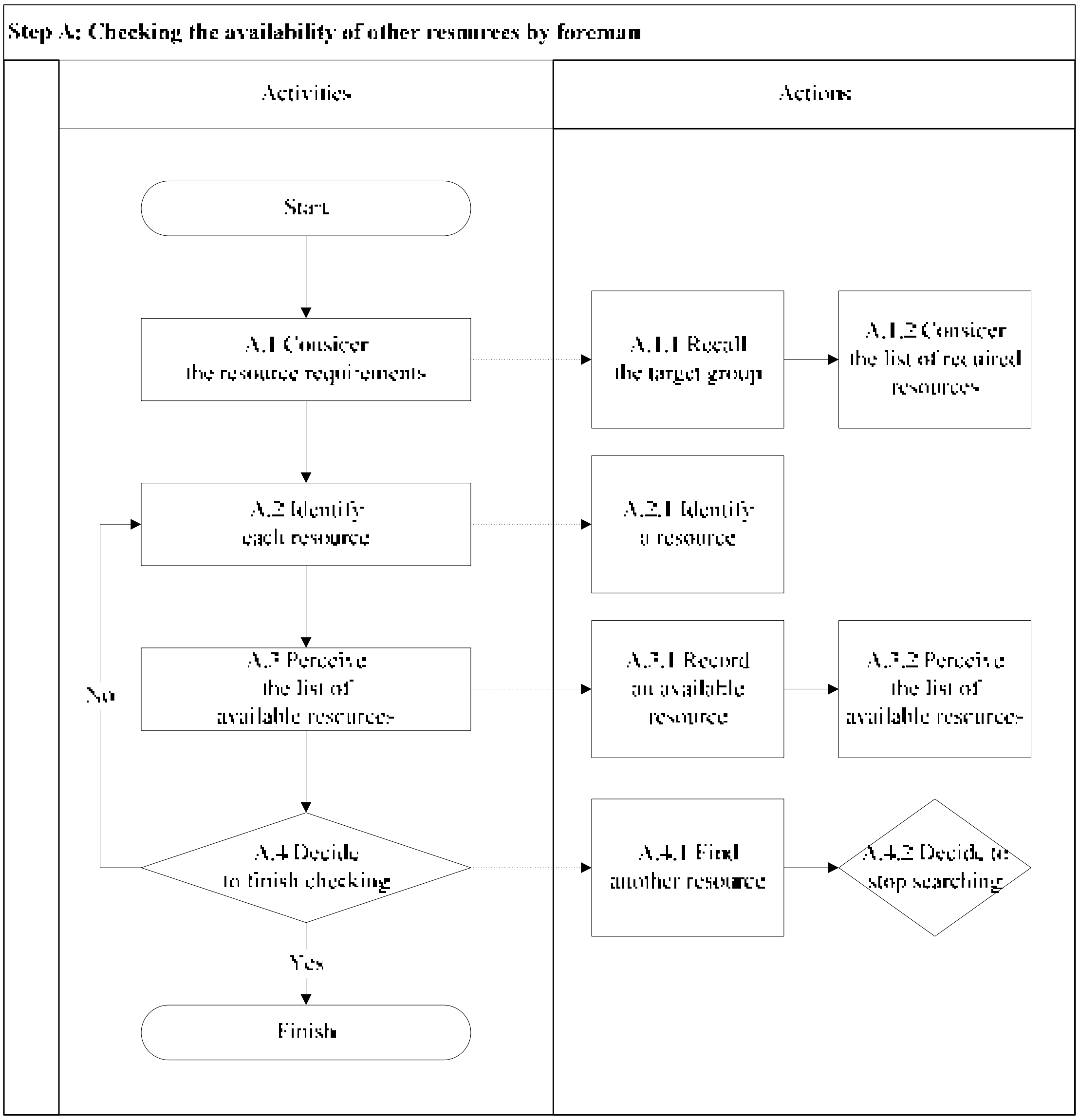

Figure 5.29 Work breakdown structure and actions of the foreman in Step A

Figure 5.30 Examples of resources at the installation location

Table 5.4 Knowledge and skill requirements for checking the availability of other resources

Activities / Actions	**Knowledge and skill requirements**
A.1 Consider the resource requirements A.1.1 Recall the target group of installation process from the first step	- (K) The perception of prefabricated members the in target group
A.1.2 Consider the list of required resources based on the installation of members in target group	- (K) The perception of resource requirements for each structural type and each prefabricated member in the target group
A.2 Identify each resource A.2.1 Identify a resource by its appearance	- (K&S) The resource identification
A.3 Perceive the list of available resources A.3.1 Record an available resource	- (K&S) The data collection
A.3.2 Perceive the list of all available resources and its quantity	- (K&S) The data collection including accumulating the resource quantity

Table 5.4 Knowledge and skill requirements for checking the availability of other resources (Cont.)

<u>Activities</u> / Actions	Knowledge and skill requirements
<u>A.4 Decide to finish checking</u> A.4.1 If the required resources are not complete, find another by redoing A.2 or try to search at other possible locations.	- (K) The perception of resource requirements for each structural type and each prefabricated member in the target group (All knowledge requirements, which were required in activity A.2 and A.3)
A.4.2 Decide to stop searching in case of complete requirements or cannot find the resource anymore	- (K) The decision making

5.2.5 Comparing the required resources and the available resources

The operation in this step involves non-physical work. The work starts with <u>B.1.1 Recall the list of resource and prefabricated member requirements,</u> as shown in Figure 5.31. This action required the knowledge and information to perceive the requirements of resources and prefabricated members to install the members in the target group. Then, <u>B.2.1 Recall the list of available resources</u> and <u>B.2.2 Recall the list of available prefabricated members</u> were performed. The foreman required the information of available resources and available prefabricated members in these actions respectively. After that, the requirement and the availability of resources and prefabricated members were compared by the foreman in <u>B.3.1 Compare the required resources and the available resources</u>. Thus, the knowledge for comparing the required resources and the available resources was required. Finally, the unavailable resources and prefabricated members were considered in <u>B.3.2 Perceive the list of unavailable resources</u>. Therefore, the knowledge requirements in each action were summarised in Table 5.5.

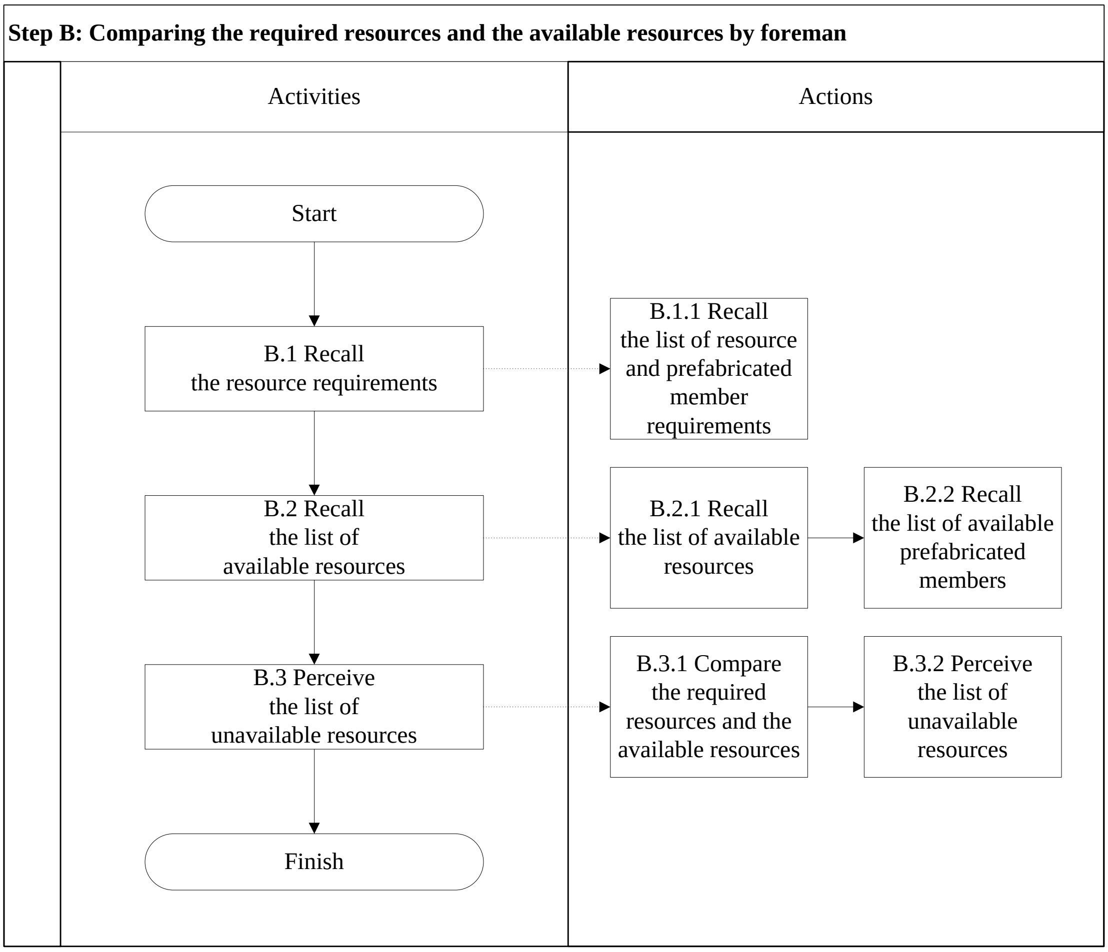

Figure 5.31 Work breakdown structure and actions of the foreman in Step B

Table 5.5 Knowledge requirements for comparing the required resources and the available resources

Activities / Actions	Knowledge requirements
B.1 Recall the resources requirements B.1.1 Recall the list of resource and prefabricated member requirements based on the installation of target group	- (K) The perception of resource and prefabricated member requirements based on the installation of members in target group
B.2 Recall the list of available resources B.2.1 Recall the list of available resources	- (K) The perception of available resources
B.2.2 Recall the list of available prefabricated members	- (K) The perception of available prefabricated members

Table 5.5 Knowledge requirements for comparing the required resources and the available resources (Cont.)

Activities / Actions	**Knowledge requirements**
B.3 Perceive the list of unavailable resources B.3.1 Compare the required resources and the available resources	- (K) The comparison between the required resources and the available resources
B.3.2 Perceive the list of unavailable resources	- (K) The perception of unavailable resources

5.2.6 Deciding the work location of the mobile crane

This step was performed by the mobile crane operator and related workers. The work of the mobile crane operator was both physical and non-physical work. Most of the work of the workers was physical. The work breakdown structure and actions of the mobile crane operator and workers are shown in Figure 5.32 and Figure 5.33 respectively. The process started from C.1.1 Perceive the target group of installation process. The mobile crane operator required the information of the target group of installation from the foreman. Then C.1.2 Consider the expected working location, the mobile crane operator required the knowledge to consider the expected work location of the machine. The consideration depended on the list of prefabricated members in the target group. Then, the information of weight and the installed location of members in the target group were required. The operator perceived the working range of the mobile crane using his knowledge. The range was the mobile crane workability, which was the individual characteristic of each machine. The capacity is indicated in the rated lifting capacity chart as shown in Figure 5.34. Thus, in order to perceive the working range of the mobile crane, the operator must be able to understand the rated lifting chart. After that, the weight and installed location of prefabricated members were compared with the capacity and working range of the mobile crane to consider the expected working location. Then C.1.3 Consider the condition of ground, the mobile crane operator considered the condition of the ground in terms of accessibility and resource requirements.

C.2.1 Recall the list of available resources and C.2.2 Consider the required resources based on the actual situation were the next actions. The mobile crane operator required the information of resource availabilities and considered the resource requirements respectively. The resource requirements were considered in terms of type, size, and quantity to set up the machine at the expected location. From

Figure 5.35, the figure shows that the machine base plates are employed in a variety of sizes.

The list of available resources, especially the machine base plates, was compared with the required resources in C.3.1 Compare the required resources and the available resources. The expected location was confirmed in case the comparison was done without incomplete resources and the area could be accessed. However, in case of unavailability of required resources or inaccessibility of the expected location, the work location was reconsidered. Then C.3.2 reconsider the working location was operated based on the actual condition. Therefore, the information of available resources and required resources were also required in this action. The resources were compared again and the work location was reconsidered. The required knowledge for reconsideration was the same as the requirements in the activity C.1.

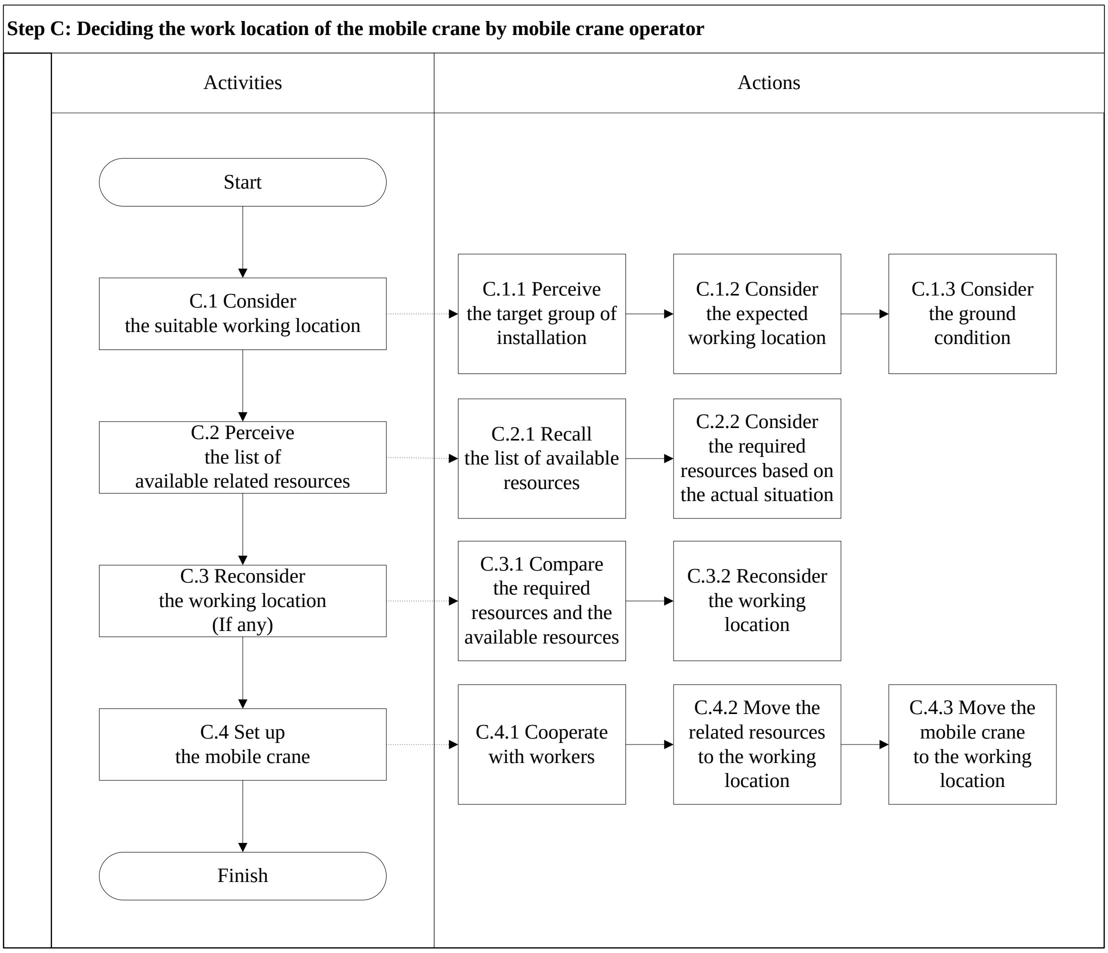

Figure 5.32 Work breakdown structure and actions of the mobile crane operator in Step C

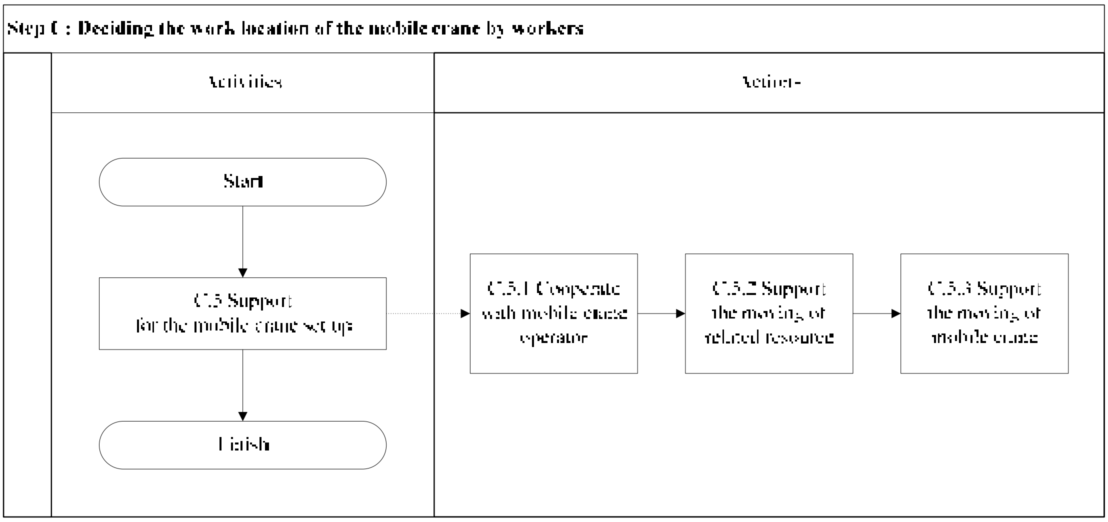

Figure 5.33 Work breakdown structure and actions of workers in Step C

■RATED LIFTING CAPACITY

9.35m — 30.5m Boom

Working radius (m)	(6.6m) Outriggers fully extended (360° full range)				(6.0m) Outriggers intermediately extended (over side)				(5.0m) Outriggers intermediately extended (over side)				(3.8m) Outriggers intermediately extended (over side)				(blocked on vartical cylinders) Outriggers completely retracted (over side)			
	9.35m Boom	16.4m Boom	23.45m Boom	30.5m Boom	9.35m Boom	16.4m Boom	23.45m Boom	30.5m Boom	9.35m Boom	16.4m Boom	23.45m Boom	30.5m Boom	9.35m Boom	16.4m Boom	23.45m Boom	30.5m Boom	9.35m Boom	16.4m Boom	23.45m Boom	30.5m Boom
2.5	30.00*	19.00	12.50		30.00*	19.00	12.50		30.00*	19.00	12.50		30.00*	19.00	12.50		12.00	10.35	9.10	
3.0	30.00*	19.00	12.50		30.00*	19.00	12.50		30.00*	19.00	12.50		26.00	18.90	12.50		11.15	8.25	7.50	
3.5	27.20*	19.00	12.50	7.50	27.20*	19.00	12.50	7.50	27.20*	19.00	12.50	7.50	20.20	15.20	12.50	7.50	9.00	6.75	6.30	5.50
4.0	23.00	19.00	12.50	7.50	23.00	19.00	12.50	7.50	23.00	19.00	12.50	7.50	16.35	12.60	11.40	7.50	7.45	5.60	5.35	5.15
4.5	21.20	18.65	12.50	7.50	21.20	18.65	12.50	7.50	21.20	17.30	12.50	7.50	13.65	10.65	9.85	7.50	6.25	4.65	4.60	4.50
5.0	19.40	17.30	12.50	7.50	19.40	17.30	12.50	7.50	18.85	14.70	12.50	7.50	11.40	9.10	8.60	7.50	5.30	3.95	3.95	3.95
5.5	17.80	16.15	12.50	7.50	17.80	16.15	12.50	7.50	15.65	12.65	11.80	7.50	9.50	7.90	7.55	7.25	4.50	3.30	3.45	3.45
6.0	16.30	15.15	12.25	7.50	16.30	15.15	12.25	7.50	13.15	11.05	10.45	7.50	8.10	6.90	6.70	6.50	3.85	2.80	3.00	3.05
6.5	15.10	14.25	11.50	7.50	15.10	13.50	11.50	7.50	11.25	9.75	9.35	7.50	7.05	6.05	6.00	5.85	3.30	2.35	2.60	2.70
7.0		13.45	10.80	7.50		12.00	10.80	7.50		8.70	8.40	7.50		5.35	5.40	5.35		2.00	2.25	2.40
7.5		12.70	10.20	7.50		10.75	10.20	7.50		7.75	7.60	7.40		4.75	4.85	4.85		1.65	1.95	2.15
8.0		11.80	9.65	7.50		9.65	9.35	7.50		7.00	6.95	6.80		4.25	4.40	4.45		1.40	1.70	1.90
9.0		9.70	8.65	6.80		7.95	7.85	6.80		5.75	5.80	5.75		3.40	3.60	3.70		0.90	1.25	1.50
10.0		7.90	7.85	6.15		6.50	6.70	6.15		4.70	4.90	4.95		2.75	3.00	3.15		0.55	0.90	1.15
11.0		6.50	6.90	5.60		5.35	5.75	5.60		3.85	4.20	4.30		2.20	2.50	2.65			0.60	0.85
12.0		5.45	6.00	5.10		4.50	5.00	5.05		3.15	3.60	3.75		1.75	2.10	2.30				0.65
13.0		4.55	5.20	4.70		3.75	4.35	4.50		2.60	3.10	3.30		1.35	1.70	1.95				
13.5		4.20	4.85	4.50		3.45	4.05	4.20		2.40	2.90	3.05		1.20	1.55	1.80				
14.0			4.50	4.35			3.75	4.00			2.70	2.90			1.40	1.65				
15.0			3.90	4.05			3.25	3.55			2.30	2.55			1.15	1.40				
16.0			3.45	3.75			2.85	3.20			2.00	2.25			0.95	1.15				
17.0			3.00	3.35			2.50	2.85			1.70	1.95			0.75	1.00				
18.0			2.65	2.95			2.15	2.50			1.45	1.75			0.60	0.80				
19.0			2.35	2.65			1.90	2.20			1.20	1.55				0.65				
20.0			2.05	2.35			1.65	2.00			1.05	1.35				0.50				
20.5			1.95	2.25			1.55	1.85			0.95	1.25								
21.0				2.10				1.75				1.15								
22.0				1.90				1.55				1.00								
24.0				1.50				1.20				0.70								
26.0				1.20				0.95				0.50								
27.9				0.95				0.70												
Standard hook	for 30 ton				for 30 ton				for 30 ton				for 30 ton				for 30 ton			
Hook mass	250kg				250kg				250kg				250kg				250kg			
Parts of line	9*/7	6	4	4	9*/7	6	4	4	9*/7	6	4	4	9*/7	6	4	4	7	6	4	4
Critical boom angle	—	—	—	—	—	—	—	—	—	—	—	20°	—	—	28°	41°	—	40°	55°	62°

(Unit : Metric ton)

Figure 5.34 Rated lifting capacity (from http://www.kato-works.co.jp)

Figure 5.35 Use of the machine base plates

After that, the movement of related resources and the mobile crane begins. While the C.4 Set up the mobile crane and the C.5 Support for the mobile crane set up is under way, the mobile crane operator and workers communicate with each other. Normally, hand signals were used for communication between the workers and the mobile crane operator. Thus, the mobile crane operator requires and skill to communicate using hand signals and the workers require knowledge and skill about the use of hand signals for communication as stated in C.4.1 Cooperate with the workers and C.5.1 Cooperate with the mobile crane operator.

In order to set up the mobile crane, the related resources were moved for the operation as stated in C.4.2 Move the related resources to the location. Machine base plates are normally required for the operation. Then, the mobile crane operator operated the machine to lift and move the resources as shown in Figure 5.36. Next, the machine was set up at the desired working location as stated in C.4.3 Move the machine to the location and shown in Figure 5.37. The operator must be able to move and set up the machine.

Figure 5.36 Move the related resources

Figure 5.37 Move the machine

The workers supported the resource moving and machine moving in this step as stated in Figure 5.33. In the resource moving operation, C.5.2 Support the moving of related resource required the knowledge and skill to identify the resources, especially the machine base plates. In Figure 5.35, three sizes of machine base plates were differently required based on the ground condition. Thus, the workers had to identify the base plates based on the requirements of the mobile crane operator. In addition, the workers had to be able to identify the related resources, such as the cable, shackle, and hook. After the resource identification, the workers hooked the resources using cable, shackles, and hooks as shown in Figure 5.38. The resources were unhooked after arriving at the desired position. Therefore, knowledge and skills of the resource identification and use of cable, shackles, and hooks for resource hooking and unhooking were required by the workers for this operation.

The workers also supported the machine moving as stated in <u>C.5.3 Support the machine moving</u>. Figure 5.37 to Figure 5.39 shows the support work from the workers. The workers guided the machine movement and supported the machine set up using the workforce and communication.

Figure 5.38 Hook the required resource

Figure 5.39 Support work from workers

Table 5.6 Knowledge and skill requirements for deciding the work location of the mobile crane

Activities / Actions	**Knowledge and skill requirements**
C.1 Consider the suitable working location C.1.1 Perceive the target group of installation process by getting the information from foreman	- (K) The perception of the target group in installation process
C.1.2 Consider the expected working location	- (K) The perception of prefabricated members in the target group - (K) The perception of weight for each prefabricated member - (K) The perception of the installed location for each prefabricated member - (K) The perception of the working range of the mobile crane by understanding the rated lifting capacity chart - (K) The consideration of the expected work location
C.1.3 Consider the condition of ground	- (K) The consideration of ground conditions
C.2 Perceive the list of available resources C.2.1 Recall the list of available resources	- (K) The perception of available resources, especially the machine base plates

Table 5.6 Knowledge and skill requirements for deciding the work location of the mobile crane (Cont.)

Activities / Actions	Knowledge and skill requirements
C.2.2 Consider the required resources based on the actual situation	- (K) The perception of required resources in terms of type, size, and quantity to set up the machine
C.3 Reconsider the working location C.3.1 Compare the required resources and the available resources	 - (K) The comparison between required resources and the available resources
C.3.2 If the required resources are not complete, reconsider the working location by redoing activity C.1.	- (K) The perception of required resources - (K) The perception of available resources (All knowledge requirements, which were required in activity C.1)
C.4 Set up the mobile crane C.4.1 Cooperate with the workers	 - (K&S) The communication using hand signals
C.4.2 Move the related resources to the location	- (K&S) The operation of the mobile crane to lift and move resources
C.4.3 Move the machine to the location	- (K&S) The operation of the mobile crane to move and set up the machine
C.5 Support for the mobile crane set up C.5.1 Cooperate with the mobile crane operator	 - (K&S) The communication using hand signals
C.5.2 Support the related resource moving	- (K&S) The resource identification, especially the machine base plates - (K&S) The use of cable, shackle, and hook for resource hooking and unhooking
C.5.3 Support the machine moving	- (K&S) The communication using hand signals

5.2.7 Inspection of the installed prefabricated members

The installed prefabricated members were inspected by an inspector as shown in Figure 5.40. This action involved the combination of physical and non-physical work. The inspector required the information of installed members in the structure as stated in D.1.1 Perceive the list of prefabricated members. Then, D.2.1 Identify a prefabricated member was performed. The inspector required the knowledge and skill to identify the prefabricated member. After identification, the inspector required knowledge and information to select the checklist or specification to perceive the correct quality terms as stated in D.2.2 Perceive the quality terms of a prefabricated member.

In D.3.1 Inspect a prefabricated member, the inspector must have knowledge and skills and able to understand the quality terms of each member. The inspection was performed using measurement tools to measure the dimensions and related distance. The construction drawings may be used as a reference in the inspection step. In addition, the other inspection methods were performed in accordance to the quality terms. Then D.3.2 Record the inspection results, the inspection results were recorded in the specified document or form. After finishing each prefabricated member inspection, the inspector considers to stop the inspection as stated in D.3.3 Make a decision to stop the inspection using information of installed and inspected prefabricated members. The further inspection was decided to stop when all installed members were inspected. The summary of knowledge and skill requirements in this step is shown in Table 5.7.

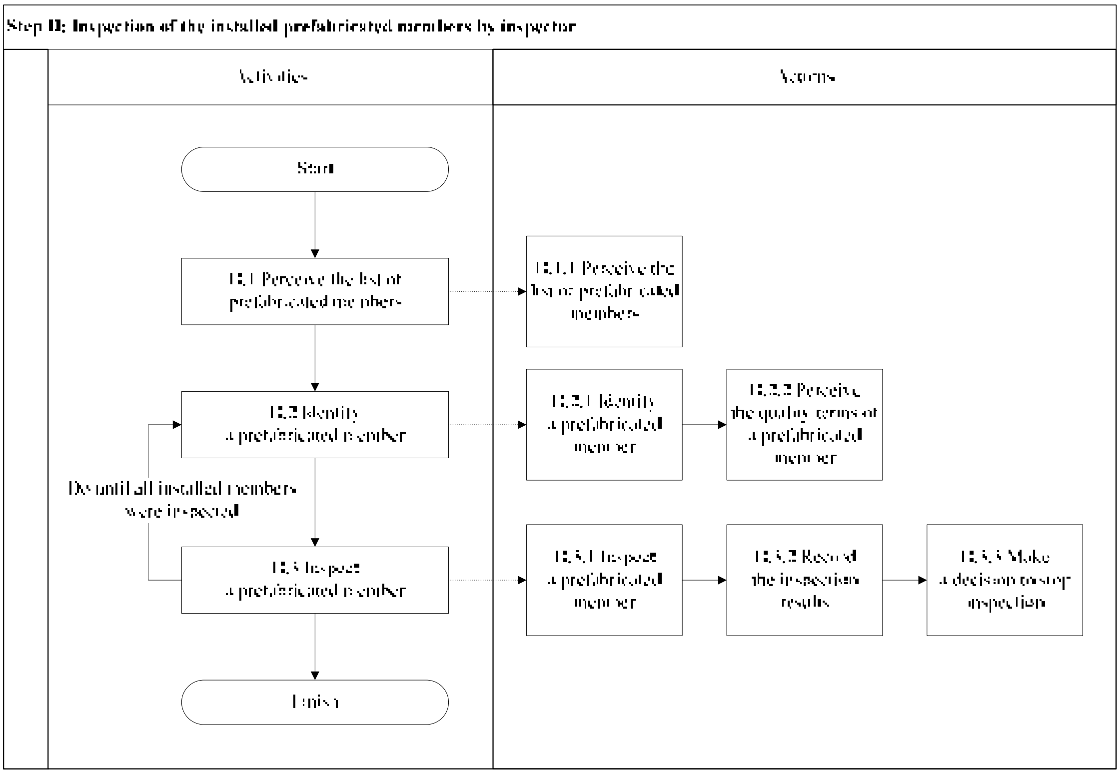

Figure 5.40 Work breakdown structure and actions of the inspector in Step D

Table 5.7 Knowledge and skill requirements for inspection of the installed prefabricated members

Activities / Actions	Knowledge and skill requirements
D.1 Perceive the list of prefabricated members D.1.1 Perceive the list of prefabricated members	- (K) The perception of installed prefabricated members in a structure
D.2 Identify a prefabricated member D.2.1 Identify a prefabricated member	- (K&S) The prefabricated member identification
D.2.2 Perceive the quality terms of a prefabricated member from the checklists or specifications	- (K) The selection of checklist or specification
D.3 Inspect a prefabricated member D.3.1 Inspect a prefabricated member	- (K) The perception of quality terms for each prefabricated member - (K) The understanding of quality terms - (K&S) The interpretation of construction drawings - (K&S) The use of measurement tools - (K&S) The inspection according to the quality terms
D.3.2 Record the inspection results	- (K&S) The data collection
D.3.3 Make a decision to stop inspection	- (K) The perception of installed and inspected prefabricated members - (K) The decision making

5.3 Summary

From the current practice analysis, the three main steps and four supplementary steps of the installation process were analysed based on the work breakdown structure, activities, action flows, and information from investigations. In each action, the physical work or movement and the related data and information were analysed to acquire the knowledge and skill requirements. In addition, the requirements also received from personnel interviews to fulfill the completeness of requirements.

The knowledge and skill requirements were revealed in this step. Some requirements are the knowledge (K), while some are the integration of knowledge and skill (K&S). The requirements were affected by the roles and responsibilities of personnel, the installation step, the changes, and mistakes in the installation process. Thus, the requirements for each position varied in each step of installation. The knowledge and skill requirements from this step will be used for the automation approach development in the next step.

Chapter 6
Automation approach development

6.1 Introduction

In this chapter, the automation approach development is described, including the scope of system, technology consideration, system architecture, hardware, programming, and automation approach development in each installation step. The automation approach was developed to reduce the knowledge and skill requirements of personnel. The work breakdown structure of the installation process, work breakdown of each step of installation, and the knowledge and skill requirements of each person in each step were employed for automation approach development.

6.2 Scope of system

From the current practice analysis, the installation process of prefabricated members was broken down into seven steps as follows:

Step 1: Checking the available prefabricated members
Step 2: Making a decision for an installation process
Step 3: Installing the prefabricated member
Step A: Checking the availability of other resources
Step B: Comparing the required resources and the available resources
Step C: Deciding the work location of the mobile crane
Step D: Inspection of installed prefabricated members

Each step required different knowledge and skills of each related person. The steps also related to the installation resources including personnel, materials, tools, and equipment. Thus, the scope of system was defined by covering the work in seven steps and the related resources as follows:

6.2.1 Personnel

The personnel include the people who operate in the installation process of the prefabricated members. From the current practice investigations, there are four types of personnel involved in the installation steps directly. The four types include foreman, worker, mobile crane operator, and inspector.

6.2.2 Materials

Many construction materials are required and utilised for the installation process of prefabricated members, such as prefabricated members, shimplates, cement, polyurethane, etc. Some of these materials differ from the materials in the conventional construction method. Thus, personnel with little experience or personnel from the conventional construction method may have a problem with material identification and usage. The providing of identification and information of these materials are important for the installation process.

The prefabricated member is the main resource for the installation process. Thus, the member is included in the developed approach. Other materials are also included but have a lower level of significance.

6.2.3 Tools and equipment

The installation process of prefabricated members is supported through tools and equipment. Tools are required by personnel to lift resources, set up the machine, measure distances, or handle and adjust the prefabricated member. The requirements are considered in terms of type, size, and the number of tools. The examples of tools include mobile crane base plates, lifting hooks, shackles, cables, props, wrenches, and drillers. An inadequate number of tools could mean the cancellation of the installation process, or affect the installation sequence and the overall results of the installation process.

The main equipment in the installation process is the lifting machine. For a housing construction project, the work area is large and the duties are not limited to only prefabricated member installation. The other work responsibilities, such as material lifting and infrastructure construction, are included in the job of the lifting machine. Therefore, the mobile crane is generally employed because of its mobility. The unavailability of a mobile crane significantly affects the installation process, which likely means the installation must be canceled.

As mentioned above, the installation process of prefabricated members requires various types, sizes, and number of resources. For some resources, an inadequate number could lead to the cancelation of installation, while an inadequate number of other resources could lead to a shortened sequence or prolonged duration of the installation process.

Resources such as personnel, materials, tools, and equipment are very important to the installation process and significantly affect the installation results. Thus, the seven steps of installation, personnel, materials, tools, and equipment are in the scope of this automation approach.

6.3 Technology consideration

From previous researches, many technologies supported the operation in the construction process, such as identifying the object, tracking the component, collecting data, processing the data, managing the data and information, providing the information, etc. The use of these technologies has proven that technology can support and improve the construction process.

The knowledge and skill requirements for the installation of a prefabricated member can be relaxed and enhanced using the technologies for data collection, identification, information providing, especially in graphical format, processing the data, as well as data and information manipulation.

6.3.1 Hardware for users

Personal computers, including laptops and mobile types, have been widely used in the construction industry. The computer is always employed for data collection, information providing, and data and information manipulation. Thus, with the features of the personal computer, it is employed as part of the automated approach.

According to the scope of work, an installation group and inspector are the main personnel in the installation process. The work scheme and the location of personnel work must be considered in order to select the appropriate kind of hardware.

For the foreman, the work is at and around the installation location. Thus portable hardware, which is light and convenient to carry, is chosen. In this case, the personal digital assistant (PDA) is employed.

The inspector examines the quality of the installation at the site location. Portable hardware is required for the foreman, while the personal digital assistant (PDA) is employed for the inspector as well.

For the mobile crane operator, work involves the operation of the machine in the cabin. Thus, the hardware, which can be moved and implemented in the cabin, is considered. However, the PDA, which is employed by the foreman and inspector, has limitations in terms of data storage and the processing speed. Therefore, hardware for the mobile crane is employed for processing and collecting data and information instead. In addition, the operator has to concentrate on controlling the machine. A moderately sized user interface and display is required, while the level of mobility is of slight concern as well. Thus, a laptop computer is employed for the mobile crane operator.

The workers are also in an installation group. Most of the work is carried out using the worker’s body and hands. Thus, the worker’s agility is important for productivity and safety. In addition, some of the workers may have limitations on their ability to use certain technology. Therefore, no hardware is assigned to workers. The foreman distributes the data and information to the workers under his supervision.

6.3.2 Identification technology

At the moment, many identification technologies are employed in people’s daily lives, businesses, and the construction industry, for example, barcode, smart card, voice recognition, finger scan, iris scan, Optical Character Recognition (OCR), touch probe, and Radio Frequency Identification (RFID) technology. Identification technology allows identification to be more accurate and faster. This features advantage for data acquisition.

According to the construction characteristics and environment, which is defined as a harsh environment, RFID technology is selected for the automation approach because of these characteristics, including contactless reading, the survival from outdoor and harsh environment, reading without line-of-sight, and the speed of reading.

6.4 System architecture

The system architecture was developed under the installation steps, personnel roles and responsibilities, knowledge and skill requirements, and related resources in the installation process. The system architecture is composed of the following components: users, user interfaces, hardware, connections, modules, and a database. The system architecture is shown in Figure 6.1.

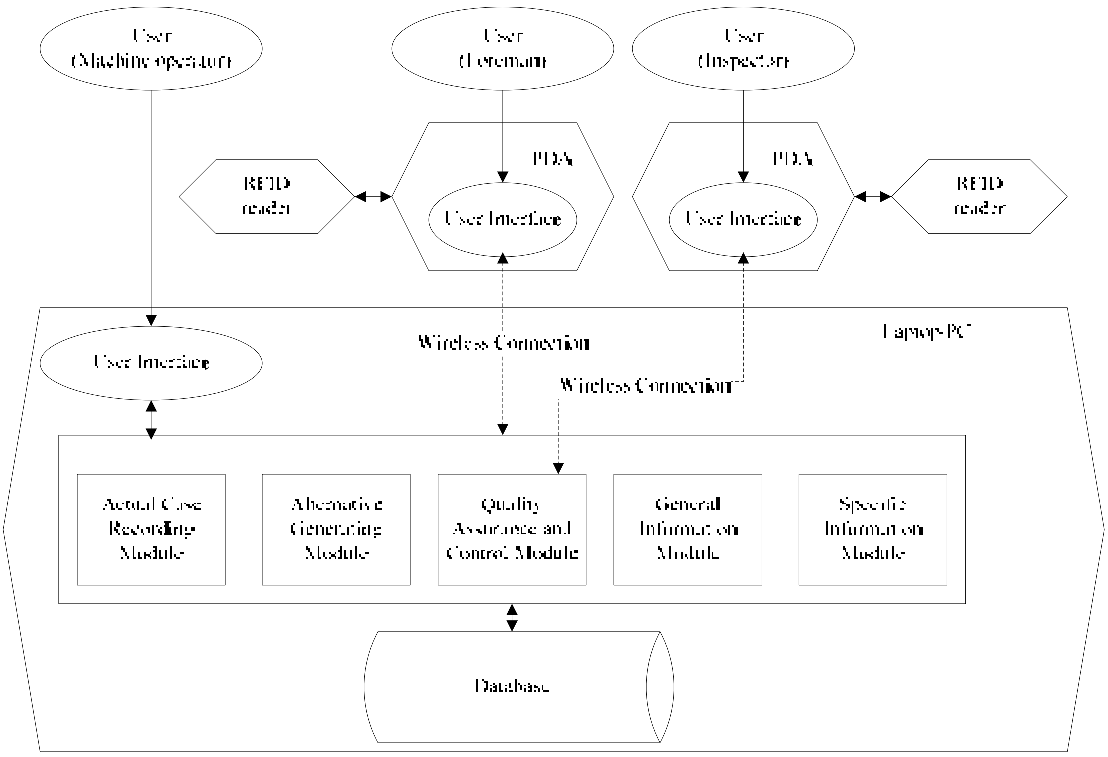

Figure 6.1 System architecture

From the main personnel in the installation process, three user interfaces were developed to support the foreman, mobile crane operator, and inspector. The computer hardware consists of PDAs with RFID reader, and laptop computer. The hardware is used as the user interface. The five modules and a database system were developed and implemented in the laptop computer. The details of each module are as follows:

6.4.1 Actual case recording module

This module was developed for recording actual conditions related to the installation process. For example, the available prefabricated members, the available resources, the resource usage, and the selected installation sequence. In addition, the module calculates the resource requirements and compares the available resources with the required resources.

6.4.2 Alternative generating module

The module was developed for generating several alternatives for the installation process with expected results. The module is required because the unavailability of prefabricated members always occurs. The input requires the actual conditions, and general data and information.

6.4.3 Quality assurance and control module

The module was developed to serve the inspector. The module provides the quality checklist and records the inspection results. In addition, the module provides related information to the inspector, such as the location of installed the prefabricated member, the appearance of the prefabricated member, and the illustration of quality inspection.

6.4.4 General information module

The module was developed to provide general information, such as project information, organisational chart, assignments, drawings, schedules, etc. The module also includes troubleshooting, so that personnel can access the correct knowledge to solve the problems.

6.4.5 Specific information module

The module provides the information, which is specific to the current construction conditions and the selected installation sequence. In addition, the input and feedback from the button pressing are used as time recording. The time data are recorded for further analysis.

While the prefabricated members are being installed, the information from this module is shown in a graphical format and step-by-step manner to the foreman and mobile crane operator.

The database is implemented in the laptop computer. The laptop computer and PDA communicate with each other through a wireless network using the ad-hoc network function in the hardware.

6.5 System hardware

The system hardware was considered based on the needs of the developed framework and the characteristics of each person's work. For the foreman and inspector, the work is at the installation location of the prefabricated member. The work of the foreman and inspector require a high level of mobility, and the weight of the hardware must be considered. For the mobile crane operator, the workplace is inside the cabin of the machine. The operator requires good concentration for this operation. Thus, the screen and input interface must be large enough, while the level of mobility and the weight of the hardware are not a big issue.

The system hardware in this system includes a Personal Digital Assistant (PDA), a laptop computer, RFID tags, and RFID reader. The prototype system employs the following hardware:

PDA: HP IPAQ model 212 with Microsoft Windows Mobile operating system and driver software for RFID reader. The figure of the PDA is shown in Figure 6.2.

Laptop computer: The laptop model is Toshiba Portégé M800. The laptop is using Microsoft Windows Vista operating system. The figure of the laptop is shown in Figure 6.3.

RFID tags: ICODE PVC blank card 13.56 MHz. The figure of the RFID tags is shown in Figure 6.4.

RFID reader: The series 6E of CF type RFID tag reader. The reader was made by Socket Mobile Inc., and comes with the driver to install on the PDA. The figure of the RFID reader is shown in Figure 6.5.

The estimated price of hardware in the automation approach is 65,370 baht or approximately US$1,925.60. The details are shown below in Table 6.1.

Table 6.1 Estimated price of hardware

Number	**Item**	**Date of purchase**	**Price in Baht**	**Estimated price in US Dollar**
1	Laptop computer	12/02/2009	35,900.00	1,017.35
2	PDA	21/06/2010	13,700.00	362.71
3	RFID reader	21/06/2010	11,770.00	422.19
4	100 RFID tags	21/07/2010	4,000.00	123.35
Total			65,370.00	1,925.60

In Table 6.1, the estimated price in US dollars was calculated using the exchange rate on the day of purchase, which was announced by the Bank of Thailand at www.bot.or.th.

Figure 6.2 HP IPAQ 212

Figure 6.3 Toshiba Portégé M800

Figure 6.4 RFID tags

Figure 6.5 CF type RFID tag reader

6.6 Programing

The automation approach requires programming for (1) user interface development, (2) data input by using the manual method and RFID reader, (3) data processing, (4) communication, (5) database recording, and (6) display of the information. The Microsoft Visual Studio 2008 was used in the automation approach programing.

6.7 Automation approach development in each installation step

According to the seven steps of installation, the automation approach was developed to reduce the knowledge and skill requirements. In this part, the development in each installation step is described as follows:

6.7.1 Checking the available prefabricated members

This step aims to select the target group of installation and check the available prefabricated members for the target group. The summary of knowledge and skill requirements for the foreman related to the automation approach is shown in Table 6.2.

In the automation approach development, the approach was developed based on process flow as shown in Figure 6.6. The user interface is simulated from the stock rack at the construction site as shown in Figure 6.7. The process starts with the foreman using a RFID reader to read the tag at each location. The identification number of a RFID tag is compared and the identification number of a prefabricated member is returned. The stock location is engaged as shown in Figure 6.8. Then, the related information is recalled and displayed as illustrated in Figure 6.9. The information includes the appearance of the prefabricated member and the identification number of the prefabricated member. Once the stock location is engaged, the colour of the location will turn green as shown in Figure 6.10. The approach also checks for the completeness of the checking process, the process will be repeated in the case that all stock locations have not been engaged.

When all stock locations are engaged as shown in Figure 6.11, the automation approach automatically records the data of available prefabricated members as shown in Figure 6.12. After that, the available prefabricated members and the combination of members in a structure are compared. The information is shown in Figure 6.13. Finally, the foreman selects the target group of installation based on the provided information. The details of the selected group are recorded in the database.

Table 6.2 Knowledge and skill requirements of the foreman compared to the developed automation approach in Step 1

Knowledge and skill requirements	**Developed automation approach**
The interpretation of construction drawings	The knowledge and skill requirements were reduced through simplifying construction drawings and providing related information to personnel.
The prefabricated member identification	The identification by personnel was changed. RFID technology is employed for prefabricated member identification.
The perception of prefabricated members or combination in the structure	The prefabricated members or combination in each structure are stored in the database and provided to the personnel.
The consideration of target group in the installation process	The automation approach compares the available prefabricated members and the combination in each structure automatically. After that, the information is provided to the user.
The data collection	The data of available prefabricated members is recorded using RFID technology with the modules in the automation approach.
The decision making	The checking process will stop when all stock locations are engaged. The information is provided to the personnel. Then, the knowledge requirement is reduced.

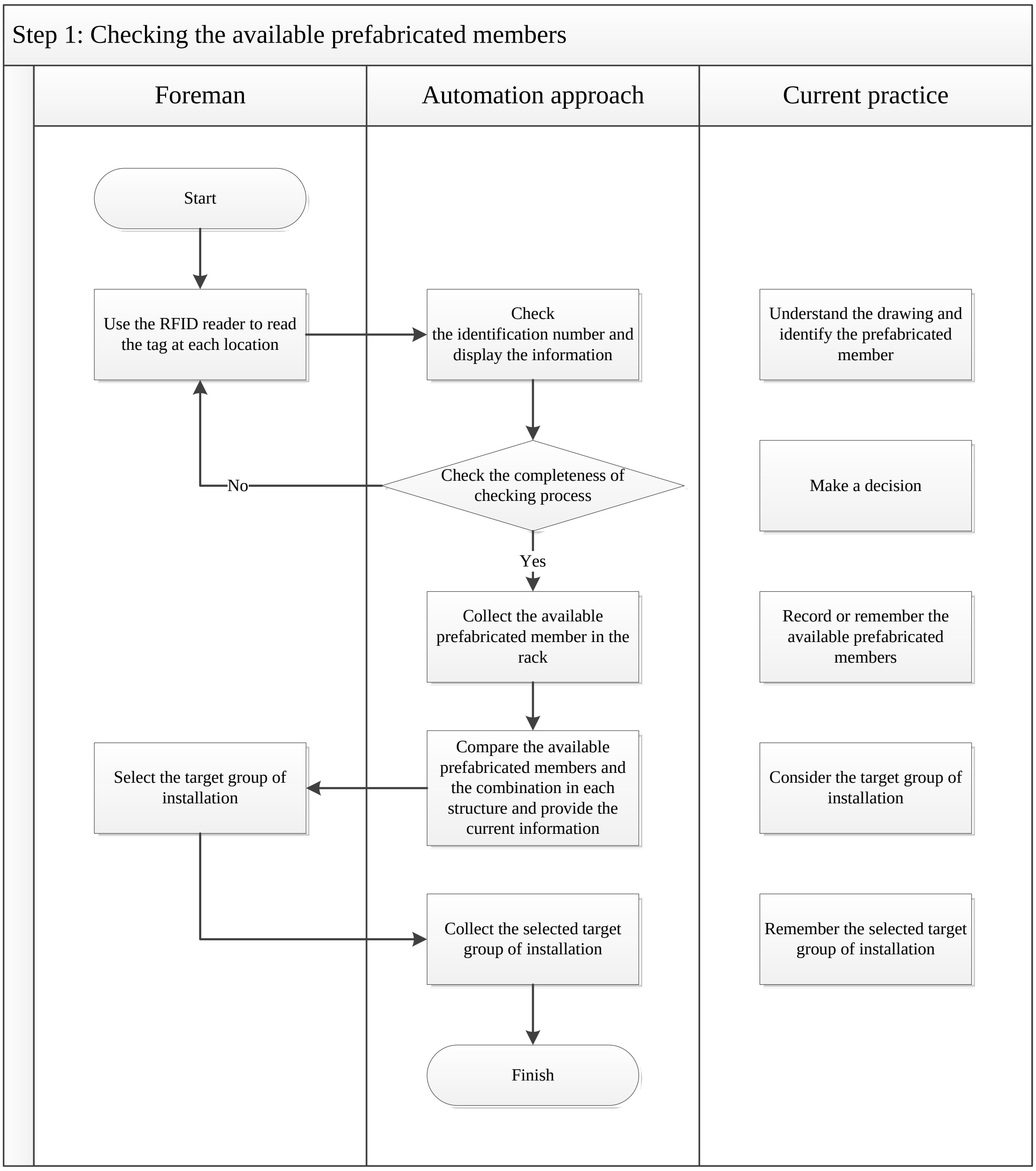

Figure 6.6 The process flow of the automation approach in Step 1

Figure 6.7 Stock rack at the construction site

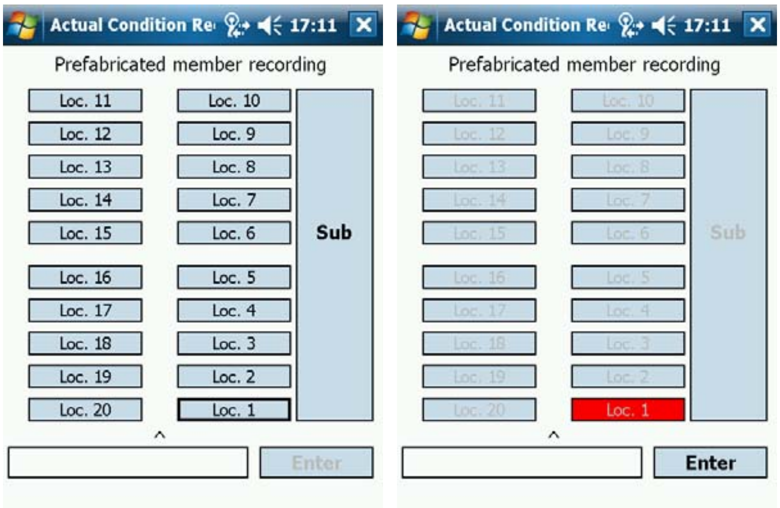

Figure 6.8 Engage the stock location

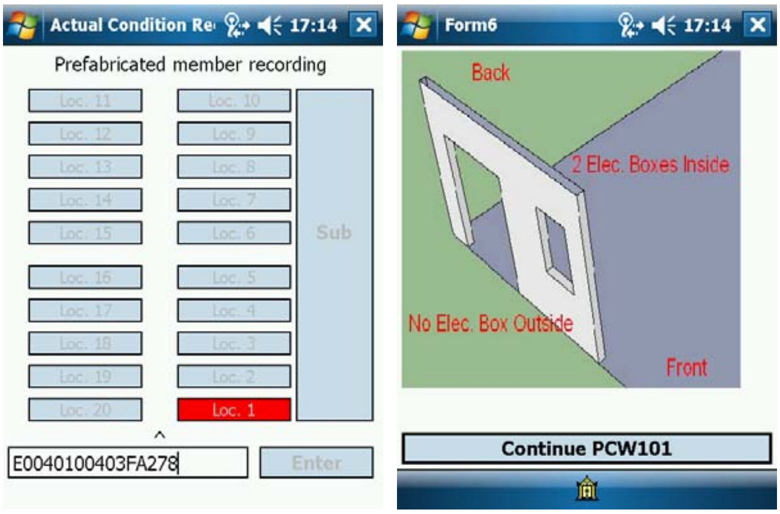

Figure 6.9 Information of prefabricated member

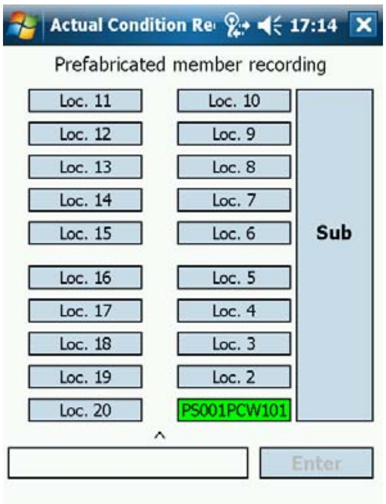

Figure 6.10 Display of engaged location

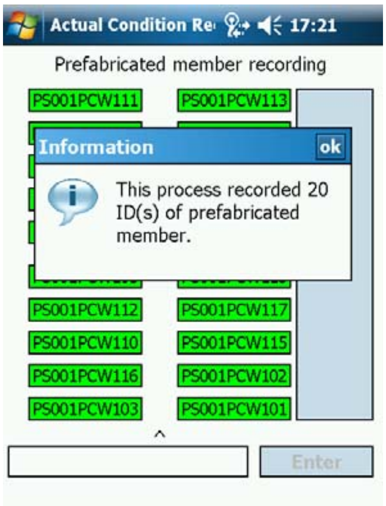

Figure 6.11 All locations were engaged

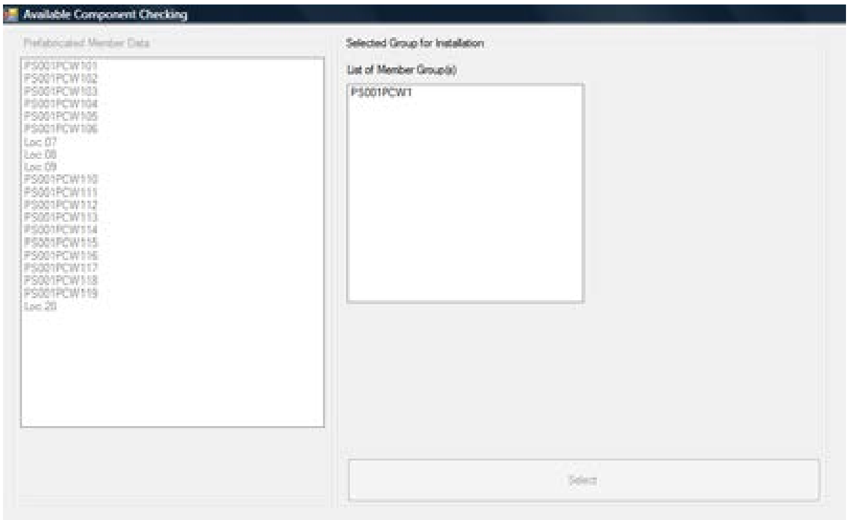

Figure 6.12 The list of available prefabricated members

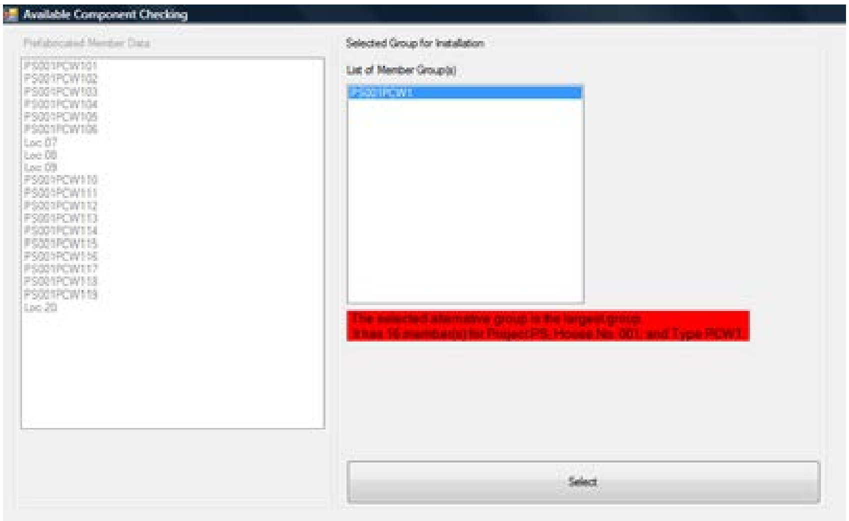

Figure 6.13 The information of the selected target group

6.7.2 Making a decision for an installation process

The installation is decided in this step whether to postpone or continue the process. In the case of complete resources, the foreman generates the installation sequence based on the relative location of the house and stock. In the case of incomplete resources and installation process is continued, the installation sequence is generated from the foreman. Both cases are based on the individual knowledge and skill of the foreman.

The knowledge and skill requirements, which are related to the automation approach, are shown in Table 6.3. The process flow is shown in Figure 6.14.

The module is automatically opened. Then, the list of available prefabricated members in the target group is recalled. After that, the list is compared with the combination members of each structure to get the list of unavailable prefabricated members. The information of unavailable prefabricated members is displayed as illustrated in Figure 6.15. Then, the related members of each unavailable member are recalled from the database. The related members have to be considered in generating the installation sequence because some members are covered by related members. The installation without consideration for related members leads to line-of-sight blocking and the installation between prefabricated members.

After related members of unavailable prefabricated members are considered, the pre-alternatives are generated for the next sequence as shown in Figure 6.16. When the pre-alternative is selected, the installation sequences are generated in various alternatives and expected results as shown in Figure 6.17. Normally, four alternatives are generated, which are shown in Table 6.4.

In the case of complete prefabricated members, the installation sequence is generated based on the location of stock, when compared to the house.

In the case of incomplete prefabricated members, the first alternative is to postpone the installation process to avoid the double move of resources, line-of-sight blocking, and installation between prefabricated members.

In the case of incomplete prefabricated members, the second alternative is to continue the installation process. However, the installation sequence will be shortened from the sequence that the first unavailable member or related member is located. The reason for this is to avoid line-of-sight blocking and installation between prefabricated members. However, the double move of resources will occur.

In the case of incomplete prefabricated members, the third alternative is to continue the installation process. However, the installation sequence will be shortened by means of cutting the unavailable members and its related members out from the installation sequence. The reason for this is to avoid the installation between prefabricated members. However, the double move of resources will occur and line-of-sight blocking tends to occur.

In the case of incomplete prefabricated members, the fourth alternative is to continue the installation process. However, the installation sequence will be shortened by means of cutting only the unavailable members from the installation sequence. However, the double move of resources will occur. The line-of-sight blocking and installation between prefabricated members tend to occur as well.

The tendency situation of each situation is shown in Table 6.5. The examples of the four alternatives mentioned above are shown in Table 6.6.

Table 6.3 Knowledge and skill requirements of the foreman compared to the developed automation approach in Step 2

Knowledge and skill requirements	**Developed automation approach**
The perception of unavailable resources	The unavailable prefabricated members are informed as shown in Figure 6.15.
The consideration of the effect from resource unavailability to the installation process	In the case where resources were inadequate to start the installation process, such as a mobile crane was not available, the process was stopped automatically in Step B.
The consideration of the effect from house, mobile crane, and stock location to the installation sequence	The prototype of installation sequence for each relative location is put into the database. The module recalls the information based on the actual conditions, which was entered by the mobile crane operator.
The consideration of the effect from unavailable prefabricated members to the installation sequence	The effect of prefabricated member unavailability is considered by the automation approach. The consideration is not only for the unavailable prefabricated member but also its related members. The reason being is to avoid the line-of-sight blocking and installation between prefabricated members.

Table 6.3 Knowledge and skill requirements of the foreman compared to the developed automation approach in Step 2 (Cont.)

Knowledge and skill requirements	Developed automation approach
The consideration of the effect from resource unavailability to the installation sequence	The installation sequence will be shortened later based on the resource requirement and resource unavailability.
The installation sequence generation	The installation sequence will be generated based on the relative location of the house and stock and the unavailable prefabricated members.

Table 6.4 The details of each alternative

Alternatives	Complete resources	Situation and installation sequence
Alternative 1 (Alt. 1)	✓	The installation process is continued. The planned installation sequence is selected based on the location of stock.
Alternative 1 (Alt. 1)	×	The installation process is postponed.
Alternative 2 (Alt. 2)	×	The installation sequence is shortened from the first missing member or the first related member.
Alternative 3 (Alt. 3)	×	The missing member and its related member are excluded from the installation sequence.
Alternative 4 (Alt. 4)	×	Only the missing member is excluded from the installation sequence.

Table 6.5 The tendency situation of each alternative

Situation	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Double move of resources	×	✓	✓	✓
Line-of-sight blocking	×	×	✓	✓
Installation between prefabricated members	×	×	×	✓

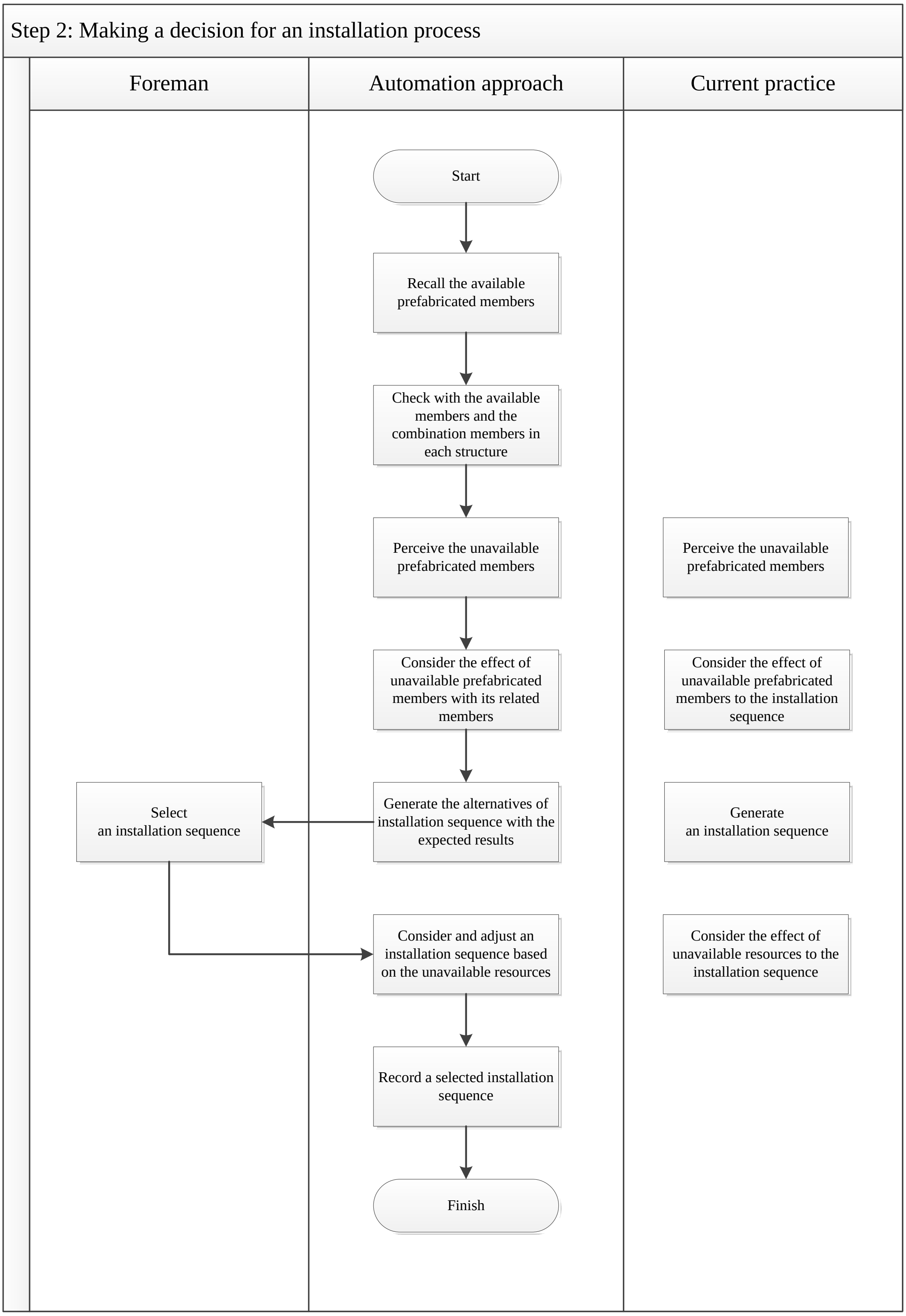

Figure 6.14 The process flow of developed framework in Step 2

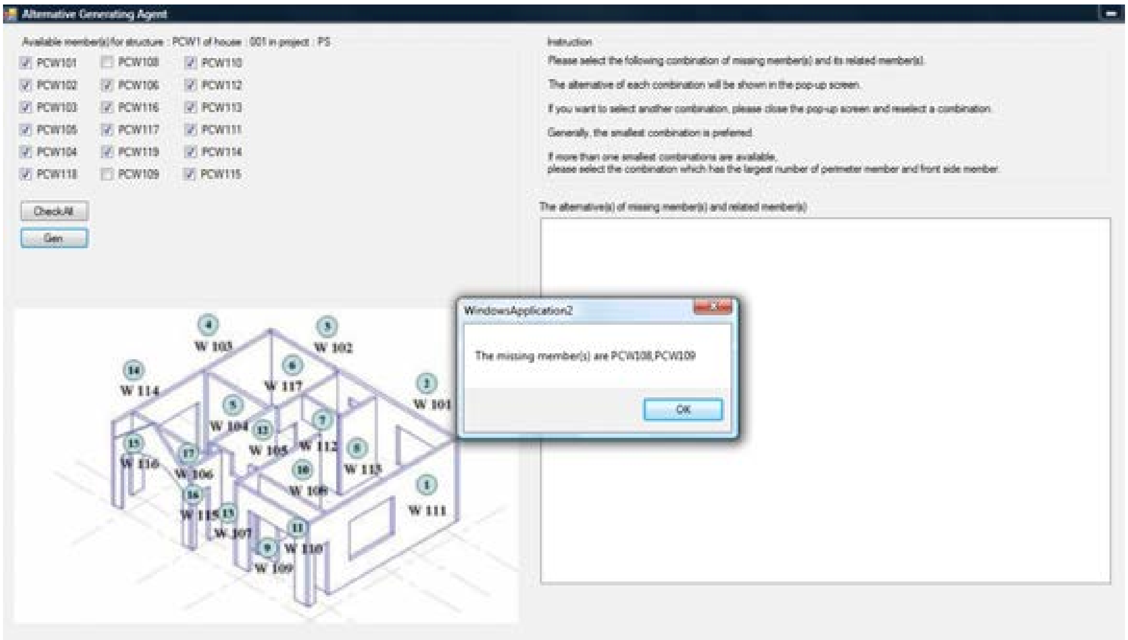

Figure 6.15 The information of unavailable prefabricated members

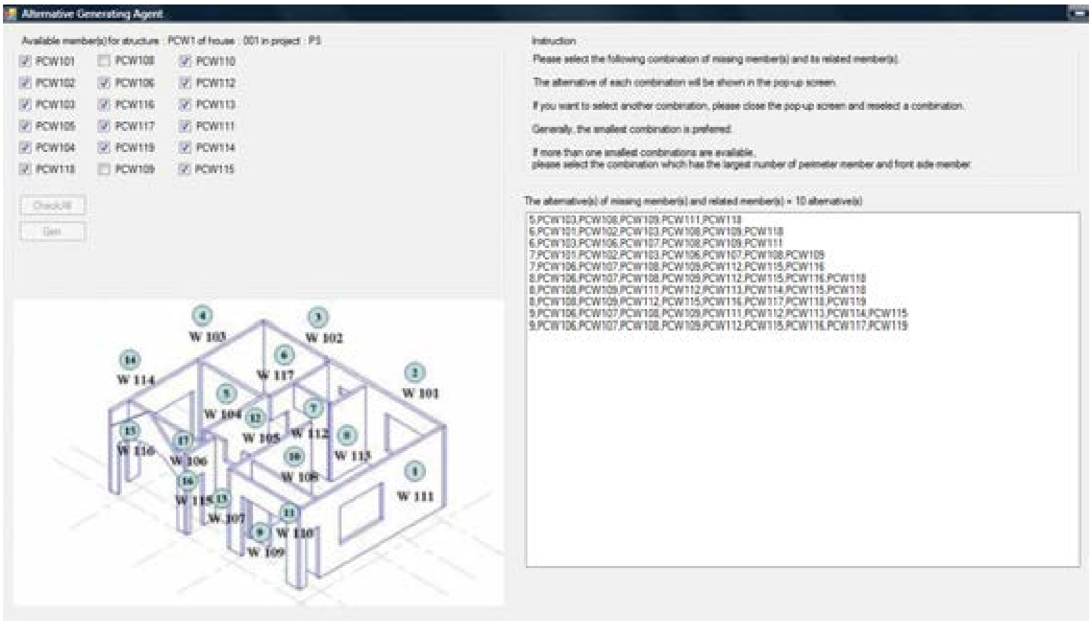

Figure 6.16 Alternatives of missing members and its related resources

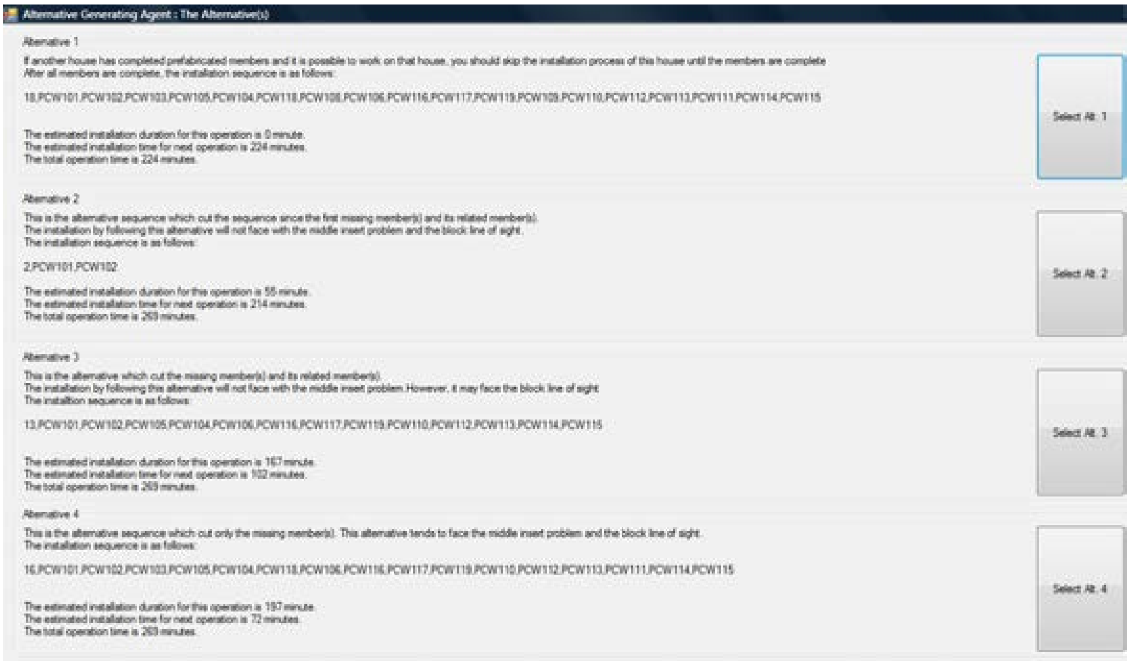

Figure 6.17 Alternatives for an installation process with expected results

Table 6.6 The examples of installation sequence

Installation sequence	1	2	3	4	5	6	7	8	9	10	11	12
Availability	A	A	A	A	A	A R	U	A	A	A	A	A
Alt. 1	-	-	-	-	-	-	U	-	-	-	-	-
Alt. 2	✓	✓	✓	✓	✓	-	U	-	-	-	-	-
Alt. 3	✓	✓	✓	✓	✓	-	U	✓	✓	✓	✓	✓
Alt. 4	✓	✓	✓	✓	✓	✓	U	✓	✓	✓	✓	✓

"A" represents the prefabricated member is available. "U" represents the prefabricated member is unavailable. "R" represents the prefabricated member relates to the unavailable member. The symbol "✓" means the member will be installed, and "-" means the member will not be installed.

After the alternative step is selected, the selected installation sequence is informed to the user as shown in Figure 6.18. Then, the installation sequence is adjusted based on the available resources as shown in Figure 6.19.

Figure 6.18 The selected installation sequence

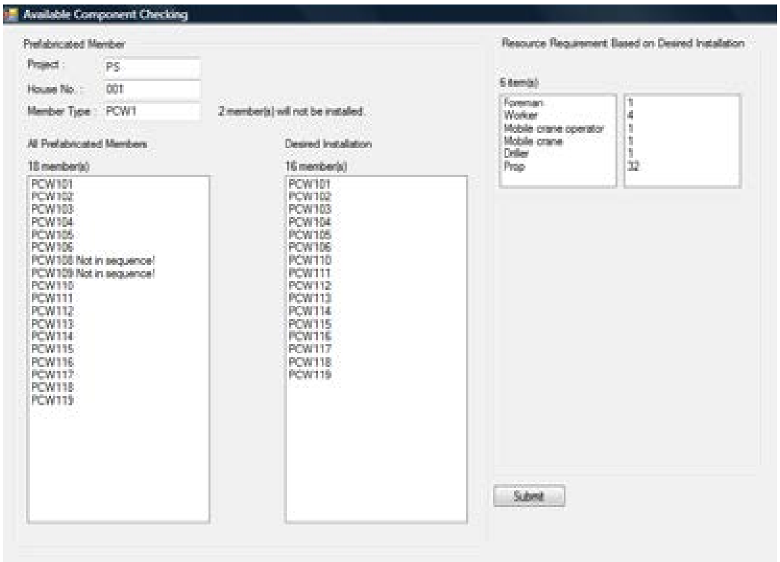

Figure 6.19 Installation sequence adjustment

6.7.3 Installing the prefabricated members

This step aims to install the prefabricated members by following the selected installation sequence. The installation has to follow the procedures and specifications.

The foreman and mobile crane operator are the main users in this step. The requirements of knowledge and skill, which are related to the developed automation approach for the foreman and mobile crane operator, are shown in Table 6.7 and Table 6.8 respectively.

However, the stock location and the installed location of the prefabricated member in Table 6.8 are additional locations for the mobile crane operator. In the current process, the operator perceives the location from the signal. The stockman gives the signal to the operator for moving the boom to the stock location while the erector gives the signal to the operator for moving the boom to the installed location. The locations, which are provided to the operator, aim to improve the duration of the installation process and reduce any mistakes due to miscommunication. The operator perceives the destination of work in advance instead of waiting for the signal from the stockman or erector. In addition, the appearance of the current prefabricated member is displayed on the user interface for the mobile crane operator so mistakes from the installation process can be observed.

Table 6.7 Knowledge and skill requirements of the foreman compared to the developed framework in Step 3

Knowledge and skill requirements	Developed automation approach
The perception of selected installation sequence and the details in a selected installation sequence	The selected installation sequence with its details is automatically transferred to the module.
The interpretation of construction drawings	The construction drawing is simplified to the perspective view. The clear view of prefabricated member reduces any mistakes that may occur during the installation process. Thus, only the details for installation and obvious points are displayed.
Prefabricated member identification	RFID technology is used to identify the prefabricated members in the previous step. Information from previous steps is still recorded in the database and transferred to this step.
The perception of a prefabricated member, which will be lifted and installed	The stock location of current installation members is displayed. The information is updated based on the current installation sequence.
The perception of location, where a prefabricated member has to be installed	The installed location of current installation members is displayed. The information is updated based on the current installation sequence.
The perception of installation procedure and installation specification The resource identification The usage of materials, tools, measurement tools, cable, shackles, and hooks for resource hooking and unhooking The communication using hand signals	The general information, which is required by the personnel in an installation group, is provided.

Table 6.8 Knowledge and skill requirements of the mobile crane operator compared to the developed framework in Step 3

Knowledge and skill requirements	Developed automation approach
Operating the mobile crane to swing between the stock rack and house	The stock location of the current installation member is displayed and provided to the mobile crane operator. The information is updated based on the current installation sequence.
Operating the mobile crane to hook, lift, install, and unhook a prefabricated member	The installed location of the current installation member is displayed and provided to the mobile crane operator. The information is updated based on the current installation sequence.

For the interpretation of construction drawings, the first version of the framework development used the plan view, which was captured from the construction drawing as shown in Figure 6.20. After pilot testing the framework in the laboratory with foam prefabricated member model, the plan view was difficult to use and led to installation mistakes because it had many details and doubt about direction. Then, the perspective view was developed. However, the first version of the perspective view did not have the obvious points for installation as shown in Figure 6.21. The modified one, though, included the obvious points as shown in Figure 6.22.

From the pilot testing, another problem was found. According to the usage of button pressing for the information as time recording, the times displayed on the laptop computer and PDA might be different. Thus, the recorded time could not be used for further analysis or improvement. Therefore, the calibration of time was developed to mark the starting time of the installation process on the laptop and PDA as shown in Figure 6.23.

The flow of the developed framework is shown in Figure 6.24. The process starts at the time of calibration with the PDA and laptop computer by the foreman and mobile crane operator. Then, the starting time of installation is recorded as shown in Figure 6.25. After that, the selected installation sequence and its details and the prefabricated members in the stock rack are recalled. The computer processes and compares this information to find the unavailable and unnecessary members. The number of members in the installation sequence, the number of prefabricated members in the rack, and any unnecessary members are informed to the mobile crane operator and foreman as shown in Figure 6.26 and Figure 6.27 respectively.

The framework provides the stock location of prefabricated members, which is the current sequence. The information is changed to the installed location after the button is pressed. The information is provided and the time is recorded as a loop until all members in the selected installation sequence are installed.

Figure 6.20 Plan view

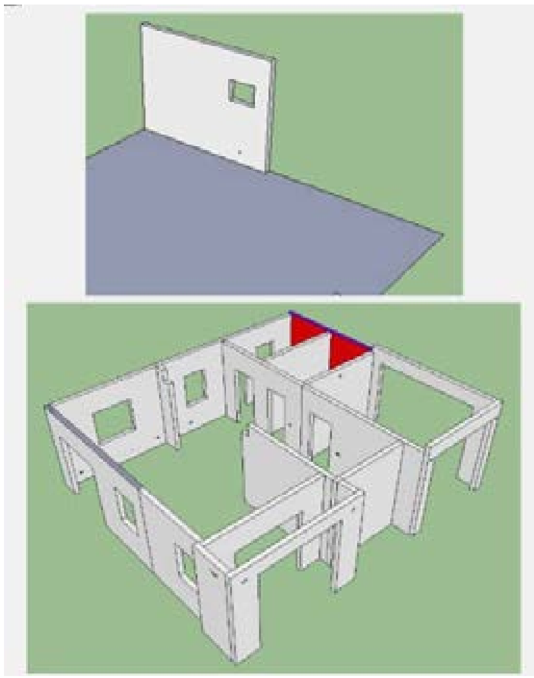

Figure 6.21 First version of perspective view

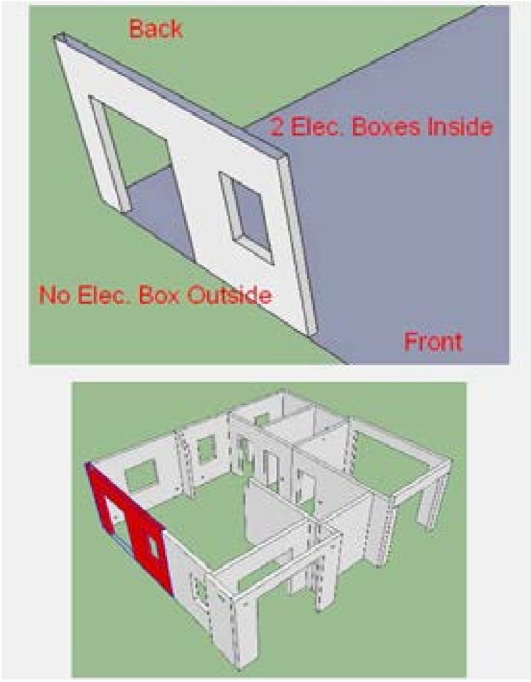

Figure 6.22 Modified version of perspective view

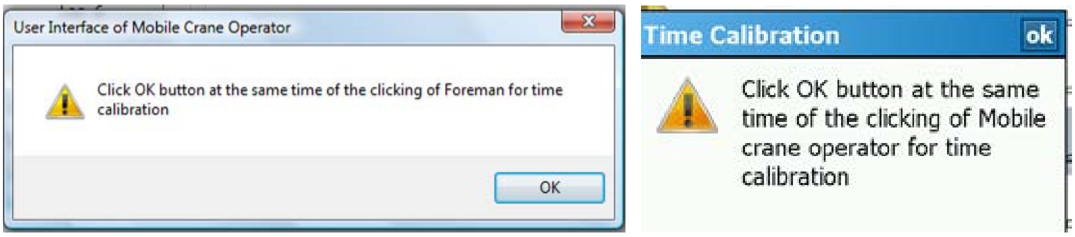

Figure 6.23 Time calibration

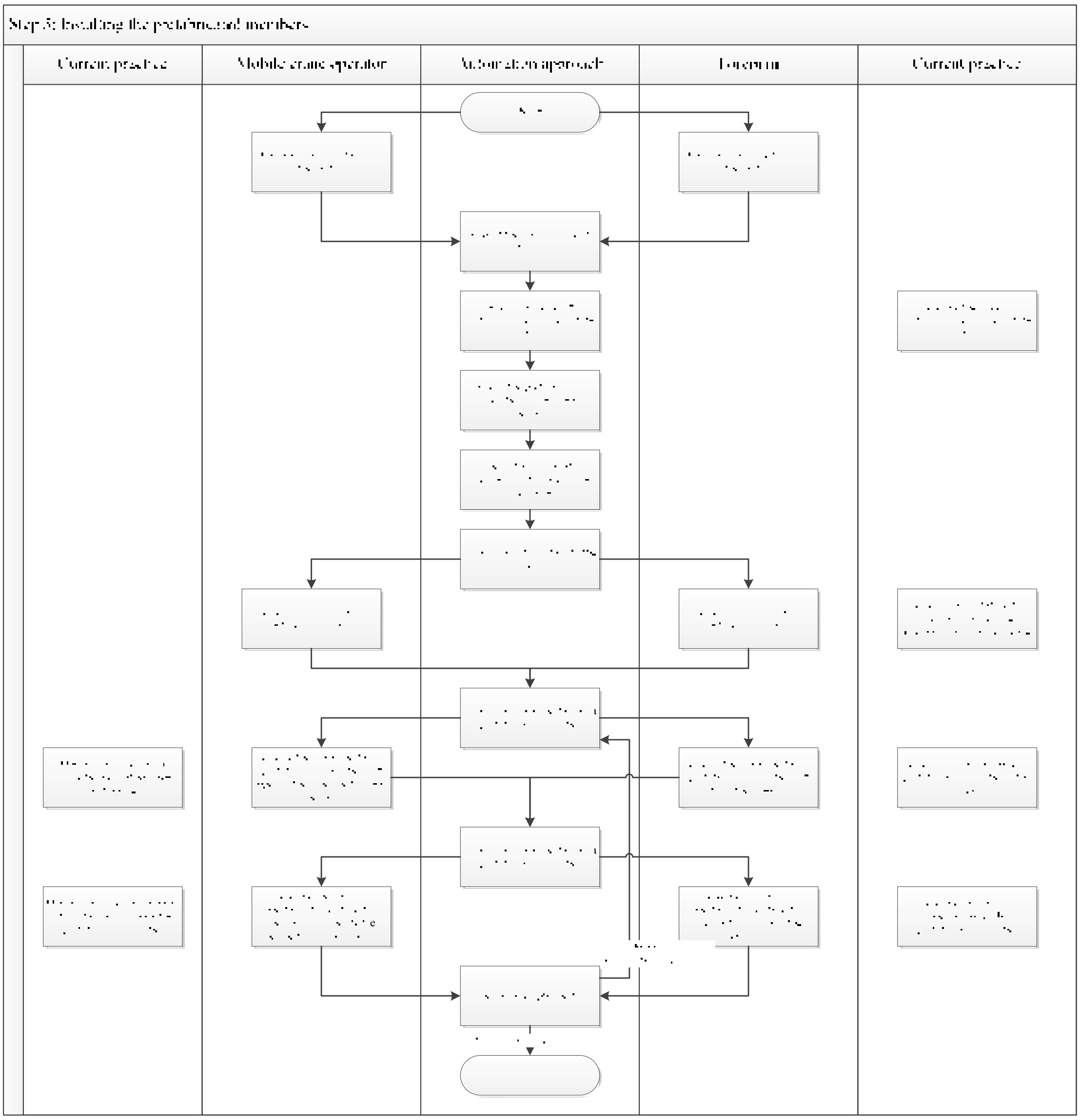

Figure 6.24 The flow of the developed framework in Step 3

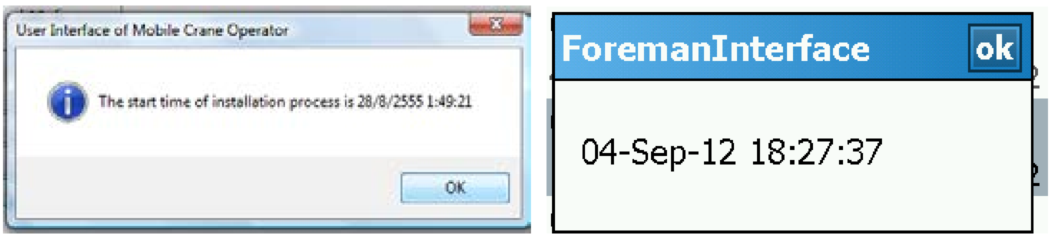

Figure 6.25 Starting time of installation

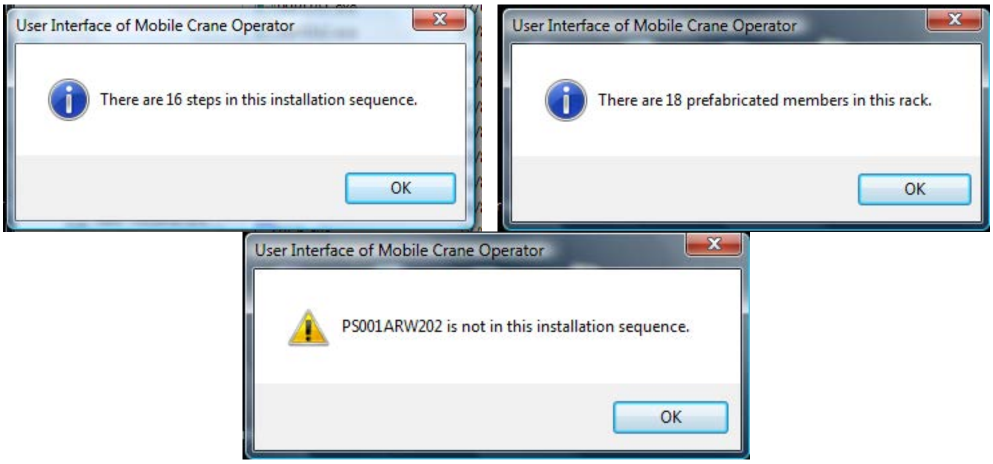

Figure 6.26 Information for the mobile crane operator before the installation process

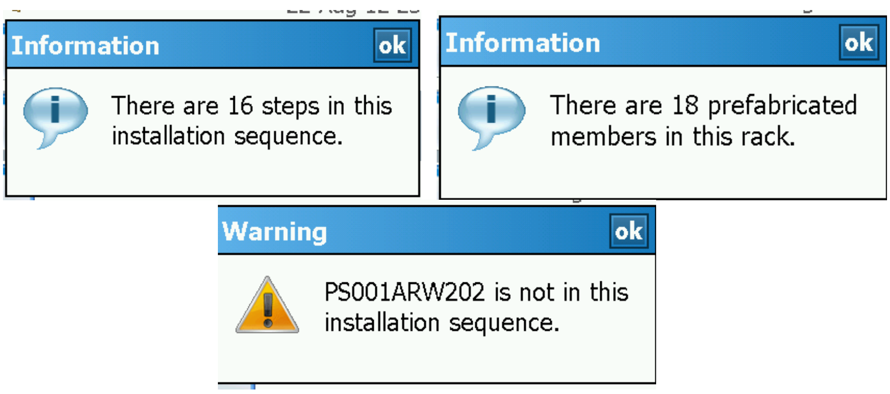

Figure 6.27 Information for the foreman before the installation process

The user interface for the mobile crane operator is shown in Figure 6.28. The provided information includes the current installation sequence, the list of members in the selected sequence, the location of each prefabricated member in the rack, the appearance of a prefabricated member, and the installed location of a prefabricated member.

The user interface for the foreman provides the same information. The only difference is the location and display arrangement as shown in Figure 6.29. In addition, the section view is also provided to the foreman as shown in Figure 6.30.

While the prefabricated members are being installed, general information can be accessed. This component was developed to reduce the knowledge and skill requirements for hand signal communication, perception of installation procedure, perception of installation specification, material usage, tool usage, measurement tool usage, working at height, adjustment of prefabricated members, and the shoring of prefabricated members. These examples are shown in Figure 6.31. With this information, the foreman can supervise the installation process and distribute the information to an installation group under the supervision. The troubleshooting is also provided to solve any problems as shown in Figure 6.32. Then, correction process is raised the correctness and consistency.

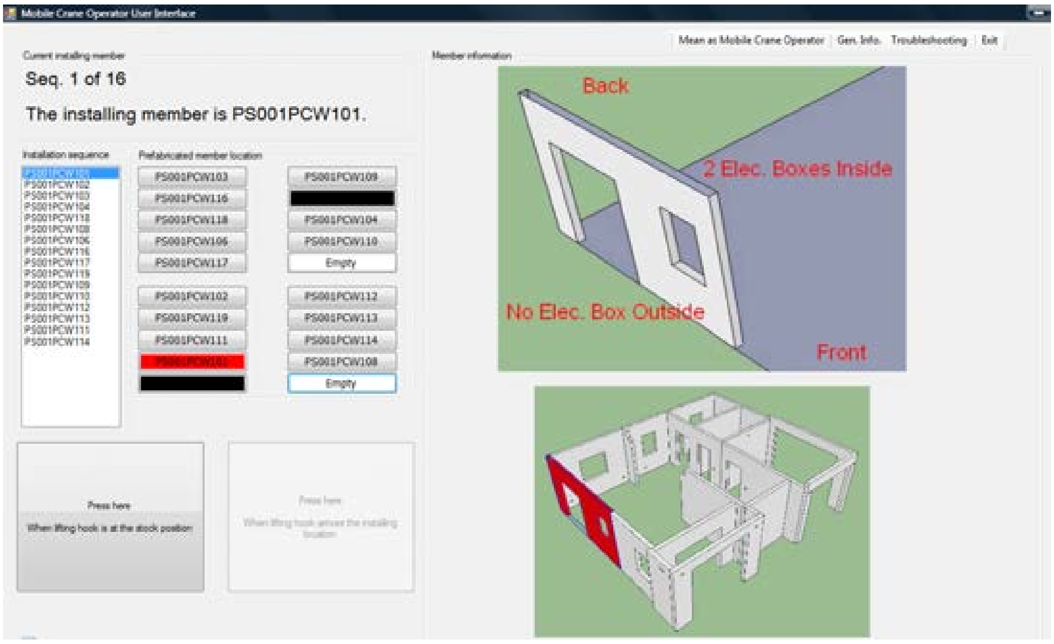

Figure 6.28 User interface for mobile crane operator

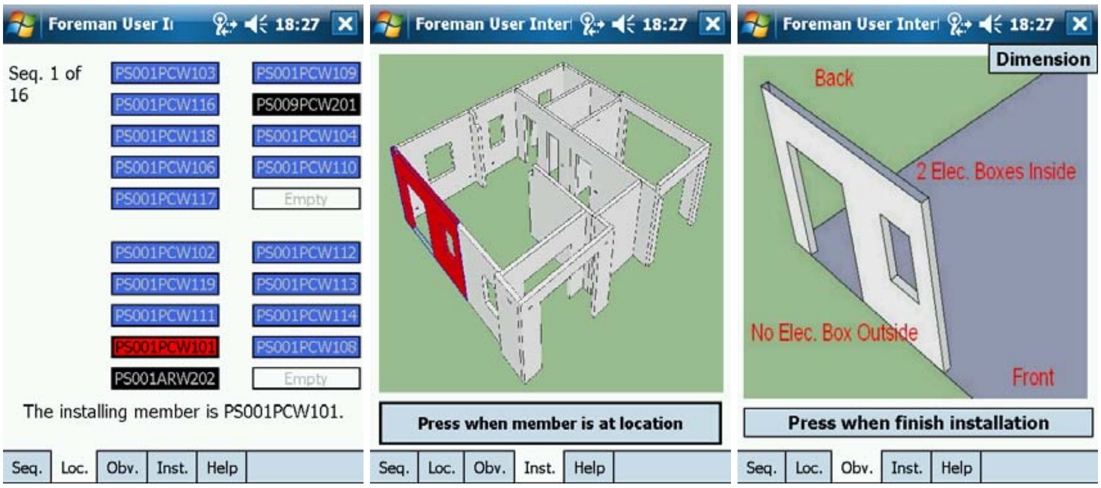

Figure 6.29 User interface for the foreman

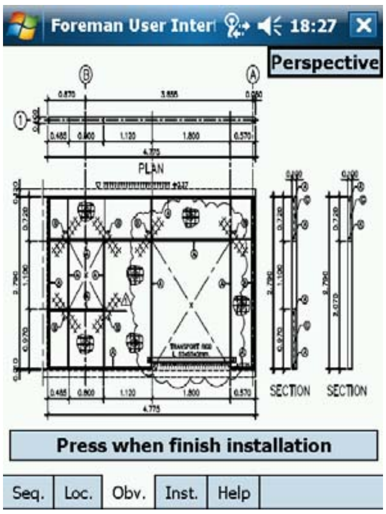

Figure 6.30 Section view

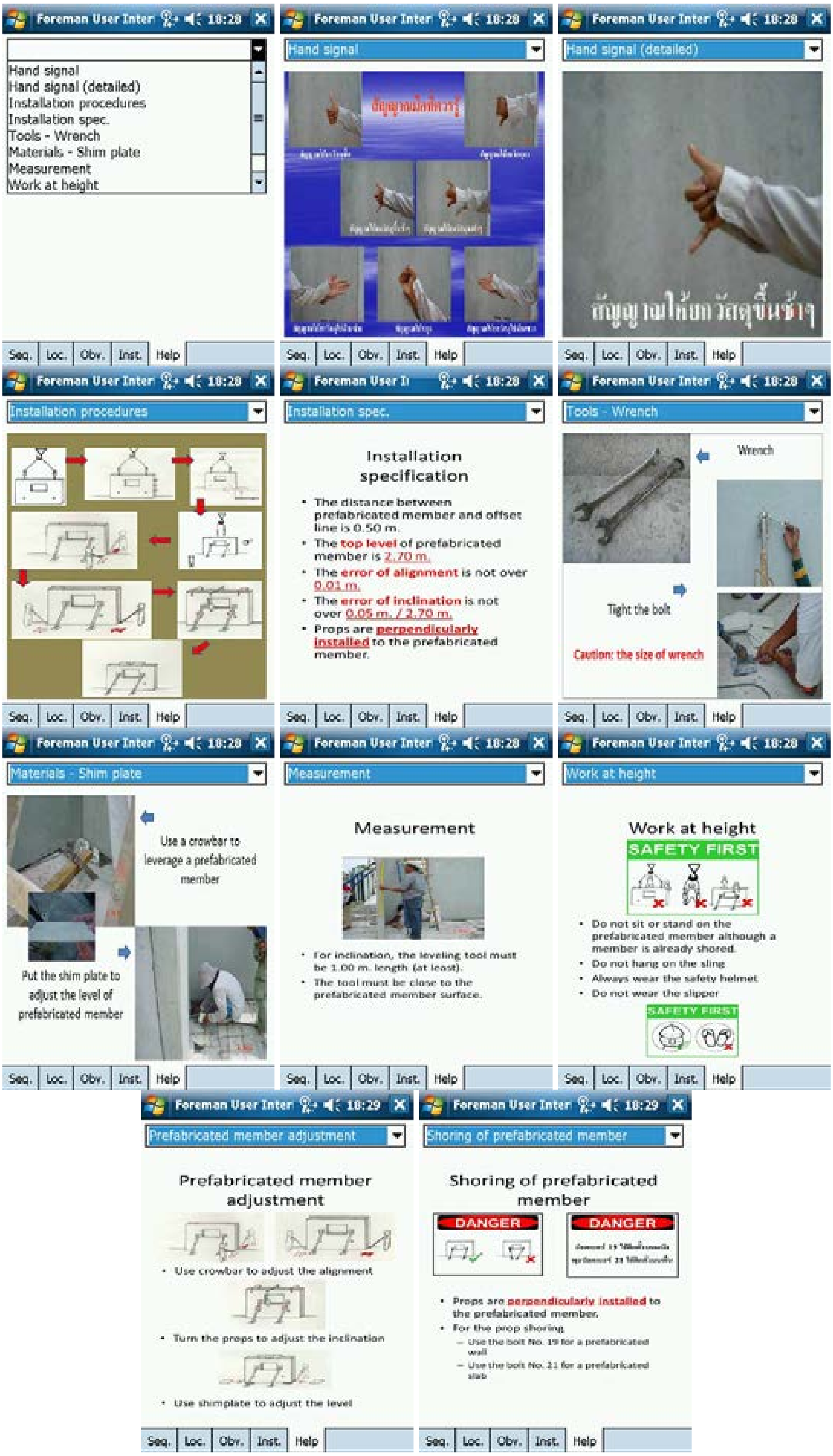

Figure 6.31 General information

Figure 6.32 Troubleshooting

When all members are installed, the framework will inform the user on how to finish the installation as shown in Figure 6.33.

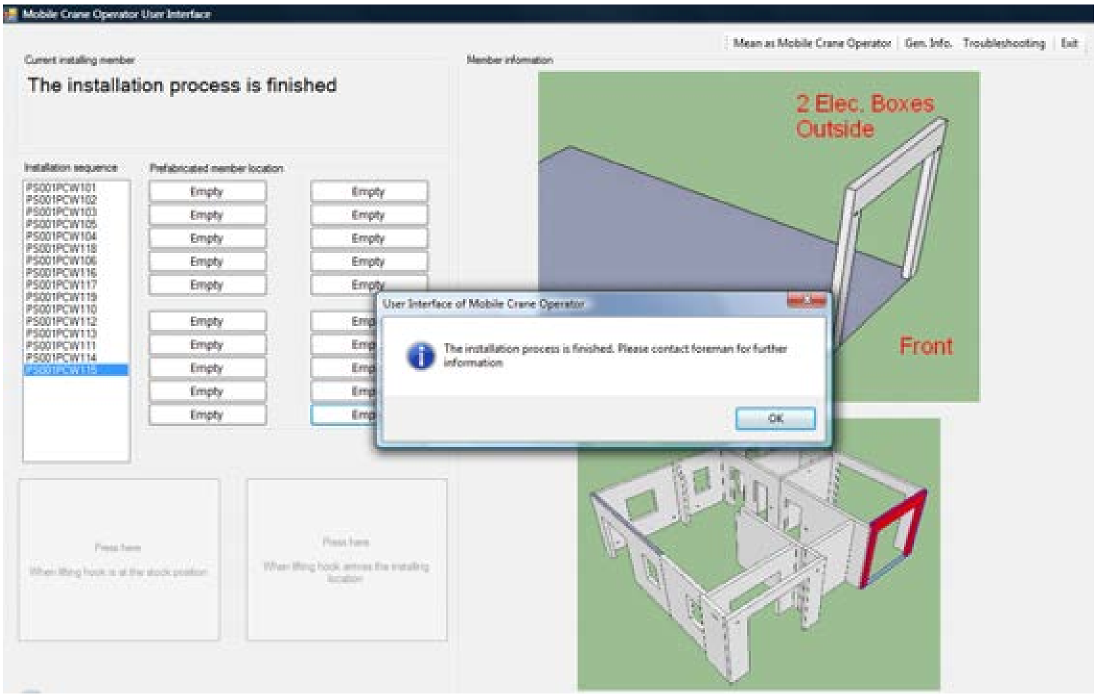

Figure 6.33 Finish of installation

6.7.4 Checking the availability of other resources

This step aims to check the available resources for the installation. The related resources are personnel, materials, tools, and equipment. The related knowledge and skill requirements of the foreman and the developed framework are shown in Table 6.9. The framework is developed based on the flow in Figure 6.34.

Table 6.9 Knowledge and skill requirements of the foreman compared to the developed framework in Step A

Knowledge and skill requirements	Developed automation approach
The resource identification	RFID technology is employed for resource identification.
The data collection and accumulating the quantity	The data of available resources is recorded using RFID technology, and the accumulative quantity is calculated using the developed module.

The foreman records the available resources by scanning the RFID tag, which is attached to each resource as shown in Figure 6.35. After reading the RFID tag, the identification number of the RFID tag is loaded. When the foreman decides to stop checking the resources, the data is automatically transferred to the next step.

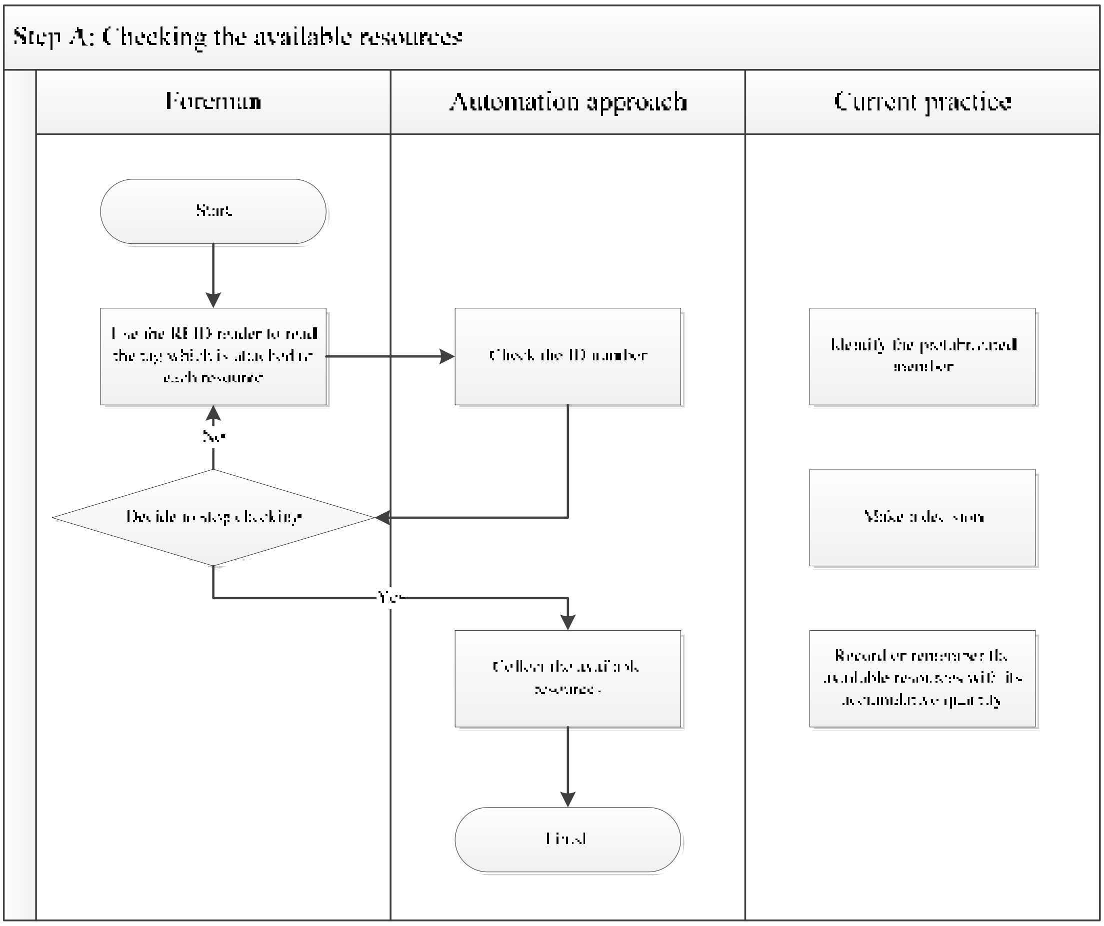

Figure 6.34 The flow of the developed framework in Step A

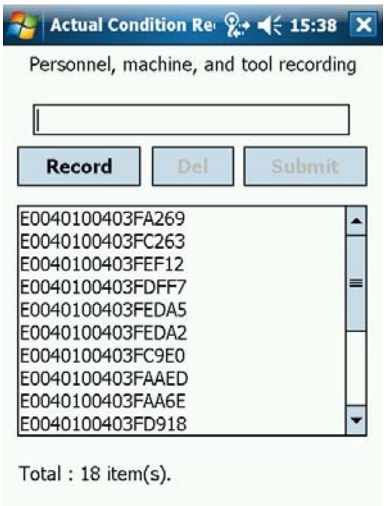

Figure 6.35 Available resource checking

6.7.5 Comparing the required resources and the available resources

In this step, the required resources and the available resources are compared. The knowledge requirements, which are related to the developed framework, are shown in Table 6.10. The flow of the developed framework is shown in Figure 6.36.

Table 6.10 Knowledge requirements of the foreman compared to the developed framework in Step B

Knowledge requirements	Developed automation approach
The perception of resource and prefabricated member requirements based on the installation of members in the target group	The requirements are automatically calculated based on the information of the structure and prefabricated member in the database.
The perception of available resources and the perception of available prefabricated members	The data of available resources and prefabricated members are automatically recalled.
The comparison between the required resources and the available resources	The required resources and available resources are compared automatically. The results of the comparison are shown to the user to adjust the resources.
The perception of unavailable resources	The effects of unavailable resources will be raised in this step or adjusted in the next step.

When the module is called, the list of available prefabricated member of target group is shown as illustrated in Figure 6.37. The related information, i.e., project, house, number, structure type, the combination of prefabricated members in a structure, the available prefabricated members, the unavailable prefabricated members, and the number of unavailable prefabricated members are shown.

The required resources are calculated automatically based on the available prefabricated members in the target group. The calculation process accesses the information of each structure and each prefabricated member in database. The available resources are also called in this step as shown in Figure 6.38. The resources are grouped and accumulate number of each resource are displayed. After that, the required resources and the available resources are compared and displayed as shown in Figure 6.39. In case of the resources are over the requirements, foreman can adjust the resources as shown in Figure 6.40 by removing some resources out. In the case that the resources are inadequate to start the installation process, such as a mobile crane is not available, the process will be stopped. However, if the resources are inadequate but the installation of the target group cannot be complete, the installation sequence will be adjusted in the next step. Finally, the use of resources for the installation process is recorded.

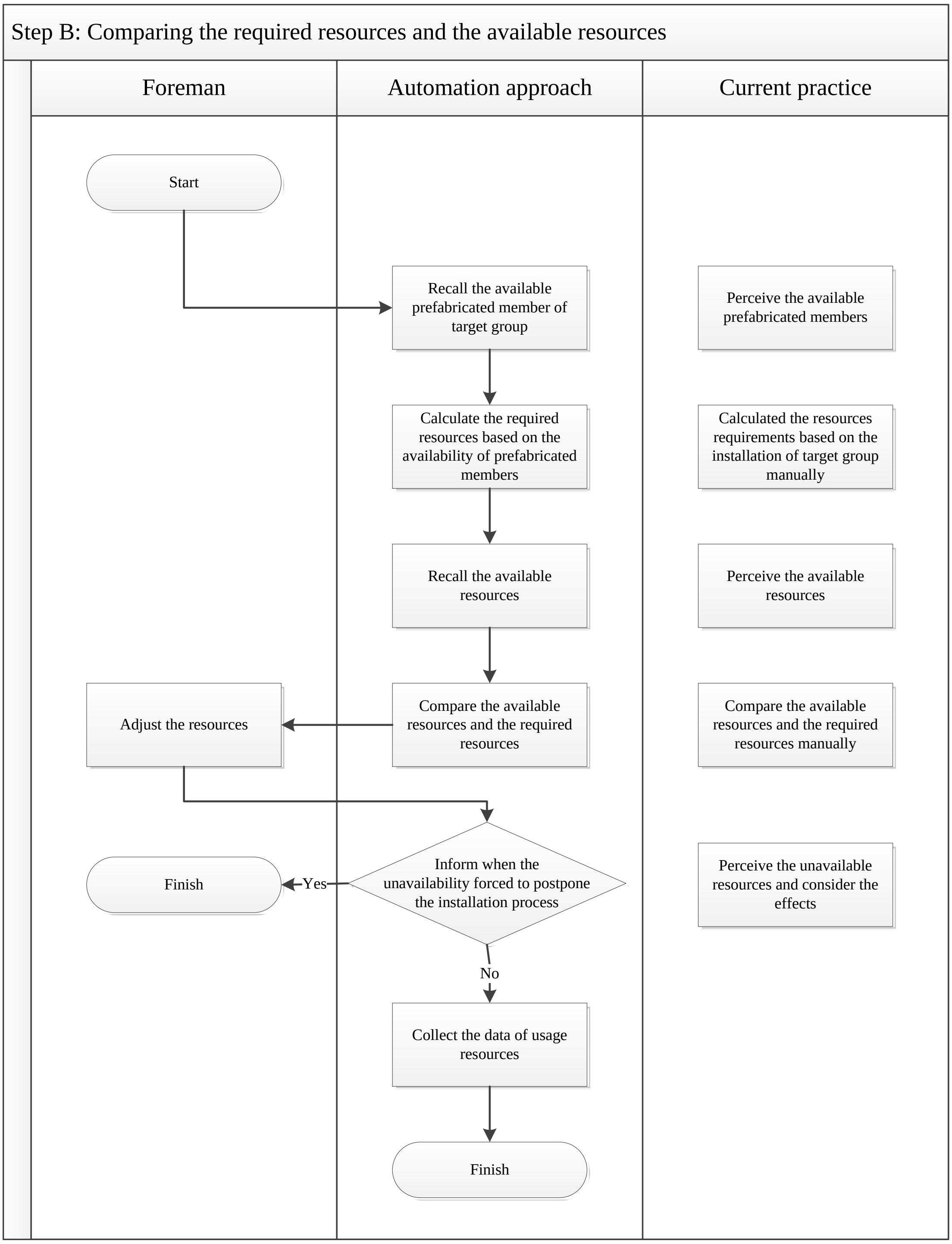

Figure 6.36 The flow of the developed framework in Step B

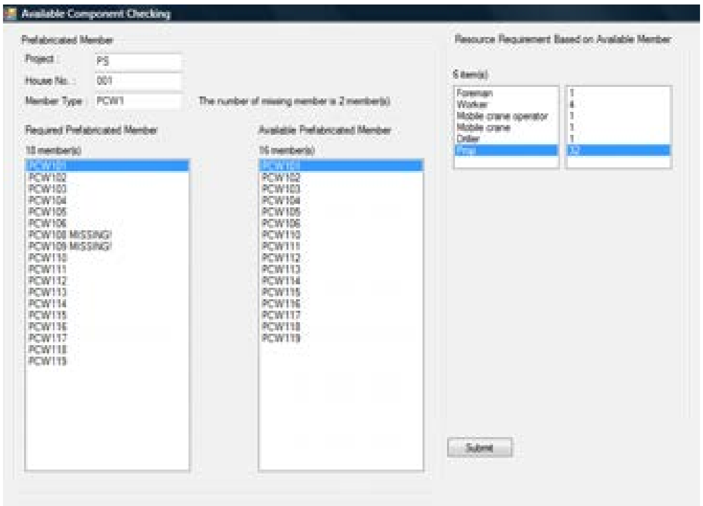

Figure 6.37 List of available prefabricated members of the target group

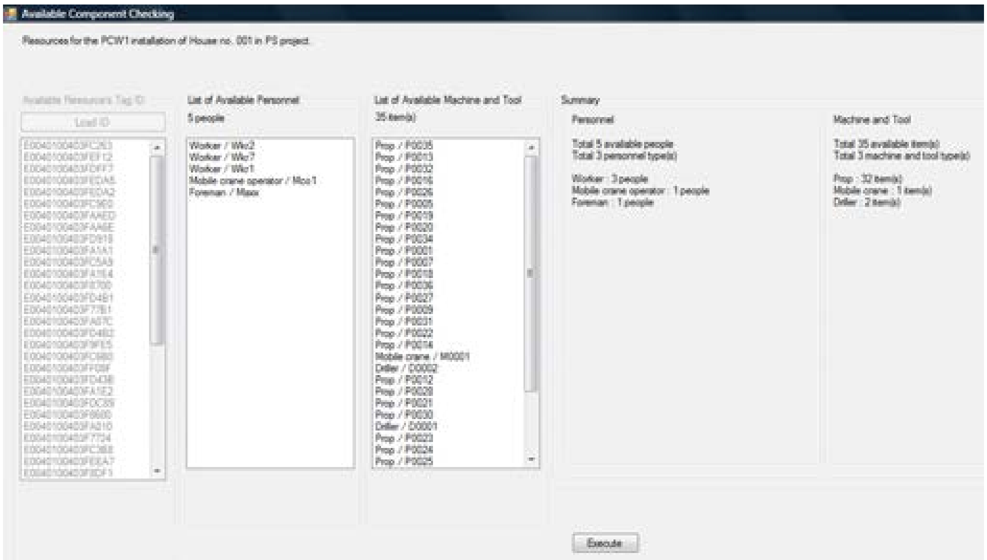

Figure 6.38 Available resources

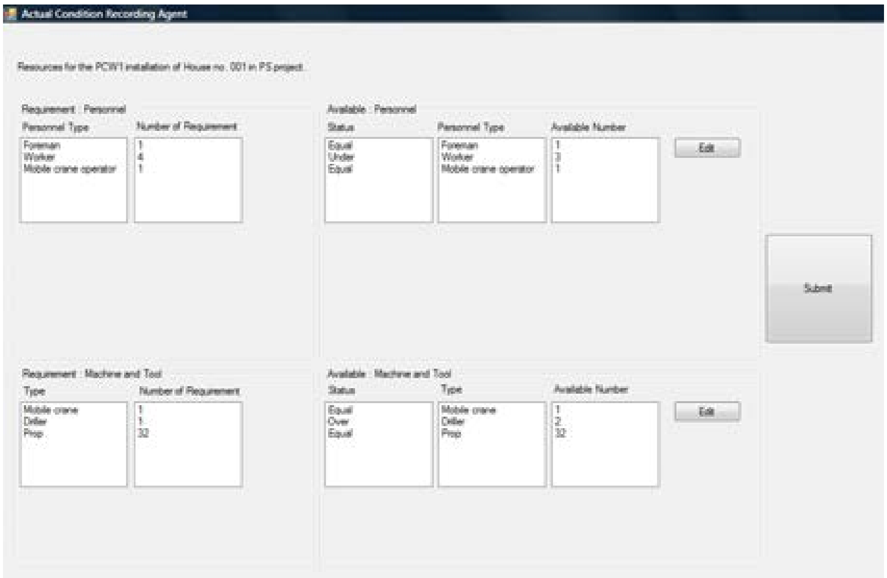

Figure 6.39 Compare the required resources and the available resources

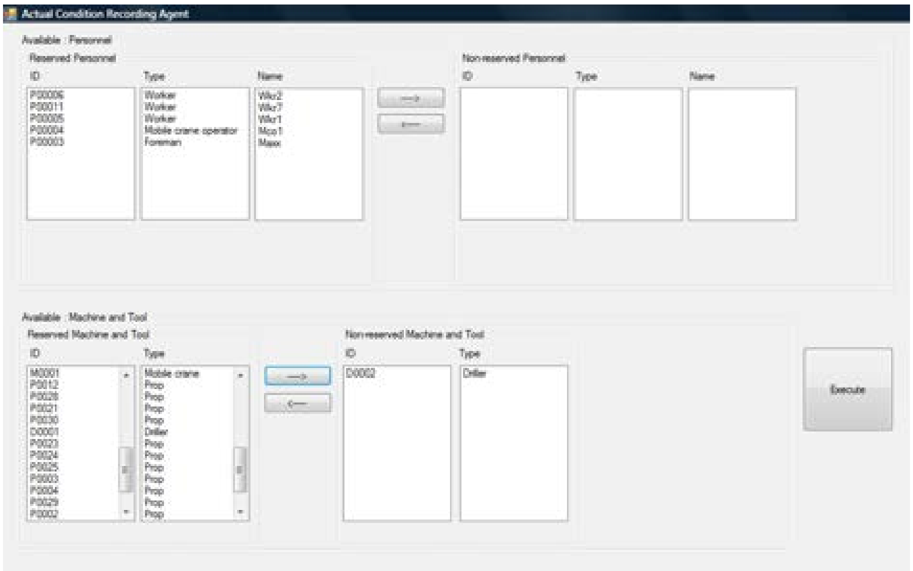

Figure 6.40 Resource adjustment

6.7.6 Deciding the work location of the mobile crane

From the current practices, knowledge and skill requirements have been revealed. Some of the requirements are supported through the developed framework as shown in Table 6.11. The flow of the developed framework in this step is shown in Figure 6.41.

This step aims to provide the information for the mobile crane operator in order to set up the machine at the location. The work location of the mobile crane must support the installation of the prefabricated members in the target group. The information includes the work location of the mobile crane and the resource requirements based on the ground conditions. In addition, the location of the prefabricated member stock is recorded in this step for generating an installation sequence later.

The module is automatically opened after the previous step is finished. The available prefabricated members in the target group are recalled. Then, the weight and installed location of each prefabricated member in the database are accessed. The weight and location are calculated and compared with the rated capacity lifting chart in the framework. After that, the information of the work location of the mobile crane is provided to the mobile crane operator in terms of the distance from the house as shown in Figure 6.42.

The mobile crane operator inputs the conditions of the ground into the framework. The resource requirement based on the ground conditions is considered using the framework. The information of resource requirements is shown to the user as illustrated in Figure 6.43. In the module, the location of stock is also inputted.

Table 6.11 Knowledge and skill requirements of the mobile crane operator compared to the developed framework in Step C

Knowledge and skill requirements	Developed automation approach
The perception of the target group in the installation process, prefabricated members in the target group, weight for each prefabricated member, installed location for each prefabricated member	The perceptions are automatically recalled from the database.
The perception of the working range of the mobile crane and understanding the rated lifting capacity chart	The rated lifting capacity chart for each mobile crane was entered in the framework. The framework calculates the work location of the mobile crane based on the weight and installed location of the prefabricated member and the data of the rated lifting capacity.
The consideration of the ground conditions	The effects of the ground conditions on the resource requirements are specified in the framework. The framework informs the operator of the requirements.
The perception of the available resources, especially the machine base plates	The available resources were already shown in the previous step.
The perception of required resources in terms of type, size, and quantity to set up the machine	The resource requirements are considered and informed based on the conditions of the soil.

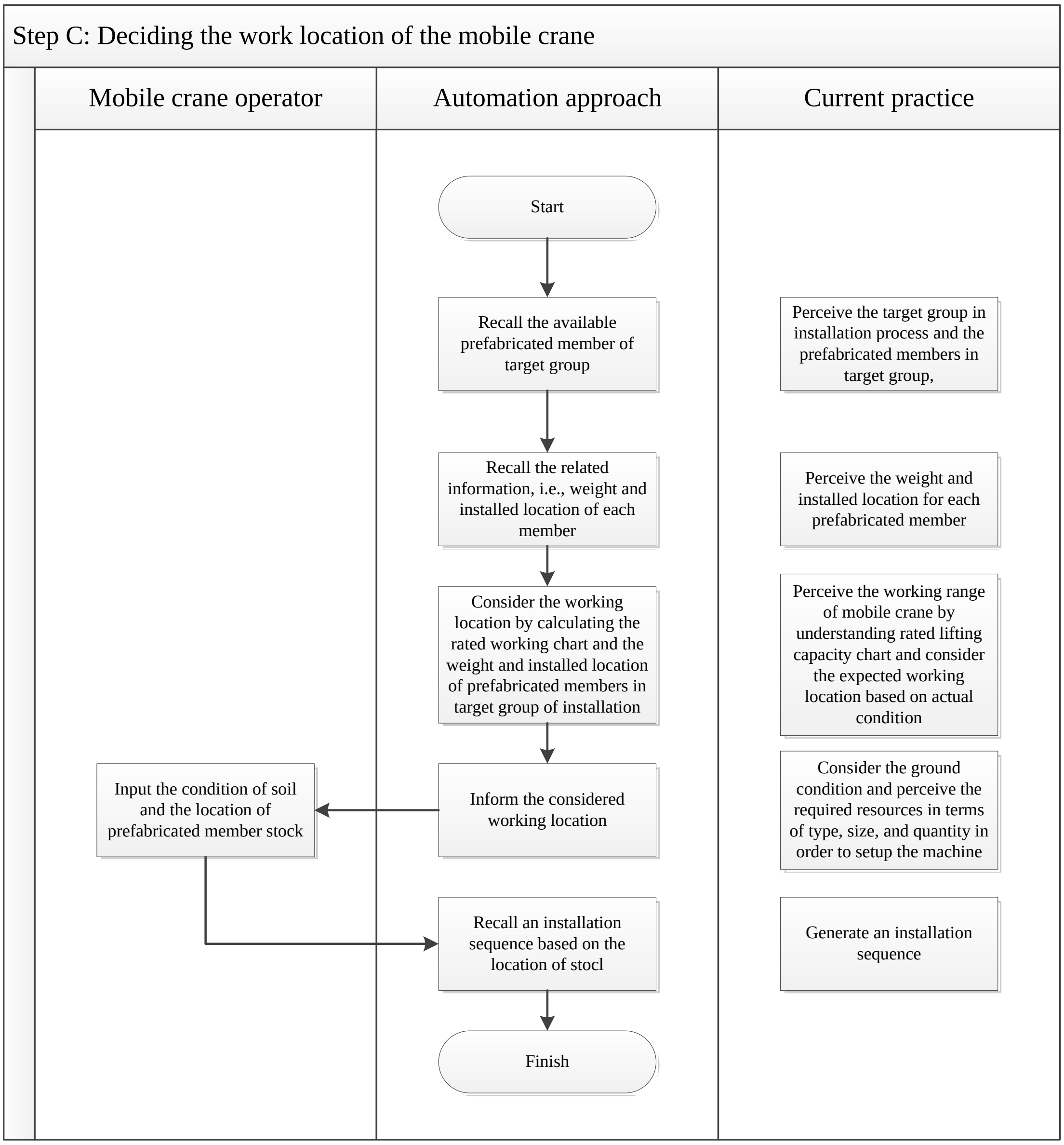

Figure 6.41 The flow of the developed framework in Step C

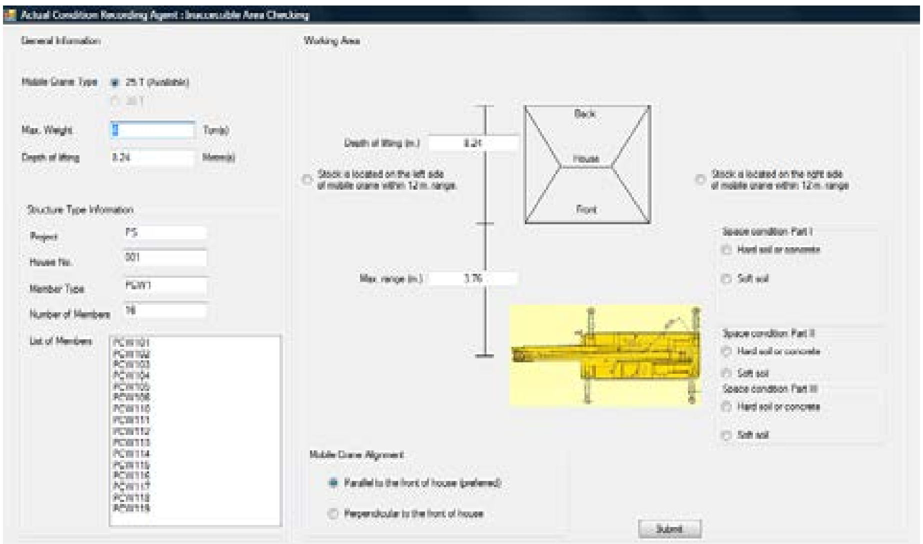

Figure 6.42 Deciding the work location of the mobile crane

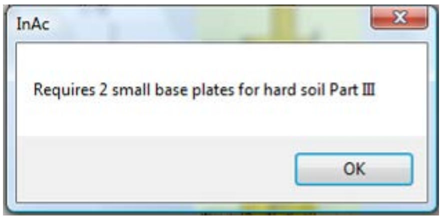

Figure 6.43 Resource requirement based on the ground conditions

6.7.7 Inspection of installed prefabricated members

The inspector inspects the installed prefabricated member. The related knowledge and skill requirements of the inspector and the developed framework are shown in Table 6.12. The framework was developed based on the flow in Figure 6.44.

Table 6.12 Knowledge and skill requirements of the inspector compared to the developed framework in Step D

Knowledge and skill requirements	**Developed automation approach**
The prefabricated member identification	RFID technology is used for identification.
The selection of checklist or specification	The checklist and related information are automatically displayed after the member is identified.
The perception of quality terms for each prefabricated member	The related information is automatically displayed after the member is identified. The examples of information are the measurement method, the illustration of related dimensions or distance, and the details of each inspection step.
The interpretation of construction drawings and quality terms	
The use of measurement tools	
The inspection by following the quality terms	
The data collection	The inspection results are recorded automatically. The name of the inspector and date and time of the inspection are also recorded.

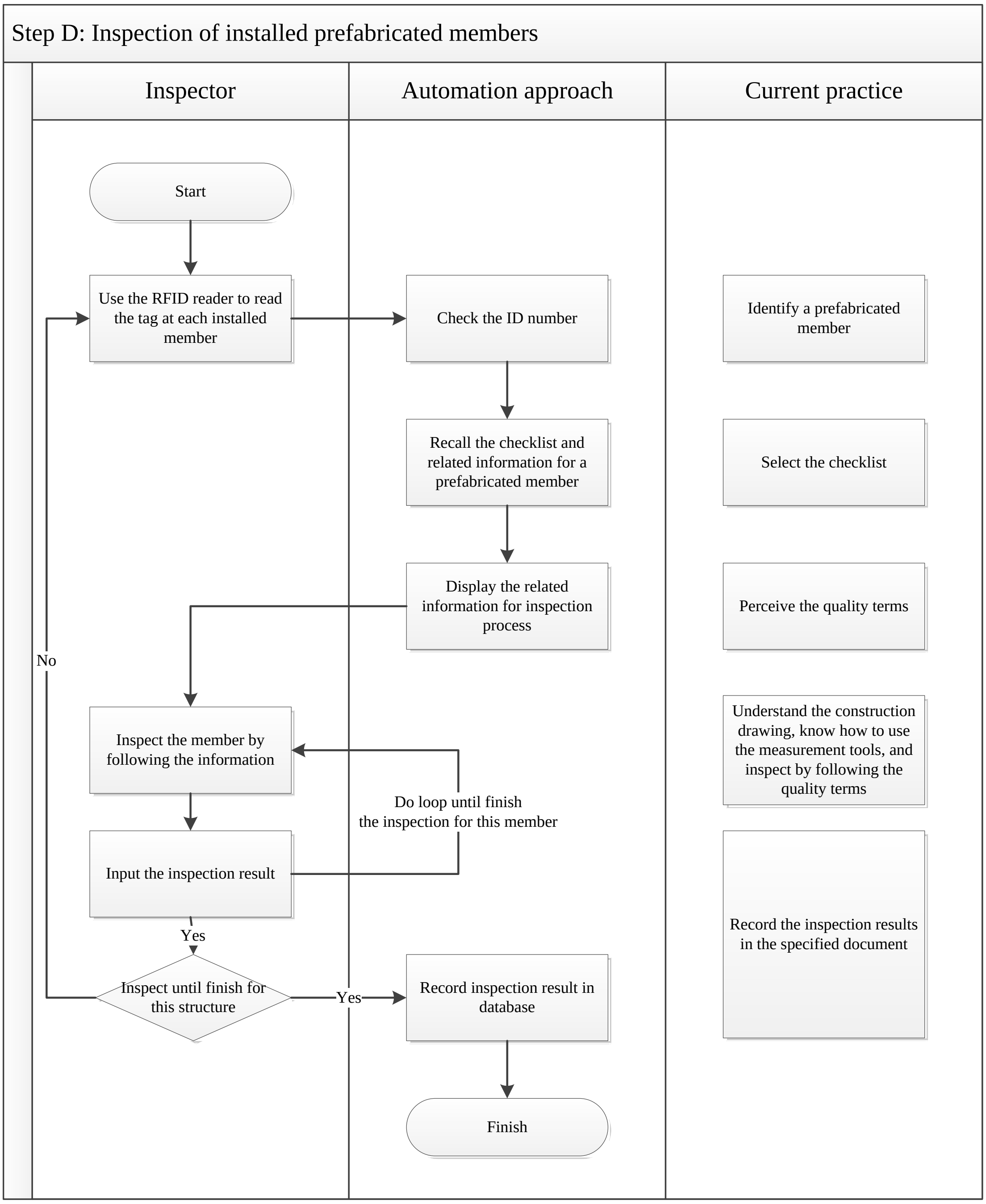

Figure 6.44 The flow of the developed framework in Step D

The inspector uses a PDA with RFID reader to read a RFID tag. Then the identification number is sent to the framework. The database is accessed to identify the prefabricated member so that the prefabricated member can be properly identified.

When the prefabricated member is identified, the checklist and related information, which are prepared by the personnel, are called and displayed. Thus, the inspector will receive the correct checklist in a timely manner as shown in Figure 6.45. The related information is also provided to the inspector, including illustrations of the inspection as shown in Figure 6.46, the appearance, and the installed location of the prefabricated member as shown in Figure 6.47. Finally, the results from the inspection are inputted into the user interface as shown in Figure 6.48.

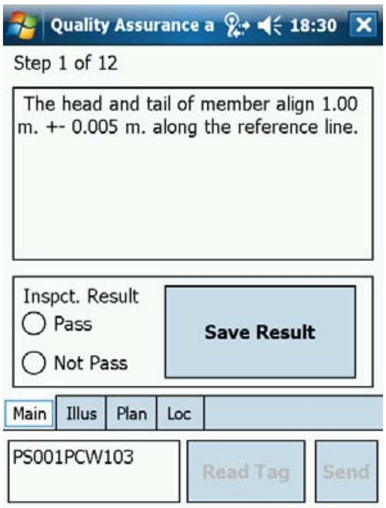

Figure 6.45 Inspection checklist

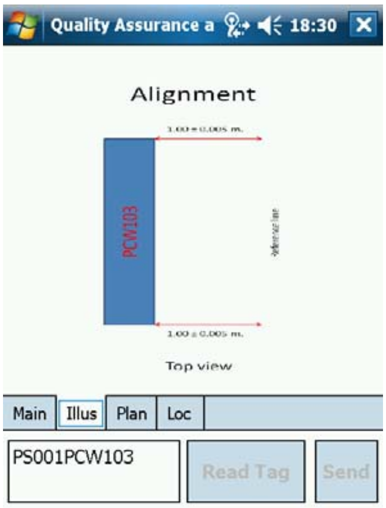

Figure 6.46 Inspection illustration

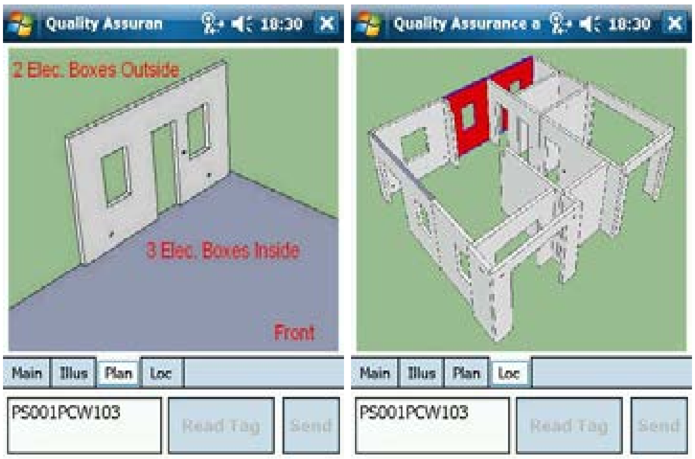

Figure 6.47 Appearance and installed location of the prefabricated member

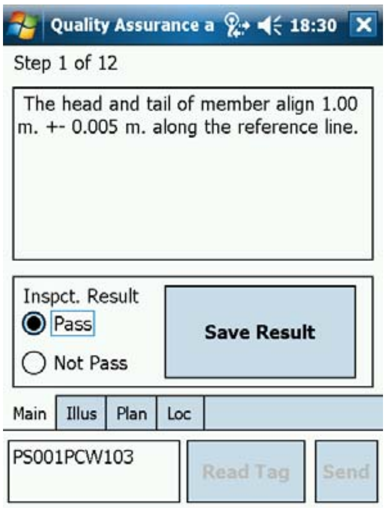

Figure 6.48 Input the result

6.8 Summary

The automation approach was developed to reduce the knowledge and skill requirements of personnel. The work breakdown structure of the installation process, the work breakdown structure of each step of installation, and the knowledge and skill requirements of each person in each step were employed for the automation approach development.

The automation approach covers the seven installation steps, which include three main steps and four supplementary steps. The three main steps are checking the available prefabricated members, checking the availability of other resources, comparing the required resources and the available resources, deciding the work location of the mobile crane, making a decision for an installation process, installing the prefabricated members, and inspection of installed prefabricated members.

The personnel, materials, tools, and equipment are in the scope of framework. Personnel include workers, foreman, mobile crane operator, and inspector. For the materials, the prefabricated member is focused because it is the main material in the installation process.

Computer and RFID technology are selected for the developed framework. Laptop computer and PDA are employed for data collection, providing information, processing data, and data acquisition. RFID technology is employed for the identification of prefabricated members and other resources.

The system architecture of the developed framework is composed of the users, user interfaces, hardware, connections, modules, and a database. The foreman, inspector, and mobile crane operator are the main users. The user interfaces are developed for the main users. A laptop computer is assigned to the mobile crane operator and located at the machine's cabin, while a PDA with RFID reader is assigned to the foreman and inspector. The five modules include actual case recording module, alternative generating module, quality assurance and control module, general information module, and specific information module. A database is used for data acquisition. For data transfer and communication, the laptop computer and PDA are linked with the ad-hoc network function.

The framework is developed for the seven steps of installation, each of which aims to reduce the knowledge and skill requirements. The related data and information is provided by the planner or designer before the installation process and stored in the database. The framework accesses the database to archive the required data and information in each step. The information is provided to the user in a graphical format. The input and identification processes are avoided using human skills by using RFID technology. The processing feature of a computer is employed to calculate and manipulate the data and information. In addition, the framework is developed to perceive the changes and select the countermeasures properly in a timely manner.

Chapter 7
Evaluation

7.1 Introduction

In this chapter, the evaluations of the automation approach are described. The evaluations are separated into three phases: (1) evaluation by the prefabricated member model, (2) evaluation at the construction site, and (3) evaluation by the experts, each of which had different purposes and methodologies, which will be described in the following parts of this chapter.

7.2 Evaluation by the prefabricated member model

7.2.1 Introduction and sampler

Prefabricated members of the first floor wall were scaled down and built to 1:10 model. The total number of prefabricated members of the model is 20. All panels were made from Medium-density Fiberboard (MDF) as shown in Figure 7.1.

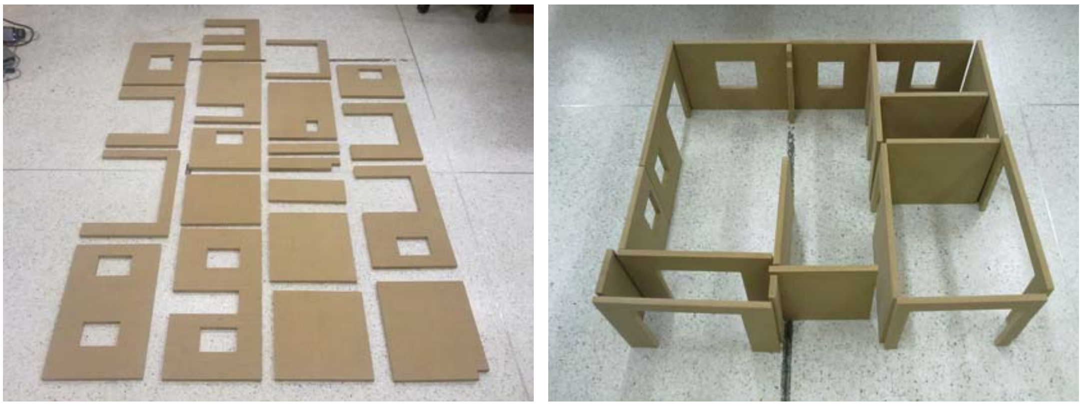

Figure 7.1 Prefabricated member model

In the evaluation, the models were laid out on the table, which represented the stock location area. This table was 0.77 meters tall and 1.55 meters apart from another table (measured from center to center). Another table represented the house area, where the sample had to install the models. When all models were installed, the structure was complete like the first floor wall of the house. The figure of testing scheme is shown in Figure 7.2.

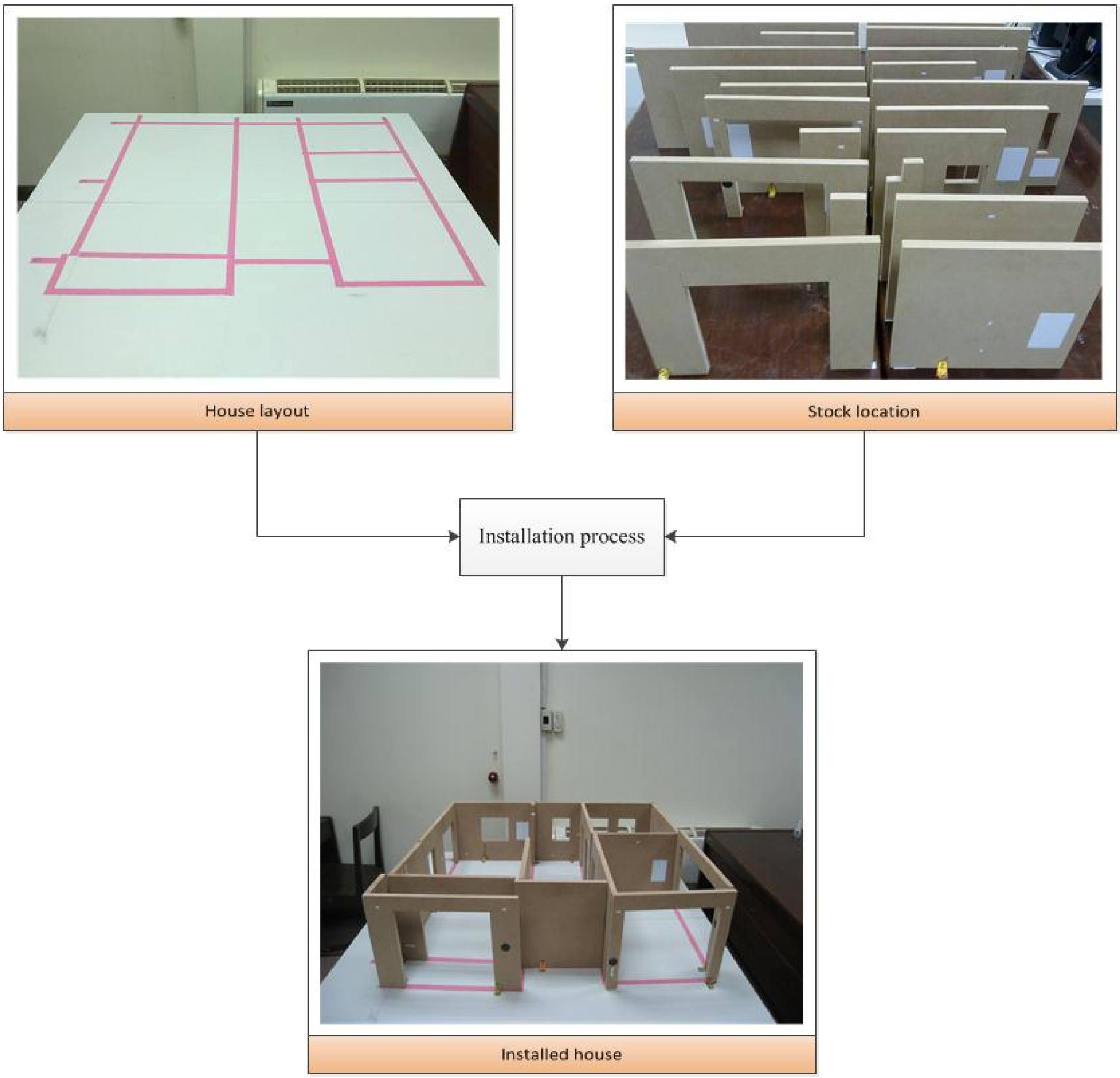

Figure 7.2 Testing scheme

In the test, ten people were selected as the sampler. All of them were civil engineers who have had different construction experience and prefabrication experience as shown in Table 7.1 and Figure 7.3. Each sampler did three rounds of tests in a random situation, comprising of two tests apiece, which included installation using the conventional method and the automation approach. Thus, each sampler did six tests and the total number of tests was 60.

From the details of sampler in Table 7.1, half of the samplers had experience in construction, while the other half had no prior construction experience. Only 20% of the sampler group had experience in prefabricated construction, while the rest had no prefabrication experience. The graphical charts are shown below in Figure 7.4.

Table 7.1 Experience in construction and prefabrication of samplers

Sampler	Experience in construction (year)	Experience in prefabrication (year)
1	8	1.5
2	17	0
3	0	0
4	9	0
5	0	0
6	0	0
7	5	0
8	0	0
9	0	0
10	5	1

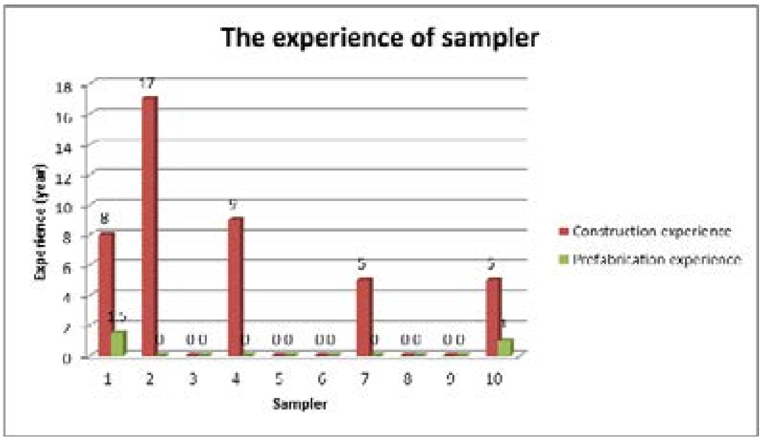

Figure 7.3 The experience of sampler

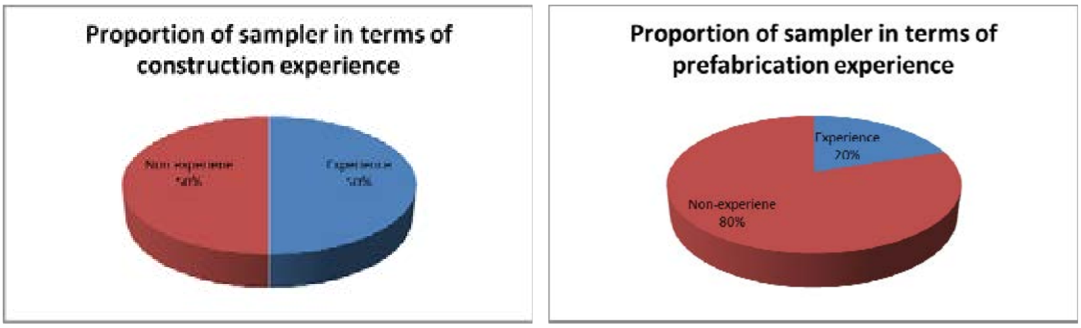

Figure 7.4 Proportion of sampler in terms of construction and prefabrication experiences

Before the test, each sampler was briefed. The contents of briefing were as follows:

- The installing house is a single house. The prefabricated member models are the members of the first floor wall, composed of 18 members.

- The installation does not include a beam member (PCW107).
- The construction drawings are provided. The details of the whole structure, including the first floor wall, are indicated in the drawings.
- The drawings are always correct.
- The marking or tag including RFID tag may be incorrect, damaged, or lost. The illustration of marking is shown in Figure 7.5.

Figure 7.5 Marking at the prefabricated member model

- The obvious points for the prefabricated member model are shape, door opening, window opening, electricity box as shown in Figure 7.6, and plumbing as shown in Figure 7.7. These points can be seen in construction drawings and at the model. The house layout can be used as a reference.

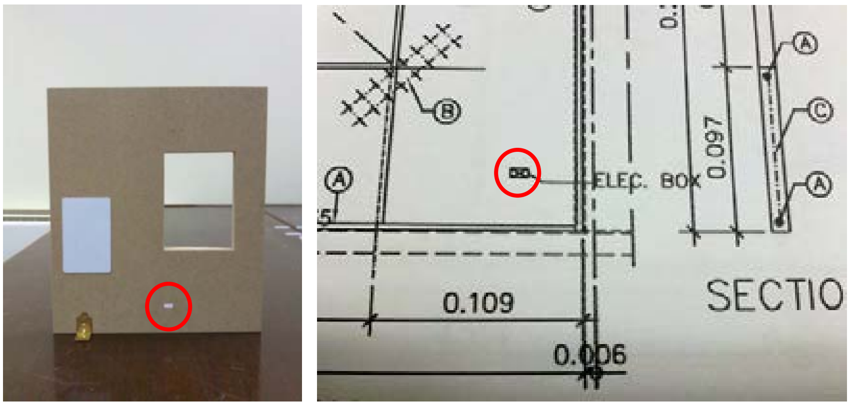

Figure 7.6 Electricity box at the model and in the drawing

- The RFID tag and angle steel plate are not part of the model and are not indicated in the construction drawings. The RFID tag and angle steel are shown in Figure 7.8.
- The measurement tools can be used to measure and identify the model.
- The number of prefabricated member models at stock location may be adequate, inadequate, or in excess for the installation.

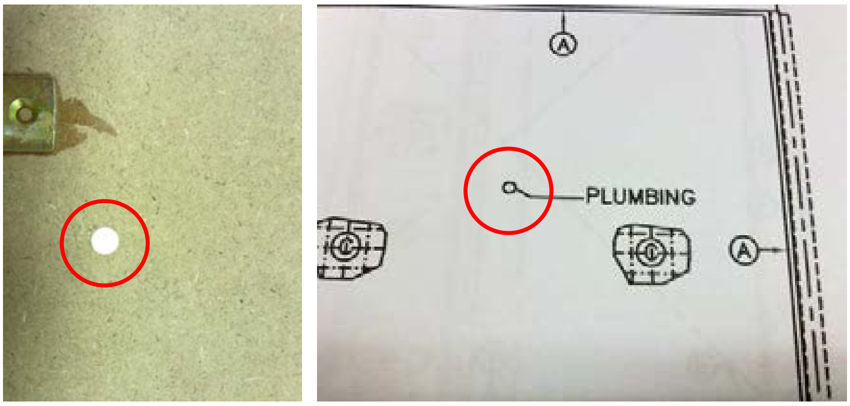

Figure 7.7 Plumbing at the model and in the drawing

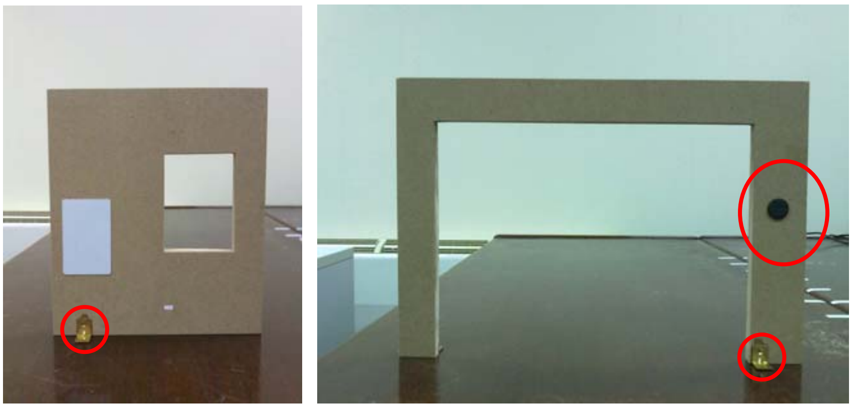

Figure 7.8 RFID tag and angle steel plate

- The installation sequence is usually considered with the relative location of stock, mobile crane, and house. The sequence should be convenient to install by avoiding the line-of-sight blocking and the installation between prefabricated member models. The sequence should start from the outermost corner from stock.
- The house layout is always correct. Some layout alignments are inclined to compensate for the thickness of model.
- For the installation, each prefabricated member model has to be lifted from the stock location and installed at the house layout. The model does not have to be totally close with another model. The acceptable installation is shown in Figure 7.9.
- If the prefabricated member model is not available, the installation sequence can skip the unavailable model.
- The invert installation of model will be counted as a mistake.
- The installation should be done correctly the first time.
- The installation duration will be recorded since the sampler examined the construction drawings until the last model was installed.


Figure 7.9 Acceptable installation

- At the stock location, the sampler does not allow to flip the model in order to find the required one. The sampler has to simulate the mobile crane movement and operation.
- For concentration, please do not use mobile phones or any devices while performing the evaluation.
- Please be careful while doing the evaluation to prevent the damage of testing tools and models.
- In the case the model collapses or there are any accidents, the evaluation will be stopped. After recovery or problem solving, the model will be reset to the previous condition before the accident, and then, the evaluation continues.

7.2.2 The situations in the test

Due to the nature of actual construction sites, many situations change, such as the location of each prefabricated member at the stock location, the number of available prefabricated members at the stock location, or incorrect or missing tags of prefabricated members. Thus, these changes were simulated in the test randomly.

The random situations were originated by the RANDBETWEEN formula in Microsoft Excel as shown in Figure 7.10. The situations could be (1) all required prefabricated member were available, (2) the marking tags were incorrect or lost, and (3) some required prefabricated members were unavailable. The details of each situation are shown in Table 7.2. The RANDBETWEEN formula also originated the list of incorrect tag members or unavailable tag members in Situation 2 and the list of unavailable prefabricated members in Situation 3. The number of each situation in each round is shown in Table 7.3 and summarised as shown in Figure 7.11 and Figure 7.12.

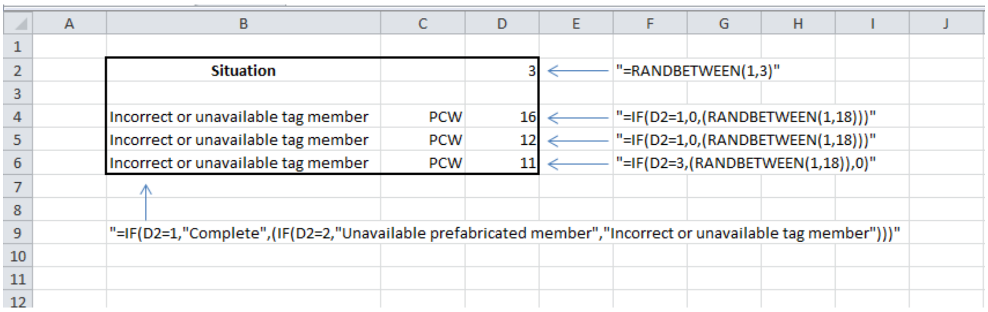

Figure 7.10 Origination of random situation

Table 7.2 The details of each situation

Detail	Situation 1	Situation 2	Situation 3
Number of prefabricated members at stock location	20	20	18
Number of prefabricated members which have to be installed	18	18	16
Number of unavailable prefabricated members	0	0	2
Number of unrequired prefabricated members	2	2	2
Number of incorrect tag panels or unavailable tag panels	0	3	0

Table 7.3 The number of each situation in each round

Test	Situation 1 (time)	Situation 2 (time)	Situation 3 (time)	Total (time)
Round 1	4	4	2	10
Round 2	5	2	3	10
Round 3	4	3	3	10
Total	13	9	8	30

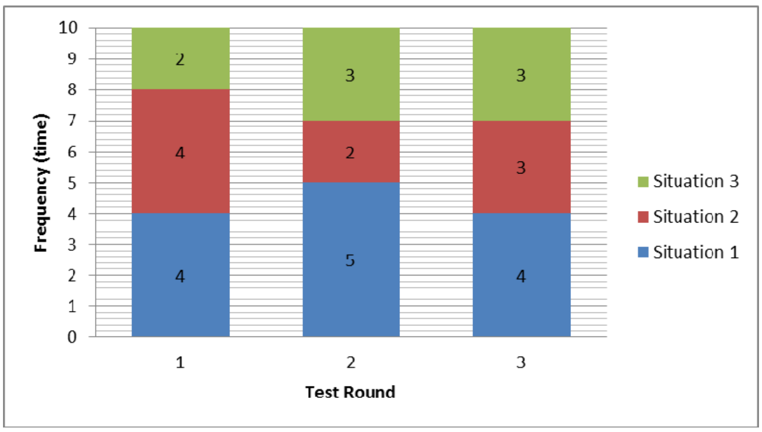

Figure 7.11 Frequency of each situation in each test round

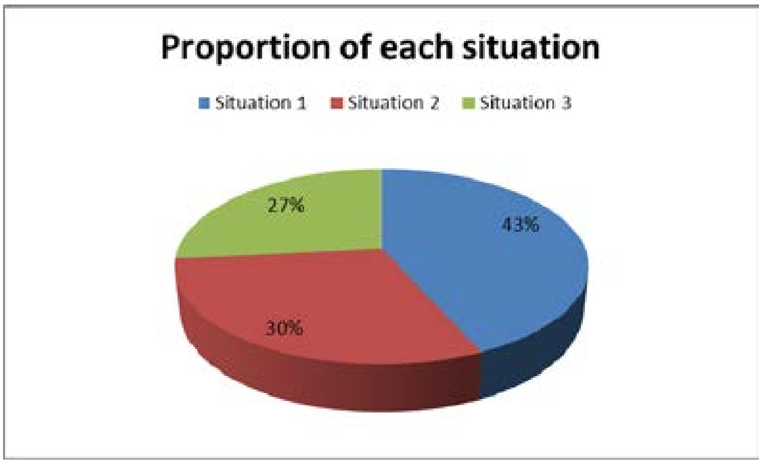

Figure 7.12 Proportion of each situation

7.2.3 The installation test

In the test, each sampler performed as an installation group in the three main installation steps. The sampler was allowed to look at the construction drawings before the installation and in the installation, as shown in Figure 7.13. Then, the sampler checked the available prefabricated member models and considered the installation sequence, as would a foreman. In Figure 7.14, a prefabricated member model was sought by the sampler at the stock location based on the considered sequence as a stockman. In the case of uncertainty or doubt, the model was identified by measuring the dimensions and related distances and using the construction drawings, as shown in Figure 7.15. An example of doubt is shown in Figure 7.16. An uncertainty occurred because the models resembled each other. After that, in Figure 7.17, the model was installed at the correct location on the house layout as a mobile crane operator and erectors. Compared to the actual installation, the test was similar to the actual installation process as shown in Table 7.4.


Figure 7.13 Sampler looked at construction drawings

Figure 7.14 Sampler sought a prefabricated member model

Figure 7.15 Use of construction drawings and measurement

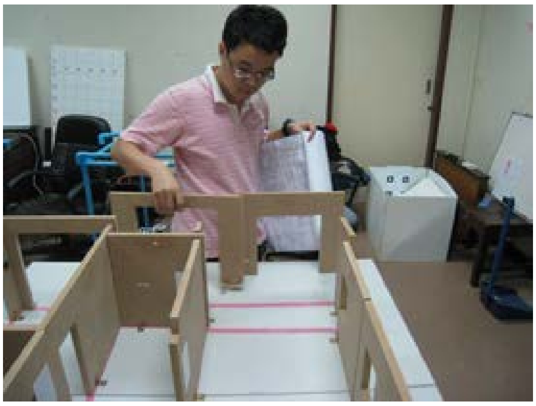

Figure 7.16 Sampler experiencing uncertainty

According to the three main installation steps, the knowledge and skill requirements are shown in Table 7.5.

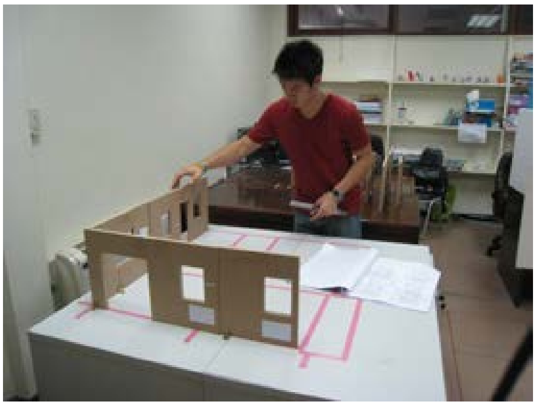

Figure 7.17 Sampler installed a prefabricated member model

Table 7.4 Comparison between main installation steps and actions in the evaluation by model

Step	Main installation steps	The evaluation by model
1	Checking the available prefabricated member	Check the available prefabricated member models
2	Making a decision for an installation process	Consider the installation sequence based on the available prefabricated member models
3	Installing the prefabricated members	Search a prefabricated member model at the stock location Install a model at the correct location

A round test was separated into two tests: (1) test by conventional method, and (2) test by automation approach. In the conventional method test, the work was operated as mentioned above. The work was carried out as a repetitive loop until the last model was installed. While the prefabricated member models were being installed, video footage was recorded and photos were taken. The installation sequence, the installation duration, and the number of wrong installations were also recorded.

In the test by automation approach, the sampler scanned the prefabricated member models at the stock location using a PDA and RFID reader as shown in Figure 7.18. The scanning process was in the actual case recording module. After that, the approach processed for an installation sequence by alternative generating module. The specific information module was employed to display the installation information and record the installation time. The sampler performed the installation by following the information from the automation approach, such as the sequence, the location of prefabricated member model at stock, the location where the prefabricated member model had to be installed, and the alignment of the prefabricated member model. The figure of installation is shown in Figure 7.19. The videos and photos were also captured in the evaluation, including the installation duration and the number of wrong installations.

Table 7.5 Knowledge and skill requirements in the evaluation by prefabricated member model

Installation step	Knowledge and skill requirements
Step 1: Checking the available prefabricated members	- The interpretation of construction drawings - The perception of prefabricated members or combination in each structure - The prefabricated member identification - The use of measurement tools
Step 2: Making a decision for an installation process	- The installation sequence generation
Step 3: Installing the prefabricated members	- The interpretation of construction drawings - The perception of details in a selected installation sequence - The perception of prefabricated member location, which will be lifted and installed (stock location) - The prefabricated member identification - The perception of location, where a prefabricated member has to be installed (installed location) - The use of measurement tools

Figure 7.18 Sampler scanned the prefabricated member models

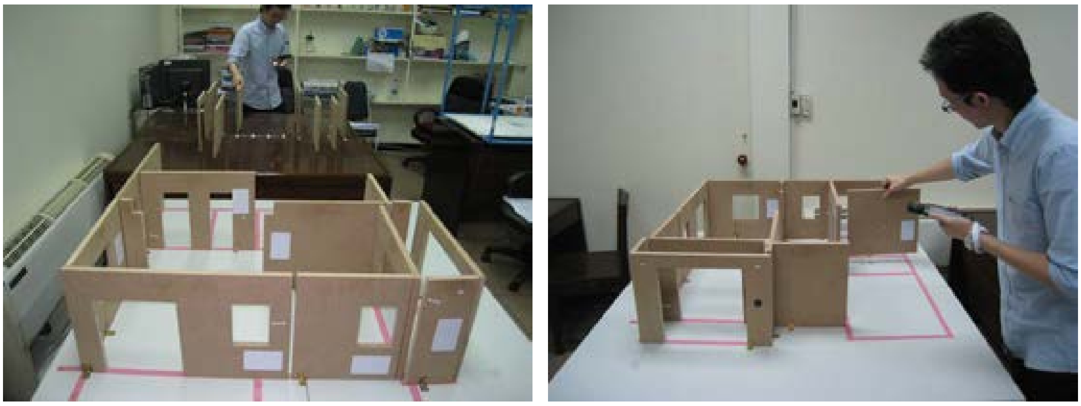

Figure 7.19 Sampler performed the installation by using the automation approach

The installation duration was clocked from the time that sampler looked at the construction drawing until the last model was installed. The duration was transformed into the installation duration per panel because the number of installed models was different to the random situation. Thus, the installation duration per panel equaled the total installation duration divided by the number of installed members. The number of wrong installations was counted by checking the mistakes in terms of wrong installation location and invert of model installation. The examples of wrong installation location and invert of model installation are shown in Figure 7.20 and Figure 7.21 respectively.

7.2.4 Result

The installations by conventional method and automation approach were the main operations of this test, each of which had two results, including the installation duration per panel and the number of mistakes in the installation process. The results from the conventional method and the automation approach are shown in Table 7.6 and Table 7.7 respectively. The comparison between the conventional method and automation approach in terms of installation duration and the number of mistakes by each sampler is shown graphically in Figure 7.22 to Figure 7.31.

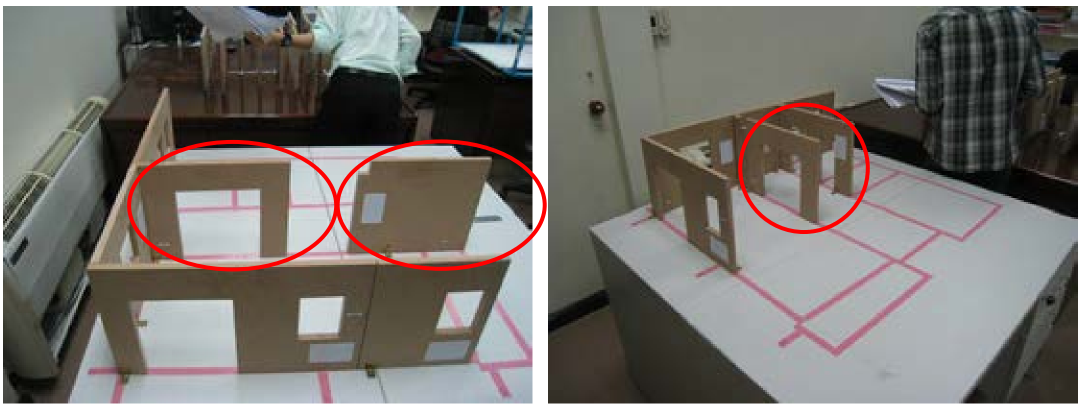

Figure 7.20 Wrong installation location

Figure 7.21 Invert of model installation

Table 7.6 Results of installation from conventional method

Sampler	Round 1		Round 2		Round 3	
	Duration per panel (sec.)	**Mistakes (time)**	**Duration per panel (sec.)**	**Mistakes (time)**	**Duration per panel (sec.)**	**Mistakes (time)**
1	51.89	1	58.06	1	37.56	0
2	83.33	5	53.56	0	53.75	1
3	38.34	1	37.50	3	31.11	1
4	55.56	4	25.11	1	41.17	2
5	103.38	2	70.89	0	55.56	0
6	69.22	4	60.89	0	40.50	0
7	110.82	4	38.94	2	29.61	1
8	91.29	6	51.94	0	41.50	0
9	183.89	1	84.75	1	55.63	0
10	68.72	1	60.11	2	39.50	1

Table 7.7 Results of installation from automation approach

Sampler	Round 1		Round 2		Round 3	
	Duration per panel (sec.)	**Mistakes (time)**	**Duration per panel (sec.)**	**Mistakes (time)**	**Duration per panel (sec.)**	**Mistakes (time)**
1	41.67	0	43.81	0	38.89	0
2	38.22	0	35.94	0	35.38	0
3	35.17	0	28.38	0	26.22	0
4	36.19	3	26.56	0	26.78	0
5	54.38	0	48.22	0	43.56	0
6	53.06	2	43.33	0	37.83	0
7	49.83	0	33.06	0	29.44	0
8	54.17	0	40.78	0	37.63	0
9	41.28	0	40.06	0	33.25	0
10	33.28	0	33.00	1	29.78	0

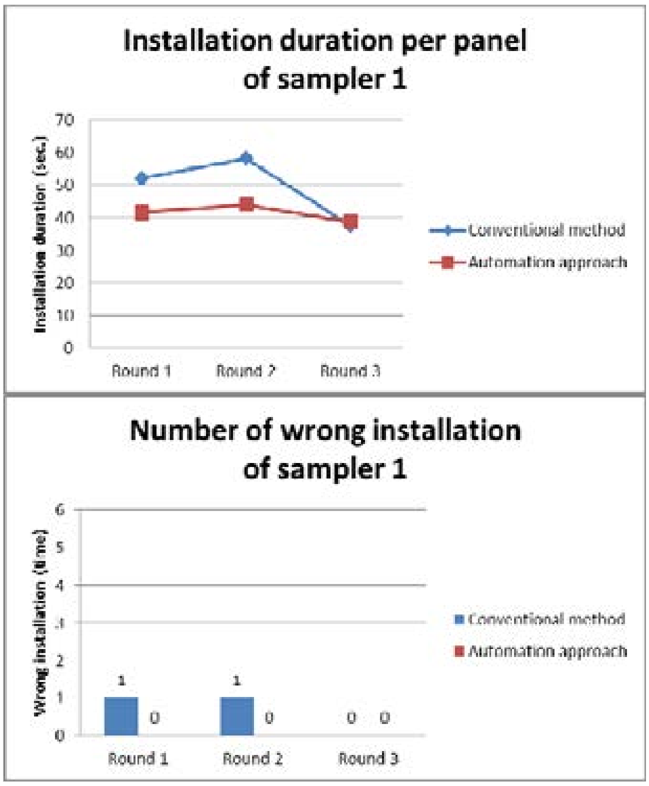

Figure 7.22 Results of sampler 1

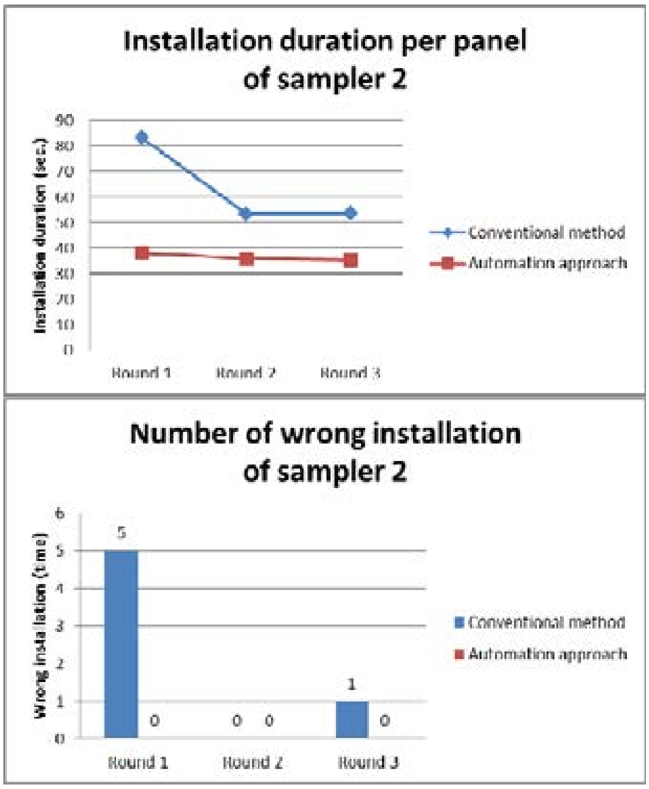

Figure 7.23 Results of sampler 2

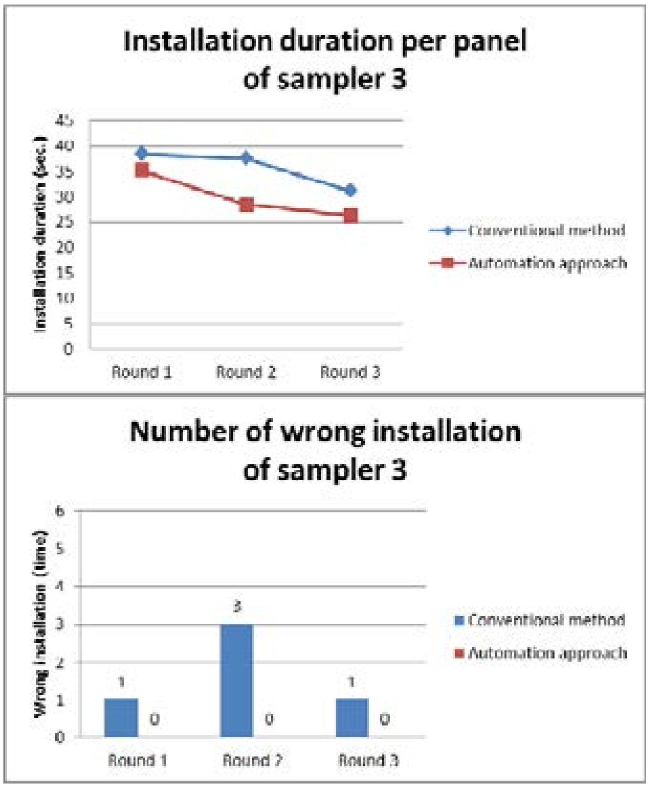

Figure 7.24 Results of sampler 3

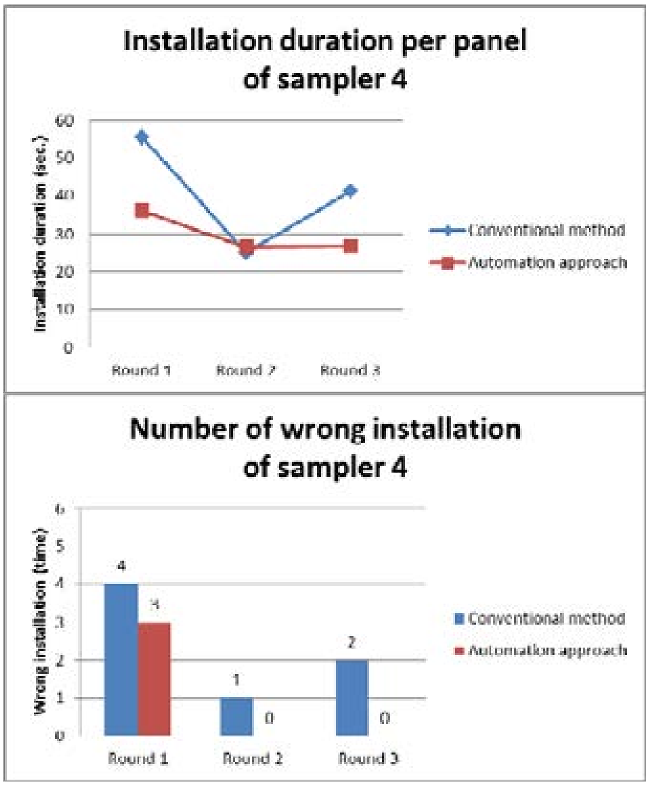

Figure 7.25 Results of sampler 4

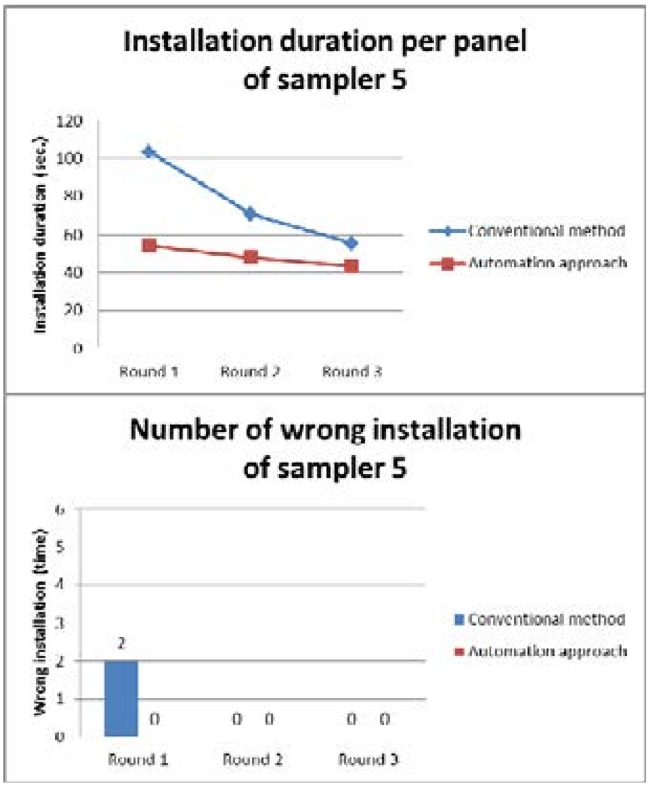

Figure 7.26 Results of sampler 5

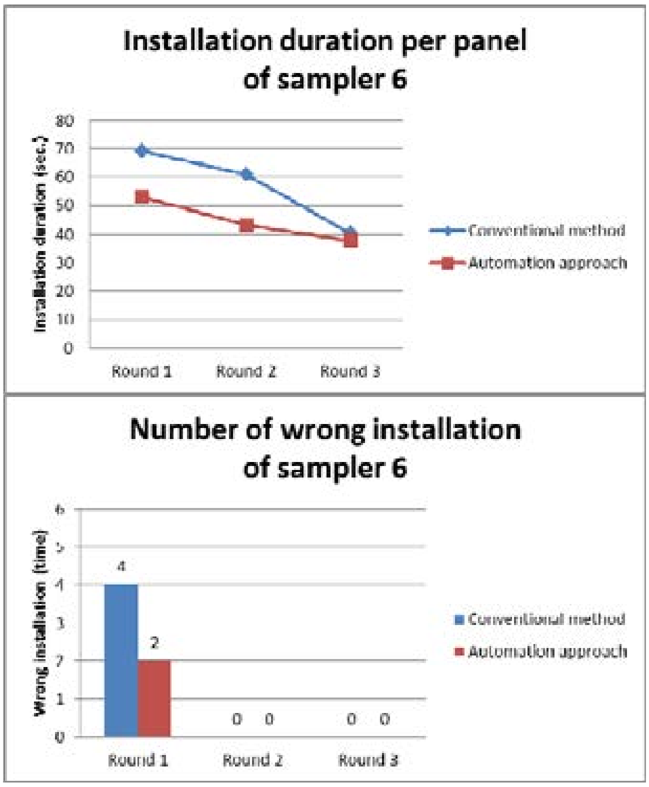

Figure 7.27 Results of sampler 6

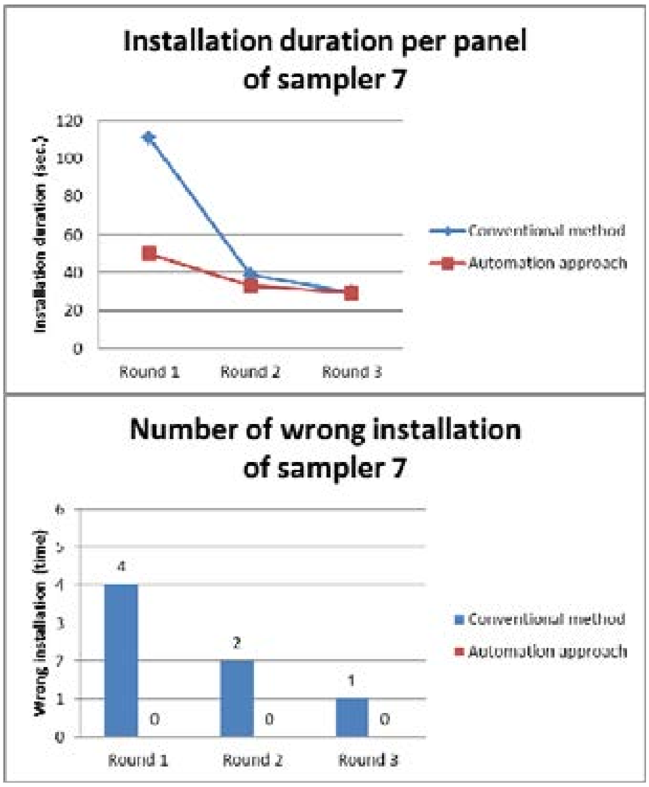

Figure 7.28 Results of sampler 7

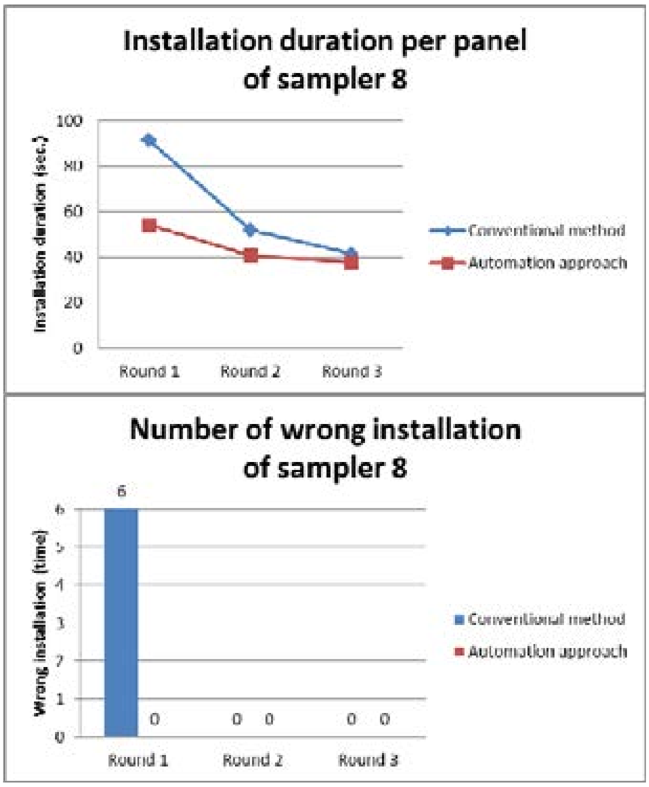

Figure 7.29 Results of sampler 8

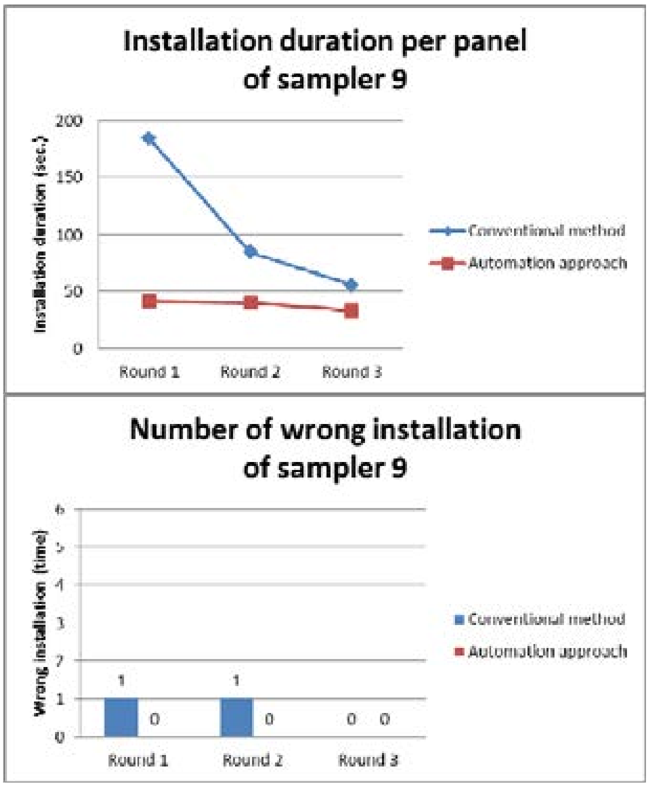

Figure 7.30 Results of sampler 9

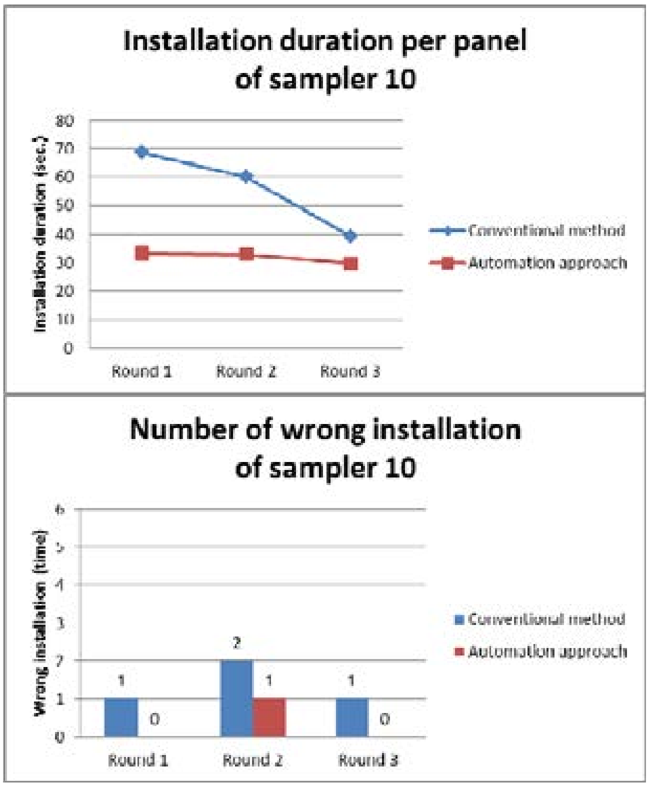

Figure 7.31 Results of sampler 10

The results from the installation of each person during the three round tests were averaged, then calculated the improvement as shown in Table 7.8.

From the results in

Table 7.8, the statistical figures were calculated and compared to the conventional method and automation approach as shown in Table 7.9 and

Table 7.10. Both results distributed as the normal distribution. The installation duration and mistakes from the automation approach had the less standard deviation value compared to the conventional method. The results from the installation by conventional method and automation approach were tested by paired sample test with 95% confidence interval of difference as shown in Table 7.11 and Table 7.12. The data in

Table 7.8 were illustrated in a graphical format as shown in Figure 7.32 to Figure 7.35. The improvement in terms of installation duration is in the range of 15.69% to 64.66%, while the improvement in terms of the number of mistakes is in the range of 50% to 100%.

Table 7.8 Average installation duration per panel and number of mistakes

Sampler	Average installation duration per panel (sec.)			Average number of mistakes (time)		
	Conventional method	Automation approach	Percent of improvement	Conventional method	Automation approach	Percent of improvement
1	49.17	41.46	15.69%	0.67	0.00	100%
2	63.55	36.51	42.54%	2.00	0.00	100%
3	35.65	29.92	16.06%	1.67	0.00	100%
4	40.61	29.84	26.52%	2.33	1.00	57%
5	76.61	48.72	36.41%	0.67	0.00	100%
6	56.87	44.74	21.33%	1.33	0.67	50%
7	59.79	37.44	37.38%	2.33	0.00	100%
8	61.58	44.19	28.23%	2.00	0.00	100%
9	108.09	38.20	64.66%	0.67	0.00	100%
10	56.11	32.02	42.93%	1.33	0.33	75%

Table 7.9 Statistical figures of installation duration per panel

One-Sample Kolmogorov-Smirnov Test

		Conventional method	Automation approach
N		10	10
Normal Parameters[a,,b]	Mean	60.8030	38.3040
	Std. Deviation	20.29873	6.49714
Most Extreme Differences	Absolute	.246	.133
	Positive	.246	.133
	Negative	-.109	-.118
Kolmogorov-Smirnov Z		.778	.421
Asymp. Sig. (2-tailed)		.580	.994

a. Test distribution is Normal.

b. Calculated from data.

Table 7.10 Statistical figures of the number of mistakes in each installation

One-Sample Kolmogorov-Smirnov Test

		Conventional method	Automation approach
N		10	10
Normal Parameters[a,,b]	Mean	1.5000	.2000
	Std. Deviation	.66926	.35867
Most Extreme Differences	Absolute	.193	.411
	Positive	.193	.411
	Negative	-.172	-.289
Kolmogorov-Smirnov Z		.609	1.301
Asymp. Sig. (2-tailed)		.852	.068

a. Test distribution is Normal.

b. Calculated from data.

Table 7.11 Pair samples test of installation duration per panel

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	Conventional method – Automation approach	22.49900	18.46692	5.83975	9.28856	35.70944	3.853	9	.004

Table 7.12 Pair samples test of number of mistakes in each installation

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	Conventional method – Automation approach	1.30000	.65566	.20734	.83097	1.76903	6.270	9	.000

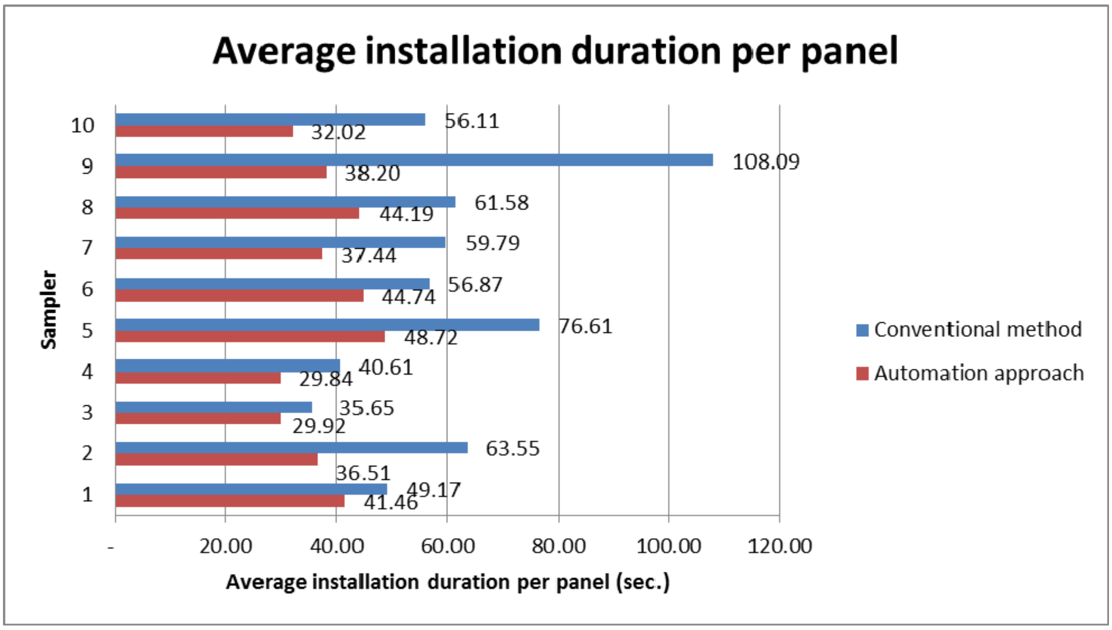

Figure 7.32 Average installation duration per panel

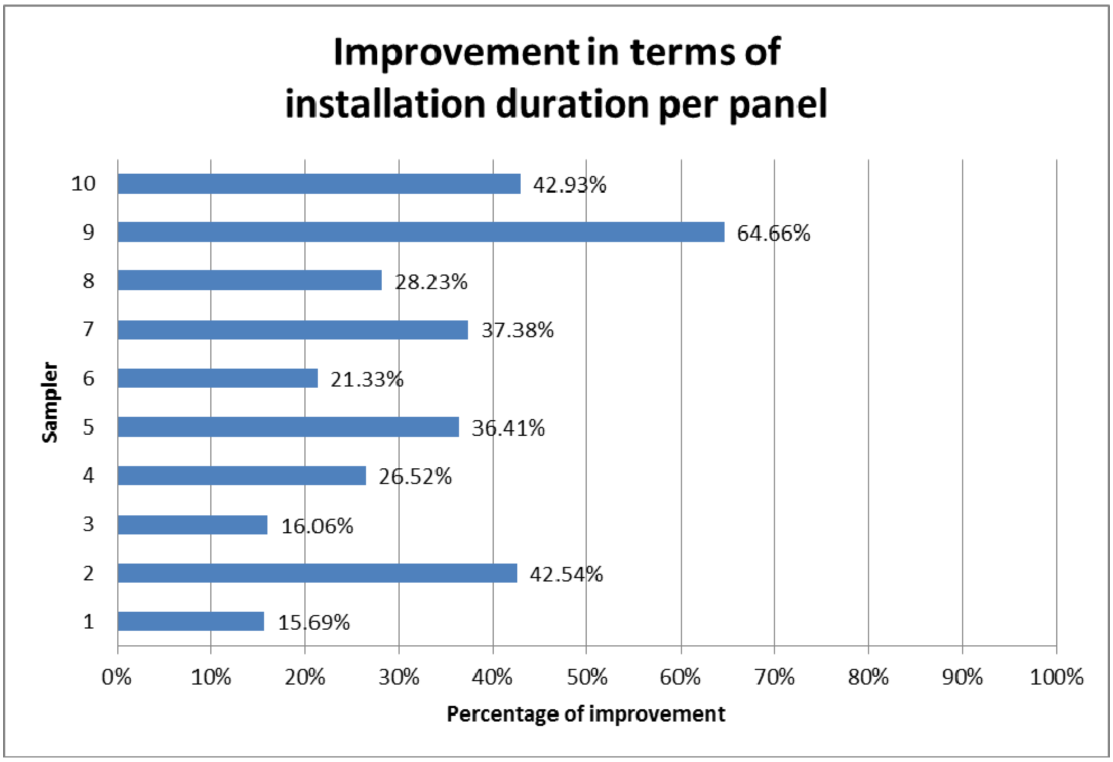

Figure 7.33 Improvement in terms of installation duration per panel

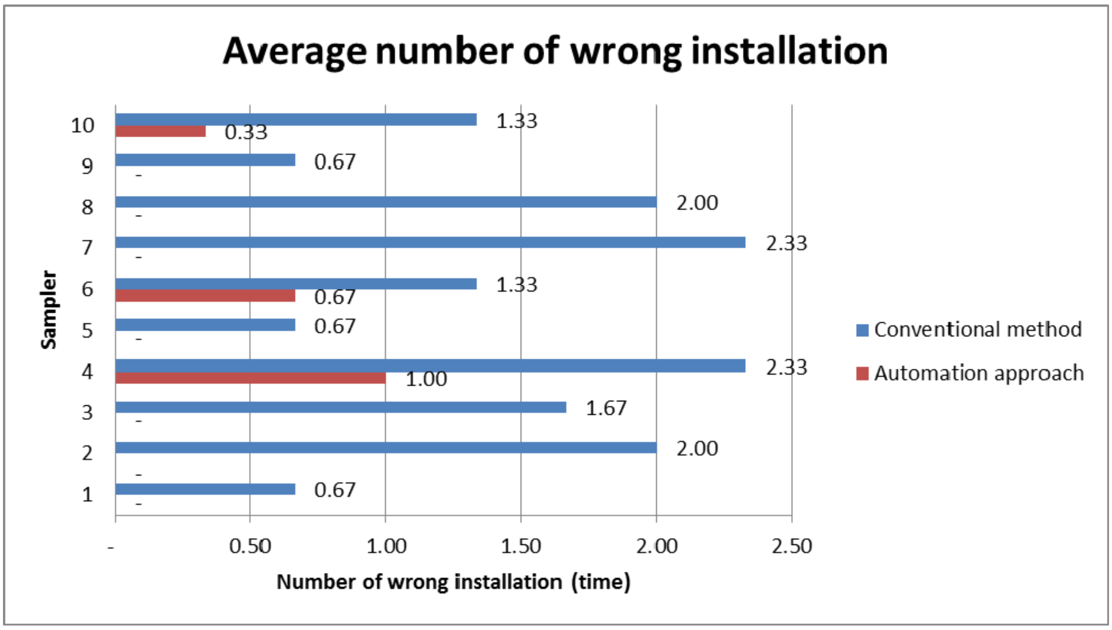

Figure 7.34 Average number of wrong installation

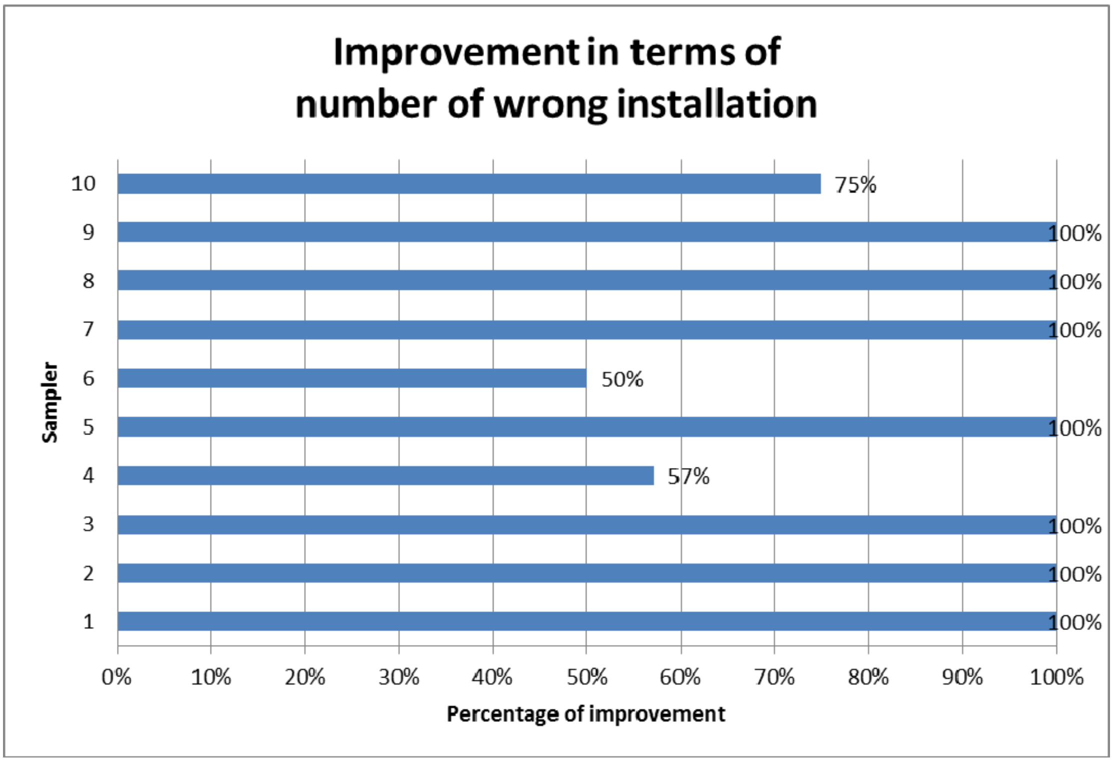

Figure 7.35 Improvement in terms of number of wrong installation

7.2.5 Evaluation by the samplers

After each sampler completed three rounds of tests, the sampler was asked to evaluate the automation approach. This evaluation had three parts: (1) the evaluation in terms of importance of related knowledge and skills, (2) the evaluation in terms of knowledge and skill requirement reduction, and (3) the evaluation in terms of the use of the automation approach.

The evaluation in terms of importance of knowledge and skills was done by evaluating each knowledge and skill requirement related to the importance of the installation duration and mistakes. The Likert scale was employed for this evaluation as shown in Table 7.13. The requirements were separately evaluated for each installation step. The results of evaluation are shown in Table 7.14 to Table 7.16.

Table 7.13 Likert scale for evaluation

Scale	Importance	Reduction	Evaluation
0	-	None	-
1	Very unimportant	Extremely poor	Extremely poor
2	Unimportant	Below average	Below average
3	Neither important or unimportant	Average	Average
4	Important	Above average	Above average
5	Very important	Excellent	Excellent

The knowledge and skill requirements were evaluated in terms of reduction by using the automation approach. The Likert scale was also employed for this evaluation as shown in Table 7.13. The requirements were separately evaluated as the previous instance. The results are shown in Table 7.17 to Table 7.19.

Table 7.14 Importance evaluation of knowledge and skill requirements in Step 1

Knowledge and skill requirements in step 1	Importance evaluation by sampler										Average	Rank
	1	2	3	4	5	6	7	8	9	10		
The interpretation of construction drawings	5	5	5	4	5	5	5	5	5	5	4.9	1
The perception of prefabricated members or combination	5	4	4	5	4	5	4	4	4	4	4.3	2
The prefabricated member identification	4	4	4	5	4	3	3	3	5	4	3.9	3
The use of measurement tools	3	4	4	3	4	4	3	4	3	3	3.5	4

The evaluations of knowledge and skill requirements in terms of importance and reduction in Table 7.14 to Table 7.19 were rearranged by ranking in each step and drawn in the graphical format as shown in Figure 7.36.

Table 7.15 Importance evaluation of knowledge and skill requirement in Step 2

Knowledge and skill requirements in step 2	**Importance evaluation by sampler**										**Average**	**Rank**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
The installation sequence generation	5	4	4	3	4	3	5	5	4	4	4.1	1

Table 7.16 Importance evaluation of knowledge and skill requirements in Step 3

Knowledge and skill requirements in step 3	**Importance evaluation by sampler**										**Average**	**Rank**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
The interpretation of construction drawings	5	5	5	4	5	5	5	5	5	3	4.7	1
The perception of details in a selected installation sequence	5	4	4	3	4	4	5	5	4	4	4.2	4
The perception of stock location of the prefabricated member	4	5	5	3	3	4	5	3	5	3	4	5
The prefabricated member identification	4	5	4	5	4	4	4	4	5	4	4.3	3
The perception of installed location of the prefabricated member	5	5	5	5	4	4	5	5	5	3	4.6	2
The use of measurement tools	3	4	4	3	3	4	3	4	3	2	3.3	6

Table 7.17 Reduction evaluation of knowledge and skill requirements for Step 1

Knowledge and skill requirements in Step 1	Reduction evaluation by sampler										Average	Rank
	1	2	3	4	5	6	7	8	9	10		
The interpretation of construction drawings	4	5	5	5	4	5	5	4	5	3	4.5	2
The perception of prefabricated members or combination	5	5	5	5	4	5	5	3	4	4	4.5	2
The prefabricated member identification	5	5	5	5	5	4	5	5	5	4	4.8	1
The use of measurement tools	3	3	4	3	2	3	4	4	3	2	3.1	4

Table 7.18 Reduction evaluation of knowledge and skill requirement for Step 2

Knowledge and skill requirement in Step 2	Reduction evaluation by sampler										Average	Rank
	1	2	3	4	5	6	7	8	9	10		
The installation sequence generation	5	5	5	5	5	5	5	5	5	5	5	1

Table 7.19 Reduction evaluation of knowledge and skill requirements for Step 3

Knowledge and skill requirements in Step 3	**Reduction evaluation by sampler**										**Average**	**Rank**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
The interpretation of construction drawings	4	5	5	4	4	5	5	3	5	3	4.3	5
The perception of details in a selected installation sequence	5	5	5	5	5	5	5	5	5	5	5	1
The perception of stock location of the prefabricated member	5	5	5	5	5	5	5	5	5	4	4.9	2
The prefabricated member identification	5	5	5	4	5	5	5	5	5	4	4.8	3
The perception of installed location of the prefabricated member	4	5	5	5	5	5	5	4	5	4	4.7	4
The use of measurement tools	3	3	4	3	3	3	4	4	3	2	3.2	6

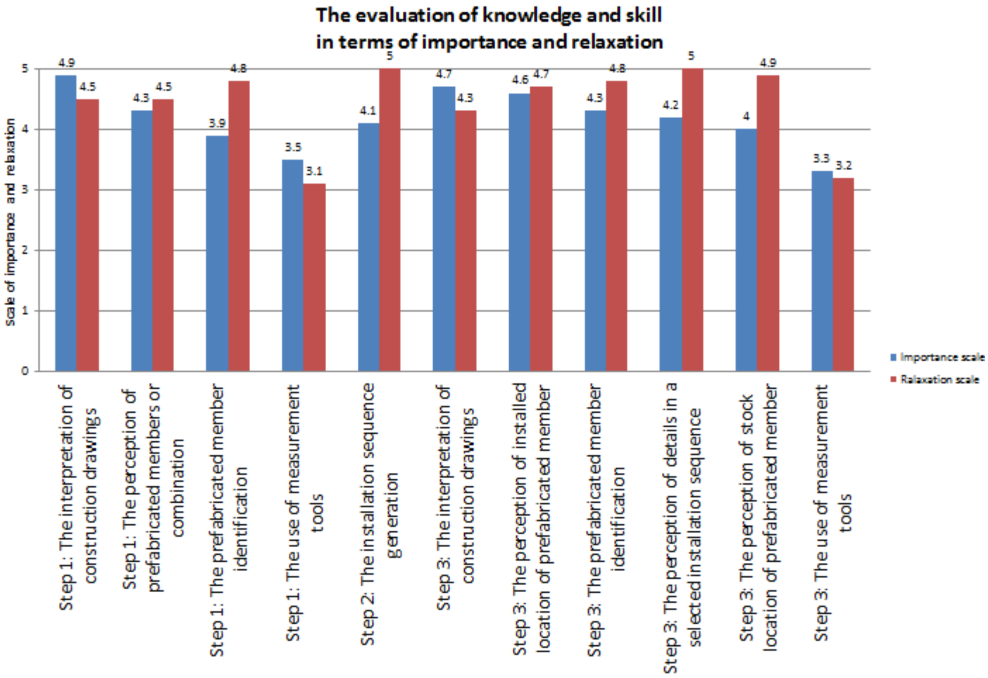

Figure 7.36 Evaluation in terms of importance and reduction

The final part was the evaluation in terms of the use of the automation approach by the Likert scale as shown in Table 7.13. The samplers were asked to evaluate the approach after performing the three round tests. The evaluation had eight topics, which included ease of use, ease of carry while working, appropriate working procedure, adequate information, appropriate information format, speed of processing, improving speed of installation, and mistake reduction using the automation approach. The results are shown in Table 7.20. In Figure 7.37, the results were illustrated in the graphical format.

Table 7.20 Evaluation of the use of the automation approach

The use of automation approach	**Evaluation by sampler**										**Average**	**Rank**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
Ease of use	4	5	4	5	5	5	5	5	5	4	4.7	3
Ease of carry while working	5	5	4	5	5	5	5	5	5	5	4.9	1
Appropriate working procedure	5	4	4	5	5	5	5	5	5	3	4.6	5
Adequate information	4	4	4	4	3	3	4	3	4	3	3.6	7
Appropriate information format	4	4	5	5	4	4	4	3	5	4	4.2	6
Speed of processing	3	4	4	4	3	4	4	3	2	3	3.4	8
Improving speed of installation	5	5	4	4	5	5	5	5	5	5	4.8	2
Mistake reduction by using the automation approach	5	5	5	4	4	5	4	5	5	5	4.7	3

At the end of evaluation form, the samplers gave additional suggestions shown in Table 7.21. These suggestions will be used for the future development of the automation approach.

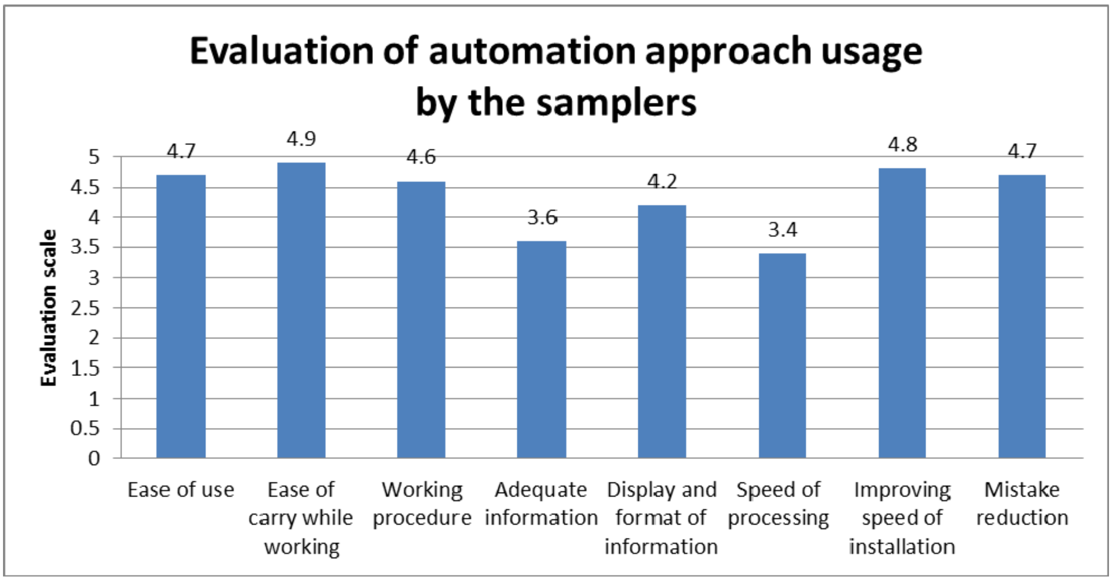

Figure 7.37 Evaluation of the use of the automation approach

Table 7.21 The suggestions from samplers

Sampler	Suggestion
1	The sampler was confused about the stock location of the prefabricated member.
1, 6, 8	In the obvious point screen, the dimensions of the panel should be displayed with zoom in and zoom out options.
2	The current language used in the automation approach is English. This may not be appropriate for the foreman or worker. Foreign language may affect the efficiency of the automation approach usage.
2	At the construction site, the prefabricated members may be stocked in the A frame, which the members are laid on each other. If the automation approach could be more flexible, such as switching the installation sequence, then the approach might improve the installation duration in that case.
3	If the automation approach is implemented in the high processing device, the efficiency might be better.
4	The automation approach should be expanded to other operation systems, such as iOS for Apple devices or Android. This would be more comfortable because the stylus is not needed.
8	The approach should have real-time data saving ability to prevent any data loss in the case of system errors.
8	The approach should have an interface to rewind and forward the prefabricated member checking or the installation process.
8	The approach should have some animation, which shows the installation sequence.

7.3 Evaluation at the construction site

7.3.1 Introduction of the case study

The case study in this phase was the installation of the first floor wall in a residential construction project. In the project, 99 units of a three-storey townhome were built in three different types. The project duration was 19 months, from January 2011 to July 2012. The figure of townhomes is shown in Figure 7.38.

Figure 7.38 The townhomes in a case study

In this project, the project owner hired the prefabrication manufacturer to produce and transport all the prefabricated members. The owner separately hired the contractor to construct the units and perform the prefabricated member installation. However, a subcontractor was hired to install the prefabricated members and operate any related work. The work of installation for the subcontractor did not include piling, roofing, electrical work, plumbing or any architectural work, such as tiling or painting. The details of house structure are summarised in Table 7.22 and the overview of the prefabricated structure is shown in Figure 7.39.

Table 7.22 The details of the house structure

Structure	Structure detail
The first floor beam	Reinforced concrete prefabricated beam
The slab	Reinforced concrete prefabricated slab (solid slab type)
The wall	Reinforced concrete prefabricated wall (load-bearing type)
The stair	Reinforced concrete prefabricated stair

Figure 7.39 The overview of the prefabricated structure

In this phase, the automation approach was evaluated in terms of its performance and operation under the actual construction environment. The construction environment was always defined as a harsh environment, which affected the performance of the identification technology. Thus, the automation approach was implemented to evaluate the system under the actual construction environment.

The installation processes by the conventional method and automation approach were observed during this phase. For the conventional method, the prefabricated members were performed as usual. The working processes, installation durations, and mistakes were observed and recorded while the prefabricated members were being installed. For the automation approach, the data and information were inputted into the system and the RFID tags were attached to the related resources prior the operation. Then, the system was implemented. As the installation process was being performed, the automation approach was employed by the mobile crane operator and headman. The working process, installation durations, and mistakes were also observed and recorded in the same fashion as the conventional one. Finally, the results from both methods were compared and analysed.

7.3.2 Installation process

From the investigations in the case study project, the installation processes of the first floor wall were performed by a group of four persons. The group composed of a headman, a mobile crane operator, and two workers, as shown in Figure 7.40. In this project, the headman was assigned to perform the foreman's work and also acted as the erector. The details of each person's roles and responsibilities in the installation process are shown in Table 7.23.

Figure 7.40 A group of personnel in the installation process

7.3.1 Data collection

As mentioned above, the installation processes of the first floor wall were the case study in this evaluation. The case study composed of the installation processes in five houses at the eleventh block of the project. The block before installation is shown in Figure 7.41, while details of the data collection for each house are shown in Table 7.24.

The installation processes of 56 prefabricated members were observed while the total number of prefabricated members in the first floor wall was 78. Thus, the percentage of data collection in this phase was 71.79 of total installed members as shown in Table 7.25.


Figure 7.41 The eleventh block before the installation process

Table 7.23 The details of each person

Personnel	**Experience in construction**	**Experience in prefabrication**	**Training**	**Roles and responsibilities**
Headman	2 years	1 year	On the job training	Check the available prefabricated members, make a decision for an installation process, supervise and perform the installation, and support for the mobile crane set up
Mobile crane operator	5 years	3 years		Decide the working location, move the resources, set up the machine, and operate the machine for installation process
Worker 1	14 years	1 year		Perform the installation including temporary shore and weld the joint, and support for the mobile crane set up
Worker 2	4 months	4 months		Hook a prefabricated member, perform the installation, and support for the mobile crane set up

Table 7.24 Details of data collection

House number	Detail of data collection
1	Observe the installation processes Test for automation approach implementation
2	Observe the data of member installations which were performed by the conventional method Observe the problems and obstacles in the installation process
3	
4	Implement the automation approach Observe the data of member installations which were performed by automation approach Observe the problems and obstacles in the installation process
5	

Table 7.25 Number of collected data and installed panels

House number	Collected data (members)	Installed member (members)	Percentage of collected data
1	14	15+3*	77.78
2	12	15	80.00
3	8	15	53.33
4	11	15	73.33
5	11	15	73.33
Total	56	78	71.79

* Three prefabricated members were the party walls, which were located between the houses, as shown in Figure 7.42. Thus, these members were installed and counted in the installation of house number one.

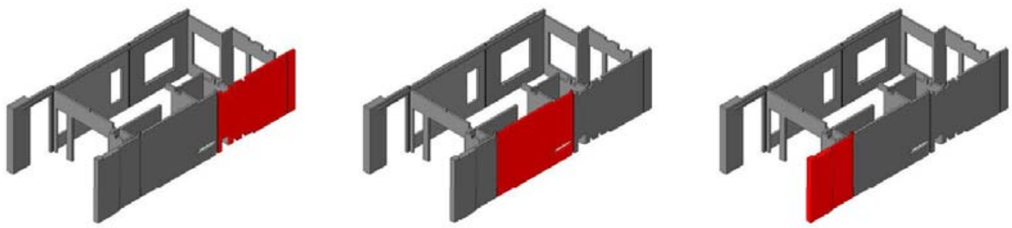

Figure 7.42 Party walls

7.3.2 Installation process by conventional method

The installations by conventional method were performed in house number one, two, and three. For these houses, the installation processes of 34 members were observed as shown in
Table 7.25.

Before the installation process began, the preparation process of moving and preparing the rack at the desired location for the prefabricated member stock, as shown in Figure 7.43, was done. After the delivery trucks arrived at the construction site, the prefabricated members were moved from the trucks and stored in the rack as shown in Figure 7.44.

Figure 7.43 Rack preparation

Figure 7.44 Stock process

Then, the installation step began. The headman checked the available prefabricated members in a rack and made a decision for an installation process. Side view and top view of the prefabricated members in a rack are shown in Figure 7.45 and Figure 7.46 respectively. In this case study, the prefabricated members were complete. All houses were allowed to continue the installation process. The mobile crane operator decided the work location, moved the resources and machine, and set up the machine as shown in Figure 7.47 and Figure 7.48, with the cooperation of the headman and workers.

Because the mobile crane operator had some work experience, the obstacle did not occur in actions of resource moving and machine set up. However, the resource for machine set up was incomplete, for example, the machine base plates. The operator applied another material for the machine set up, as shown in Figure 7.49.

Figure 7.45 Overview of prefabricated members in a rack

Figure 7.46 Side view and top view of the prefabricated members in a rack

Figure 7.47 Mobile crane operator moved machine base plates

Figure 7.48 Operator set up the machine

Figure 7.49 Operator applied another material for the machine set up

While the installation task was being performed according to the selected installation sequence, a group of personnel installed the prefabricated members in a repetitive loop. The loop started from worker 1, who performed the stockman’s roles and responsibilities. Worker 1 received the information from the headman and searched the prefabricated member, which was required for the current installation, as shown in Figure 7.50. Then, the member was hooked by worker 1 and lifted by mobile crane to the location, as shown in Figure 7.51 and Figure 7.52. After that, the headman, worker 1, and worker 2 acted as erectors to install the member at the location and shore using props as shown in Figure 7.53 and Figure 7.54. The mobile crane was operated to swing back to the rack and start the new loop after the adjusting and unhooking of the prefabricated member was finished.

Figure 7.50 Stockman searched for a prefabricated member

Figure 7.51 Stockman hooked a member

Figure 7.52 Mobile crane lifted a member

Figure 7.53 Prefabricated member was lifted and installed

Figure 7.54 Erectors temporary shored the prefabricated member

A group of installation used the construction drawings as a reference in case of uncertainty or doubt. Parts of drawings showed the floor plan of each floor and the sections of each prefabricated member. The list of prefabricated members in each floor and the location of each member were interpreted from the floor plan. The identification of each member was done using the sections of each prefabricated member and the member marking. The member marking is shown in Figure 7.55.

Figure 7.55 Prefabricated member marking

According to the repetitive characteristics in the installation of the prefabricated members step, the duration scheme was created as shown in Figure 7.56. The duration composed of (1) swing back duration, (2) find duration, (3) hook duration, (4) swing duration, and (5) install duration. The details of the durations are shown in

Table 7.26.

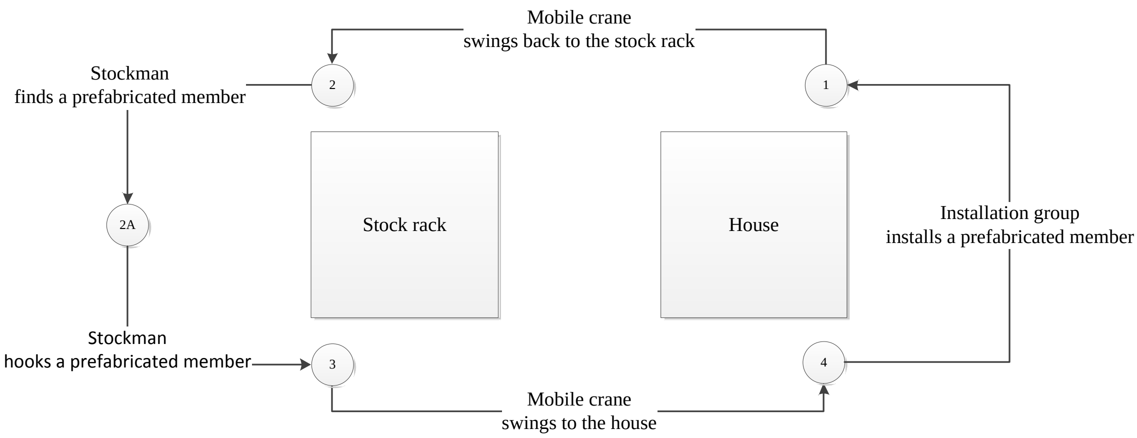

Figure 7.56 Duration scheme of installation step

Table 7.26 Details of duration scheme

From		To		Duration	Operator
Node	Location	Node	Location		
1	House	2	Stock	Swing back	Mobile crane operator
2	Stock	2A	Stock	Find	Stockman
2A	Stock	3	Stock	Hook	Stockman
3	Stock	4	House	Swing	Mobile crane operator
4	House	1	House	Install	Installation group

From data collection of the installation processes in house number two and three, the duration of the member installation was recorded as shown in Table 7.27 and

Table 7.28 respectively.

Table 7.27 Duration of installation step of house number two

No.	**Collected member**	**Duration (h:mm:ss)**					
		Swing back	**Find**	**Find + hook**	**Swing**	**Install**	**Total**
1*	104EX	-	0:01:04**	0:02:40	0:01:50	0:18:25	-
2	116	0:03:45	0:03:25**	0:00:15	0:01:55	0:23:05	0:29:00
3	117	0:04:10	0:01:10**	0:01:10	0:02:10	0:17:00	0:24:30
4	119	0:00:36	0:00:36**	0:00:39	0:01:15	0:15:00	0:17:30
5*	122	-	0:02:16	0:02:31	0:01:30	0:17:15	-
6	120	0:00:45	0:01:45	0:03:15	0:01:30	0:22:30	0:28:00
7	105EX	0:01:30	0:01:30	0:04:00	0:02:36	0:38:29	0:46:35
8	106EX	0:01:25	0:04:10	0:09:10	0:01:10	0:37:40	0:49:25
9	112	0:04:10	0:01:00	0:01:40	0:02:20	0:27:34	0:35:44
10	110	0:02:26	0:01:20**	0:02:00	0:01:30	0:23:30	0:29:26
11	121	0:00:22	0:00:22**	0:00:13	0:01:50	0:10:35	0:13:00
12	115	0:02:15	0:02:15**	0:00:30	0:02:30	0:13:30	0:18:45

* The duration was incomplete. This member was not used for analysis.

** The stockman searched a prefabricated member for the next sequence while the current member was installing. Thus, the find and hook duration did not include the find duration.

In house number three, the member number 3.1 in

Table 7.28 was the mistake in the installation process. The member (117M) looked like another member because it was the mirror type of the correct member (117). The stockman made a mistake in the prefabricated member identification and hooked the incorrect member. After handling the member to the location, the headman realised that the member was incorrect. So the member was lifted and moved back to the stock rack. Finally, the correct member was lifted and installed. This mistake wasted 27 minutes and 50 seconds in the installation process. Based on the collected data in house number two and three, the mistake represented 5% of the installed members and 4.65% of the total installation duration.

Table 7.28 Duration of installation step of house number three

No.	Collected member	Duration (h:mm:ss)					
		Swing back	Find	Find + hook	Swing	Install	Total
1	110	-	-	-	-	0:15:04	-
2	107	0:03:00	0:00:30**	0:01:10	0:01:20	0:20:14	0:25:44
3.1	117M	-	-	-	0:02:30	0:25:20	-
3.2	117	0:03:30	0:02:20**	0:01:00	0:01:50	0:19:10	0:25:30
4	108	0:06:45	0:01:40**	0:00:20	0:02:05	0:54:40	1:03:50
5	116	0:01:40	0:02:20	0:03:00	0:04:40	0:27:10	0:36:30
6	109	0:01:10	0:00:50**	0:00:35	0:06:30	0:34:25	0:42:40
7	112	0:01:20	0:01:20**	0:00:20	0:05:40	0:28:00	0:35:20
8	121	0:00:55	0:00:55**	0:02:15	0:02:20	0:12:14	0:17:44

* The duration was incomplete. This member was not used for analysis.

** The stockman searched a prefabricated member for the next sequence while the current member was installing. Thus, the find and hook duration did not include the find duration.

7.3.3 Installation process by automation approach

The automation approach was implemented and tested in the first floor wall installation of house number four and five. Prior the installation, structure details and related information were entered into a database of the automation approach. Fifty-five RFID tags were attached to personnel, prefabricated members, and equipment. The tags were attached to all prefabricated members in the rack, although some prefabricated members were not the first floor wall of house number four and five, as shown in Figure 7.57. According to the work practice of the case study project, the RFID tags were not attached to the tools, such as the props, because such resources were not prepared before the installation. The personnel brought the props from the previous installed structure when it was needed. Thus, the number of RFID tag attachments is shown in Table 7.30.


Figure 7.57 RFID tag attachment

Table 7.29 Comparison between main installation steps and actions in the evaluation at the construction site

Step	Main installation steps	The evaluation at construction site
1	Checking the available prefabricated member	Check the available prefabricated members
2	Making a decision for an installation process	Consider the installation sequence based on the available prefabricated members
3	Installing the prefabricated members	Search a prefabricated member at the stock location Install a member at the correct location

Table 7.30 The number of RFID tag attachments

Resource	The number of RFID tag attachment
Personnel	4
Prefabricated member	50
Equipment	1
Total	55

According to the system architecture, a laptop PC was assigned to the mobile crane operator, while the PDA with RFID reader was assigned to the headman. The laptop was placed in the mobile crane cabin. The figures of hardware assignments are shown in Figure 7.58 and Figure 7.59 respectively.

Figure 7.58 Laptop computer in the mobile crane cabin

Figure 7.59 Foreman with PDA and RFID reader

In this part, the installation processes of 22 panels were observed. The results, in terms of install duration, are shown in

Table 7.31 and Table 7.32.

Table 7.31 Duration of installation step of house number four

No.	Installed member	Duration (h:mm:ss)				
		Swing back	Find + hook	Swing	Install	Total
1*	104	-	0:01:25	0:02:10	0:13:32	-
2	105	0:00:53	0:01:20	0:03:55	0:29:05	0:35:13
3	116M	0:00:10	0:00:35	0:01:20	0:28:28	0:30:33
4	117M	0:01:17	0:03:00	0:01:58	0:21:57	0:28:12
5	119M	0:00:45	0:00:30	0:02:00	0:19:00	0:22:15
6	122M	0:01:00	0:00:20	0:02:40	0:18:20	0:22:20
7	120	0:01:06	0:00:19	0:03:35	0:21:14	0:26:14
8	110	0:00:37	0:00:49	0:01:00	0:09:55	0:12:21
9*	106	-	0:00:40	0:02:20	0:24:20	-
10	112	0:00:15	0:00:40	0:02:36	0:25:09	0:28:40
11	121	0:00:10	0:00:15	0:00:55	0:10:55	0:12:15

Table 7.32 Duration of installation step of house number five

No.	Installed member	Duration (h:mm:ss)				
		Swing back	Find + hook	Swing	Install	Total
1*	103AM	-	-	-	0:15:06	-
2	102AM	0:01:50	0:00:47	0:02:04	0:33:13	0:37:54
3	116AM	0:01:30	0:00:12	0:01:48	0:22:00	0:25:30
4	117AM	0:00:30	0:00:45	0:01:35	0:35:10	0:38:00
5	119AM	0:01:30	0:00:15	0:02:27	0:15:03	0:19:15
6*	122AM	-	0:00:05	0:01:38	0:16:02	-
7	120AM	0:00:33	0:00:23	0:01:49	0:19:13	0:21:58
8	110AM	0:01:43	0:00:09	0:01:55	0:23:17	0:27:04
9	101AM	0:00:47	0:00:15	0:01:43	0:41:42	0:44:27
10	112AM	0:01:09	0:00:25	0:01:36	0:22:04	0:25:14
11	121AM	0:01:19	0:00:56	0:01:22	0:14:28	0:18:05

7.3.4 Result

The results from the installation step of house number two, three, four, and five are shown in Table 7.33. In the table, the average duration per panel for swing back, find and hook, swing, and installation of a prefabricated member are shown. The data was further processed to compare between installation by conventional method and automation approach and find out any improvements as shown in Table 7.34. The automation approach improved the working duration per panel of swing back, find and hook, swing, and install. The total working duration per panel improved by 16.71%. The comparison is also displayed in the graphical format in Figure 7.60 and Figure 7.61.

Table 7.33 Average duration for each house

Method	**House No.**	**Number of member**	**Average duration per panel (h:mm:ss)**				
			Swing back	**Find + hook**	**Swing**	**Install**	**Total**
Conventional method	2	10	0:02:08	0:02:17	0:01:53	0:22:53	0:29:12
	3	7	0:02:37	0:01:14	0:03:29	0:27:59	0:35:20
Automation approach	4	9	0:00:41	0:00:52	0:02:13	0:20:27	0:24:14
	5	9	0:01:12	0:00:27	0:01:49	0:25:08	0:28:36

Table 7.34 Average duration for conventional method and automation approach

Method	**Number of member**	**Average duration per panel (h:mm:ss)**				
		Swing back	**Find + hook**	**Swing**	**Install**	**Total**
Conventional method	17	0:02:20	0:01:51	0:02:32	0:24:59	0:31:43
Automation approach	18	0:00:57	0:00:40	0:02:01	0:22:47	0:26:25
Improvement		0:01:23	0:01:11	0:00:31	0:02:12	0:05:18
Percent of improvement		59.43%	63.75%	20.45%	8.82%	16.71%

In addition, from this implementation at the construction site, the issues for improvement were captured as follows:

- The automation approach should have the user interface for details of the next installation member without interfering of the current installation. In the installation test, the mobile crane operator had idle time and wanted to get the information for the next installation member. Thus, after pressing the button for the information of the next installation member, the time was recorded and the information for the installation could not be rewound.
- The electricity needed to power the laptop should be provided in the mobile crane cabin.
- The temperature in the mobile crane cabin was quite high. The high temperature affected the performance of the laptop.

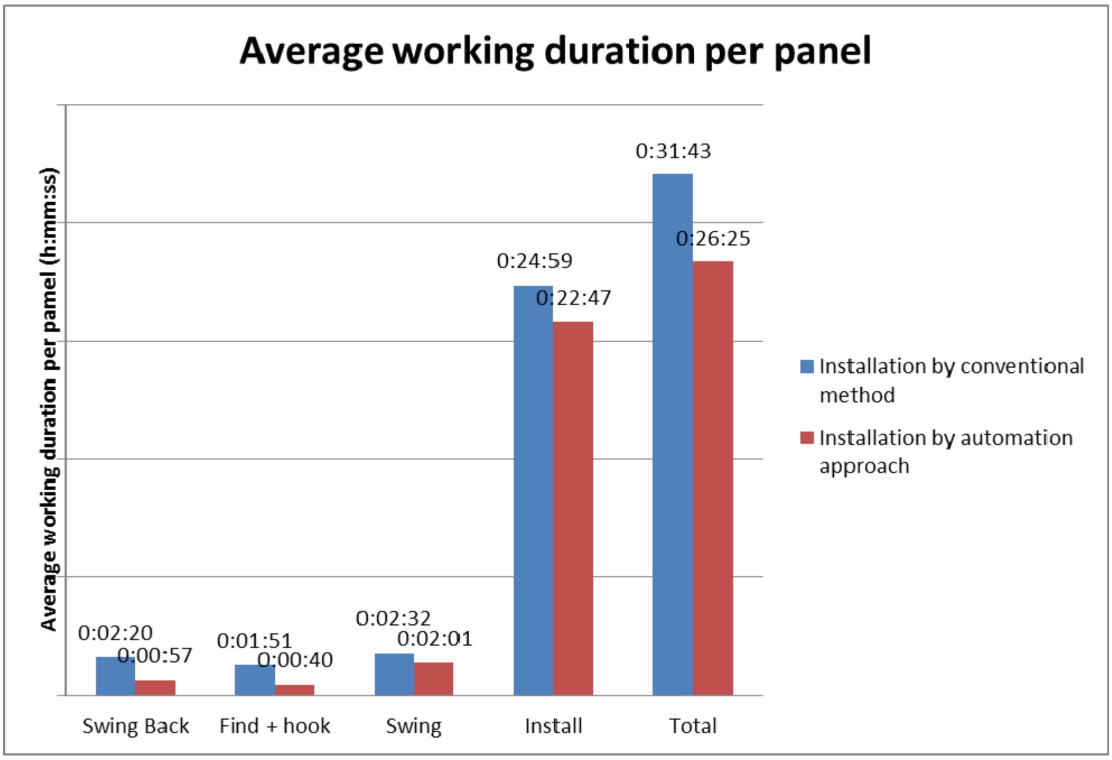

Figure 7.60 The average working duration per panel

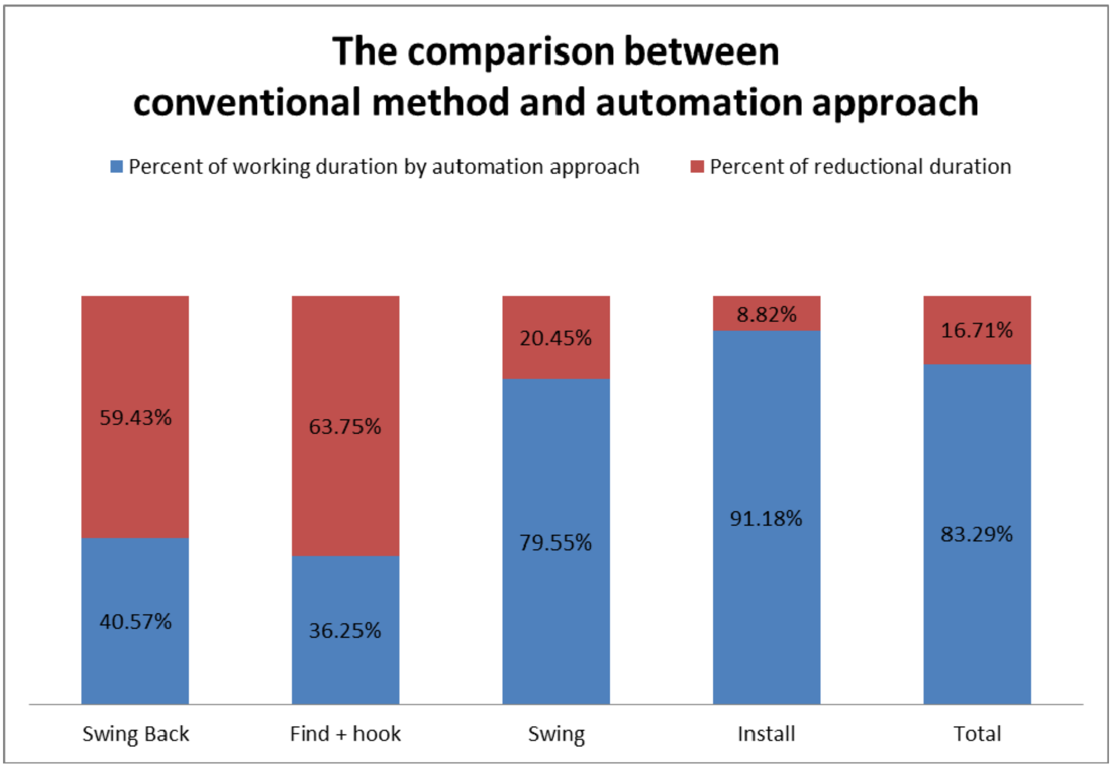

Figure 7.61 The comparison between conventional method and automation approach

7.4 Evaluation by the experts

The automation approach was evaluated by experts who had more than three years of experience in prefabricated construction. The experience in construction and prefabrication of each expert is shown in Figure 7.62. The brief details of experience in prefabricated construction are shown in Table 7.35.

In this phase, the evaluation contained six parts as follows: the suitability of the work breakdown structure, the importance of each step in the installation process, the completeness of knowledge and skill requirements in each step, the importance of knowledge and skill for each person in each step, the reduction of knowledge and skill using the automation approach, and the evaluation of the automation approach. The five Likert scale was employed for the evaluations. The meanings of each scale are shown in Table 7.36.

Figure 7.62 The experience of experts

7.4.1 The suitability of the work breakdown structure of the installation process

The experts were asked to evaluate the installation process in terms of the suitability of the work breakdown structure. Three main steps and four supplementary steps of an installation process were the work breakdown structure as mentioned in Chapter 4. The three main steps composed of (1) checking the available prefabricated members, (2) making a decision for an installation process, and (3) installing the prefabricated members. While the four supplementary steps included (A) checking the availability of other resources, (B) comparing the required resources and the available resources, (C) deciding the work location of the mobile crane, and (D) inspection of the installed prefabricated members. The results of expert evaluations are shown in Table 7.37.

Table 7.35 The details of experts

Expert	Experience in construction/ prefabrication (year)	Brief experience in prefabricated construction
1	9/5	Manufacturing process, installation process, and research and development in prefabricated construction
2	7/3	Manufacturing process and installation process of the prefabricated members for residential projects both for horizontal and vertical buildings
3	12/12	Manufacturing process in the yard and factory, and installation process of the prefabricated members in the residential projects
4	12/12	Manufacturing process, installation process, and supervision of the construction in residential projects, which employed the conventional method and prefabricated construction
5	10/10	Manufacturing process and installation process of the residential houses, buildings, public buildings, and factories
6	12/8	Installation process in the housing development company

Table 7.36 Meanings of each Likert scale

Scale	Suitable	Importance	Completeness	Reduction/ evaluation
0	-	-	-	None (For reduction)
1	Totally disagree	Very unimportant	Very incomplete	Extremely poor
2	Disagree	Unimportant	Incomplete	Below average
3	Neutral	Neither important or unimportant	Neither complete or incomplete	Average
4	Agree	Important	Complete	Above average
5	Strongly agree	Very important	Very complete	Excellent

Table 7.37 The suitability of the work breakdown structure

Evaluation	Expert						Average
	1	2	3	4	5	6	
Suitability of the work breakdown structure	5	4	4	4	5	5	4.5

From the results, the average evaluation score was 4.5, which means the experts totally agreed with the proposed work breakdown structure of the installation process.

In this part, one expert recommended that the process should include the evaluation of location/work area before the installation. In addition, the making of joints should be included in the process. The inspection of prefabricated members during unloading from the truck and before installation should be performed.

Another expert gave a useful recommendation that checking the availability of other resources should be done prior or at the same time as checking the available prefabricated members.

7.4.2 The importance of each step in the installation process

The experts evaluated each step in the installation process in terms of the importance for installation duration and installation mistakes. The results are shown in Table 7.38 and Table 7.39 respectively. The graphical format of the results is shown in Figure 7.63.

From the results, the three main steps, including checking the availability of other resources, were evaluated as the most importance for the installation duration. The decision on the work location of the mobile crane was evaluated as the least important step for the installation duration.

For installation mistakes, experts evaluated three main steps, including the decision on work location of the mobile crane, as the most three ranks that could affect installation mistakes. The step of checking the availability of other resources and inspecting the installed prefabricated members were evaluated as the least important for installation mistakes.

Table 7.38 The importance in terms of installation duration

Importance of each step in the installation process for installation duration	**Expert**						**Average**	**Rank**
	1	**2**	**3**	**4**	**5**	**6**		
(1) Checking the available prefabricated members	5	5	5	4	5	5	4.83	1
(2) Making a decision for an installation process	5	5	3	5	4	4	4.33	3
(3) Installing the prefabricated members	5	4	5	5	5	4	4.67	2
(A) Checking the availability of other resources	4	4	5	4	4	5	4.33	3
(B) Comparing the required resources and the available resources	4	5	3	4	4	5	4.17	5
(C) Deciding the work location of the mobile crane	4	4	5	3	3	4	3.83	7
(D) Inspection of the installed prefabricated members	4	4	4	3	4	5	4.00	6

Table 7.39 The importance in terms of installation mistake

Importance of each step in the installation process for installation mistake	**Expert**						**Average**	**Rank**
	1	**2**	**3**	**4**	**5**	**6**		
(1) Checking the available prefabricated members	5	5	5	4	5	5	4.83	1
(2) Making a decision for an installation process	5	3	3	4	5	5	4.17	3
(3) Installing the prefabricated members	5	3	5	4	5	4	4.33	2
(A) Checking the availability of other resources	4	4	4	4	3	4	3.83	6
(B) Comparing the required resources and the available resources	4	5	4	3	4	4	4.00	5
(C) Deciding the work location of the mobile crane	4	3	5	5	4	4	4.17	3
(D) Inspection of installed prefabricated members	4	3	5	3	4	4	3.83	6

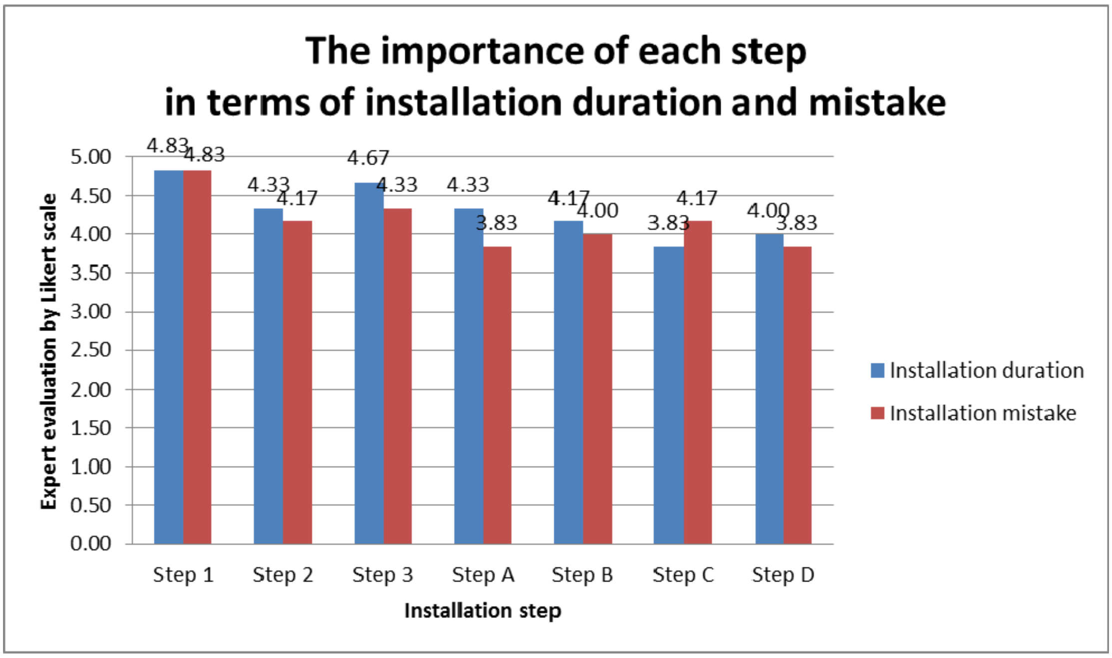

Figure 7.63 The importance of each step in terms of installation duration and mistakes

7.4.3 The completeness of knowledge and skill in each step of the installation process

In this part, the knowledge and skill requirements of each personnel in each installation step were presented to the experts. Then the experts evaluated the completeness of knowledge and skill in each step of installation. The results are shown in Table 7.40 and the graphical format of the results is shown in Figure 7.64.

From the expert evaluations, most of the installation steps were evaluated at least "complete" scale. Only Step C: Deciding the work location of the mobile crane was evaluated lower than complete scale (3.83). However, the experts did not recommend for additional knowledge and skill for each personnel in each installation step.

Table 7.40 The completeness of knowledge requirements in each step

Completeness of knowledge and skill requirements in each step of installation process	Expert						Average	Rank
	1	2	3	4	5	6		
Checking the available prefabricated members	5	4	4	5	5	4	4.50	1
Making a decision for an installation process	5	3	4	4	5	4	4.17	3
Installing the prefabricated members	5	4	4	4	5	3	4.17	3
Checking the availability of other resources	5	4	4	3	5	3	4.00	6
Comparing the required resources and the available resources	5	5	4	3	5	3	4.17	3
Deciding the work location of the mobile crane	5	5	4	3	4	2	3.83	7
Inspection of installed prefabricated members	5	4	4	5	5	4	4.50	1

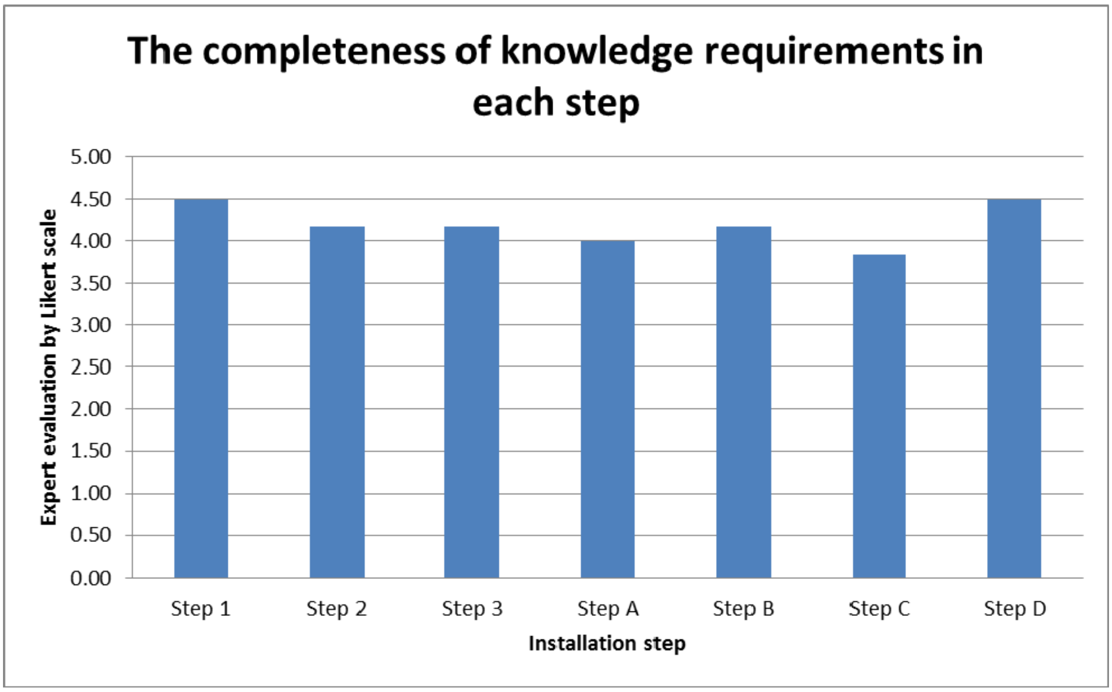

Figure 7.64 The completeness of knowledge and skill requirements in each step

7.4.4 The importance of knowledge and skill in each step of the installation process

The installation process, including the knowledge requirements of each personnel in each installation step, was presented to the experts. Then the experts evaluated the importance of knowledge and skill for each person in each installation step. The results are shown in Table 7.41 to Table 7.51. The summary of evaluation in terms of importance of knowledge and skill in each step of installation is shown in Table 7.52 and Figure 7.65.

7.4.5 The reduction of knowledge and skill in each step of the installation process using the automation approach

The working of the automation approach was demonstrated to the experts. The prefabricated members were represented as 1:10 scale prefabricated member models. The presentation covered from Step 1: Checking the available prefabricated members to Step D: Inspection of installed prefabricated members. After the presentation, the experts evaluated the reduction of knowledge and skill requirements using the automation approach. The results are shown in Table 7.41 to Table 7.51. The summary of evaluation in terms of reduction of knowledge and skill in each step of installation using the automation approach is shown in Table 7.53 and Figure 7.66.

Table 7.41 The importance and reduction of knowledge and skill requirements for the foreman in step 1

Knowledge and skill requirements for the foreman in step 1	Importance								Reduction							
	Expert						Average	Rank	Expert						Average	Rank
	1	2	3	4	5	6			1	2	3	4	5	6		
Identify the target group of installation																
The interpretation of construction drawings	4	5	5	5	5	4	4.67	1	4	2	4	4	5	2	3.50	13
The prefabricated member identification	5	4	4	5	5	3	4.33	4	5	4	4	4	5	3	4.17	2
The perception of prefabricated members or combination in each structure	4	4	4	5	5	4	4.33	4	5	2	4	4	5	3	3.83	9
The consideration of target group in installation process	5	5	4	4	4	3	4.17	8	5	4	4	4	5	3	4.17	2
Consider the list of prefabricated members in a target group																
The perception of prefabricated members or combination in target structure	5	4	5	5	4	4	4.50	2	5	4	4	4	5	3	4.17	2
The interpretation of construction drawings	4	5	5	5	5	3	4.50	2	5	2	4	4	5	3	3.83	9

Table 7.41 The importance and reduction of knowledge and skill requirements for the foreman in step 1 (Cont.)

Knowledge and skill requirements for the foreman in step 1	Importance								Reduction							
	Expert						Average	Rank	Expert						Average	Rank
	1	2	3	4	5	6			1	2	3	4	5	6		
Identify a prefabricated member																
The prefabricated member identification	5	4	4	5	3	3	4.00	10	5	4	4	4	5	3	4.17	2
The interpretation of construction drawings	4	5	4	5	5	3	4.33	4	5	2	4	4	5	3	3.83	9
Identify a prefabricated member by other methods																
The use of measurement tools	4	3	4	4	3	4	3.67	14	5	0	3	2	3	2	2.50	14
The interpretation of construction drawings	4	5	4	5	5	3	4.33	4	5	4	3	4	5	3	4.00	8
Record an available prefabricated member																
The data collection	4	5	3	5	4	4	4.17	8	5	4	4	4	5	3	4.17	2
Perceive the list of available prefabricated members																
The data collection	4	5	3	4	5	3	4.00	10	5	5	4	4	5	3	4.33	1

Table 7.41 The importance and reduction of knowledge and skill requirements for the foreman in step 1 (Cont.)

Knowledge and skill requirements for the foreman in step 1	Importance								Reduction							
	Expert						Average	Rank	Expert						Average	Rank
	1	2	3	4	5	6			1	2	3	4	5	6		
If the members in the target group are not complete, find another prefabricated member																
The perception of prefabricated members or combination in target structure	5	3	3	5	5	3	4.00	10	5	4	4	4	5	3	4.17	2
Decide to stop searching																
The decision making	5	3	3	5	4	3	3.83	13	3	4	4	4	5	3	3.83	9

Table 7.42 The importance and reduction of knowledge and skill requirements for the foreman in step 2

Knowledge and skill requirements for the foreman in step 2	Importance								Reduction							
	Expert						Average	Rank	Expert						Average	Rank
	1	2	3	4	5	6			1	2	3	4	5	6		
Recall the list of unavailable resources																
The perception of unavailable resources	5	4	4	5	5	3	4.33	4	5	4	4	4	5	3	4.17	1
Consider the lack of resources that totally affect to the installation																
The consideration of the effects from resource unavailability to the installation process	5	5	4	5	5	3	4.50	2	5	4	3	4	5	2	3.83	4
Make a decision whether to postpone or continue the installation process																
The decision making to perform the installation process	5	5	4	5	5	4	4.67	1	5	4	3	4	5	3	4.00	2
Consider the location of house, mobile crane, and stock																
The consideration of the effects from the house, mobile crane, and stock location to the installation sequence	4	4	4	4	5	4	4.17	5	5	3	3	4	5	2	3.67	6

Table 7.42 The importance and reduction of knowledge and skill requirements for the foreman in step 2 (Cont.)

Knowledge and skill requirements for the foreman in step 2	**Importance**								**Reduction**							
	Expert						**Average**	**Rank**	**Expert**						**Average**	**Rank**
	1	**2**	**3**	**4**	**5**	**6**			**1**	**2**	**3**	**4**	**5**	**6**		
Consider the effect of unavailable prefabricated members																
The consideration of the effects from unavailable prefabricated members to the installation sequence	5	4	4	4	4	4	4.17	5	5	3	3	4	5	2	3.67	6
Consider the effect of unavailable resources																
The consideration of the effects from resource unavailability to the installation sequence	5	4	4	4	5	3	4.17	5	5	3	4	4	5	2	3.83	4
Generate the installation sequence																
The installation sequence generation	5	5	4	4	5	4	4.50	2	5	4	4	4	5	2	4.00	2

Table 7.43 The importance and reduction of knowledge and skill requirements for the foreman in step 3

Knowledge and skill requirements for the foreman in step 3	Importance								Reduction							
	Expert						Average	Rank	Expert						Average	Rank
	1	2	3	4	5	6			1	2	3	4	5	6		
Recall a selected installation sequence from the previous step																
The perception of selected installation sequence	5	4	4	5	5	4	4.50	6	5	4	5	4	5	2	4.17	3
Operate the work based on an installation sequence																
The perception of details in a selected installation sequence	5	4	4	4	5	4	4.33	9	5	4	5	4	5	3	4.33	2
Inform the stockman to hook a prefabricated member																
The perception of a prefabricated member, which will be lifted and installed	5	5	5	4	5	3	4.50	6	5	4	0	4	5	4	3.67	5
Inform the erector to install a prefabricated member																
The perception of installed location	5	5	5	5	5	4	4.83	1	5	5	5	4	5	4	4.67	1

Table 7.43 The importance and reduction of knowledge and skill requirements for the foreman in step 3 (Cont.)

Knowledge and skill requirements for the foreman in step 3	Importance								Reduction							
	Expert						Average	Rank	Expert						Average	Rank
	1	2	3	4	5	6			1	2	3	4	5	6		
Supervise and cooperate with the personnel in an installation group																
The perception of installation procedure	5	5	5	4	5	4	4.67	3	5	2	2	3	5	3	3.33	6
The perception of installation specification	5	5	4	5	5	3	4.50	6	5	2	2	3	4	2	3.00	7
The interpretation of construction drawings	5	5	5	5	5	4	4.83	1	4	2	1	3	5	1	2.67	9
The refabricated member identification	5	5	4	4	5	3	4.33	9	5	4	4	3	5	2	3.83	4
The resource identification	5	5	4	5	4	3	4.33	9	5	3	0	3	5	2	3.00	7
The use of materials	4	5	4	4	5	2	4.00	12	5	2	0	3	5	1	2.67	9
The use of tools	4	5	4	4	4	2	3.83	14	5	2	0	3	5	1	2.67	9
The use of measurement tools	4	5	4	4	5	2	4.00	12	5	2	0	3	3	1	2.33	15
The use of cable, shackles, and hooks for resource hooking and unhooking	4	4	4	4	5	2	3.83	14	5	2	0	2	5	1	2.50	12

Table 7.43 The importance and reduction of knowledge and skill requirements for the foreman in step 3 (Cont.)

Knowledge and skill requirements for the foreman in step 3	Importance								Reduction							
	Expert						Average	Rank	Expert						Average	Rank
	1	2	3	4	5	6			1	2	3	4	5	6		
Supervise and cooperate with the personnel in an installation group (Cont.)																
The communication using hand signals	4	5	4	5	5	5	4.67	3	5	2	0	2	5	1	2.50	12

Table 7.44 The importance and reduction of knowledge and skill requirements for the mobile crane operator in step 3

Knowledge and skill requirements for the mobile crane operator in step 3	Importance								Reduction							
	Expert						Average	Rank	Expert						Average	Rank
	1	2	3	4	5	6			1	2	3	4	5	6		
Control the machine to move between stock location and house																
The operation of mobile crane to swing between stock rack and house	5	5	3	5	5	4	4.50	3	0	2	0	3	5	2	2.00	2
Control the machine to hook, lift, install, and unhook a prefabricated member																
The operation mobile crane to hook, lift, install, and unhook a prefabricated member	5	5	5	4	5	4	4.67	1	0	2	0	3	5	2	2.00	2
Cooperate with the personnel in an installation group																
The communication using hand signals	5	5	4	5	5	4	4.67	1	4	2	0	2	5	1	2.33	1

Table 7.45 The importance and reduction of knowledge and skill requirements for the stockman in step 3

Knowledge and skill requirements for the stockman in step 3	Importance								Reduction							
	Expert						Average	Rank	Expert						Average	Rank
	1	2	3	4	5	6			1	2	3	4	5	6		
Find a prefabricated member																
The prefabricated member identification	5	5	4	4	4	4	4.33	4	5	4	5	4	5	1	4.00	2
The perception of prefabricated member location	5	5	4	3	5	3	4.17	5	5	4	5	4	5	2	4.17	1
Hook a prefabricated member																
The working at height	5	5	4	5	5	3	4.50	1	0	0	0	2	3	3	1.33	5
The use of cable, shackles, and hooks for resource hooking and unhooking	5	5	4	4	5	4	4.50	1	5	0	0	3	5	2	2.50	3
Cooperate with the personnel in an installation group																
The communication using hand signals	5	5	4	5	5	3	4.50	1	4	0	0	2	5	1	2.00	4

Table 7.46 The importance and reduction of knowledge and skill requirements for the erectors in step 3

Knowledge and skill requirements for the erectors in step 3	Importance								Reduction							
	Expert						Average	Rank	Expert						Average	Rank
	1	2	3	4	5	6			1	2	3	4	5	6		
Handle a prefabricated member to the location																
The perception of location, where a prefabricated member has to be installed	5	5	4	5	5	4	4.67	3	5	4	5	4	5	3	4.33	1
The handling of prefabricated member	5	5	5	5	4	4	4.67	3	1	0	5	4	3	3	2.67	4
Install a prefabricated member																
The perception of installation procedure	5	5	5	5	5	4	4.83	1	5	4	1	4	5	3	3.67	2
The perception of installation specification	5	5	5	5	5	4	4.83	1	5	2	1	4	5	2	3.17	3
The use of materials	5	5	5	5	5	3	4.67	3	5	1	0	3	5	1	2.50	5
The use of tools	5	5	5	5	5	3	4.67	3	5	1	0	3	5	0	2.33	6
The use of measurement tools	5	5	5	5	5	3	4.67	3	5	1	0	3	5	0	2.33	6

Table 7.46 The importance and reduction of knowledge and skill requirements for the erectors in step 3 (Cont.)

Knowledge and skill requirements for the erectors in step 3	**Importance**								**Reduction**							
	Expert						**Average**	**Rank**	**Expert**						**Average**	**Rank**
	1	**2**	**3**	**4**	**5**	**6**			**1**	**2**	**3**	**4**	**5**	**6**		
Cooperate with the personnel in an installation group																
The communication using hand signals	5	5	4	5	5	4	4.67	3	5	0	0	2	5	1	2.17	8
Shore a prefabricated member																
The use of materials	5	4	5	5	5	3	4.50	12	5	0	0	2	5	0	2.00	12
The use of tools	5	4	5	5	5	3	4.50	12	5	0	0	2	5	0	2.00	12
The shoring of prefabricated member	5	4	5	5	5	3	4.50	12	5	0	0	3	5	0	2.17	8
Adjust a prefabricated member																
The use of materials	5	4	4	5	5	3	4.33	15	5	0	0	3	4	1	2.17	8
The use of measurement tools	5	4	4	5	5	3	4.33	15	5	0	0	3	3	0	1.83	15
The prefabricated member adjustment for inclination, leveling, and alignment by using material, tools, and workforce	5	5	5	5	5	3	4.67	3	5	0	0	3	3	0	1.83	15

Table 7.46 The importance and reduction of knowledge and skill requirements for the erectors in step 3 (Cont.)

Knowledge and skill requirements for the erectors in step 3	**Importance**								**Reduction**							
	Expert						**Average**	**Rank**	**Expert**						**Average**	**Rank**
	1	**2**	**3**	**4**	**5**	**6**			**1**	**2**	**3**	**4**	**5**	**6**		
Unhook a prefabricated member																
The working at height	5	5	4	5	4	3	4.33	15	0	0	0	2	3	1	1.00	17
The use of cable, shackles, and hooks for resource hooking and unhooking	5	5	4	5	5	4	4.67	3	5	0	0	2	5	1	2.17	8
Cooperate with the personnel in an installation group																
The communication using hand signals	5	5	4	5	5	4	4.67	3	4	0	0	2	5	1	2.00	12

Table 7.47 The importance and reduction of knowledge and skill requirements for the foreman in step A

Knowledge and skill requirements for the foreman in step A	Importance								Reduction							
	Expert						Average	Rank	Expert						Average	Rank
	1	2	3	4	5	6			1	2	3	4	5	6		
Recall the target group of installation process																
The perception of member in target group	5	4	4	4	5	3	4.17	1	5	3	0	3	5	3	3.17	5
Consider the list of required resources based on the installation of target group																
The perception of resource requirements for each structural type and each prefabricated member in the target group	4	4	4	4	4	3	3.83	2	5	3	0	3	5	2	3.00	6
Identify a resource																
The resource identification	5	3	4	5	4	2	3.83	2	5	0	0	3	5	2	2.50	7
Record an available resource																
The data collection	4	3	3	4	4	3	3.50	7	5	2	4	4	5	3	3.83	3
Perceive the list of all available resources and its quantity																
The data collection including accumulating the resource quantity	4	3	3	5	5	3	3.83	2	5	2	4	4	5	3	3.83	3

Table 7.47 The importance and reduction of knowledge and skill requirements for the foreman in step A (Cont.)

Knowledge and skill requirements for the foreman in step A	**Importance**								**Reduction**							
	Expert						**Average**	**Rank**	**Expert**						**Average**	**Rank**
	1	**2**	**3**	**4**	**5**	**6**			**1**	**2**	**3**	**4**	**5**	**6**		
If the required resources are not complete, find another or search at other possible locations																
The perception of resource requirements for each structural type and each prefabricated member in the target group	4	3	3	4	5	3	3.67	6	5	4	4	4	5	3	4.17	1
Decide to stop searching																
The decision making	4	3	3	5	5	3	3.83	2	4	4	4	4	5	3	4.00	2

Table 7.48 The importance and reduction of knowledge requirements for the foreman in step B

Knowledge requirements for the foreman in step B	Importance								Reduction							
	Expert						Averag	Rank	Expert						Averag	Rank
	1	2	3	4	5	6			1	2	3	4	5	6		
Recall the list of resource and prefabricated member requirements based on the installation of target group																
The perception of resource and prefabricated member requirements based on the installation of target group	5	4	4	5	5	3	4.33	4	5	4	4	4	5	2	4.00	5
Recall the list of available resources																
The perception of available resources	5	4	4	4	5	3	4.17	5	5	4	4	4	5	3	4.17	3
Recall the list of available prefabricated members																
The perception of available prefabricated members	5	5	4	4	5	4	4.50	1	5	4	4	4	5	3	4.17	3
Compare the required resources and the available resources																
The comparison between the required resources and the available resources	5	5	4	4	5	4	4.50	1	5	5	4	4	5	3	4.33	1

Table 7.48 The importance and reduction of knowledge requirements for the foreman in step B (Cont.)

Knowledge requirements for the foreman in step B	**Importance**								**Reduction**							
	Expert						**Averag**	**Rank**	**Expert**						**Averag**	**Rank**
	1	**2**	**3**	**4**	**5**	**6**			**1**	**2**	**3**	**4**	**5**	**6**		
Perceive the list of unavailable resources																
The perception of unavailable resources	5	5	4	5	5	3	4.50	1	5	5	4	4	5	3	4.33	1

Table 7.49 The importance and reduction of knowledge and skill requirements for the mobile crane operator in step C

Knowledge and skill requirements for the mobile crane operator in step C	**Importance**								**Reduction**							
	Expert						**Average**	**Rank**	**Expert**						**Average**	**Rank**
	1	**2**	**3**	**4**	**5**	**6**			**1**	**2**	**3**	**4**	**5**	**6**		
Perceive the target group of installation process																
The perception of target group in installation process	5	5	3	5	5	3	4.33	4	5	4	3	3	5	2	3.67	4
Consider the expected working location																
The perception of prefabricated members in target group	4	4	3	5	4	3	3.83	14	5	4	3	3	5	3	3.83	3
The perception of weight for each prefabricated member	5	4	4	5	5	5	4.67	2	5	4	4	3	5	4	4.17	1
The perception of installed location for each prefabricated member	4	4	4	5	5	3	4.17	9	5	4	4	3	5	3	4.00	2
The perception of working range for mobile crane by understanding rated lifting capacity chart	5	4	4	5	5	5	4.67	2	5	3	2	4	5	3	3.67	4
The consideration of expected working location	4	4	4	5	5	4	4.33	4	5	3	3	4	5	2	3.67	4

Table 7.49 The importance and reduction of knowledge and skill requirements for the mobile crane operator in step C (Cont.)

Knowledge and skill requirements for the mobile crane operator in step C	Importance								Reduction							
	Expert						Average	Rank	Expert						Average	Rank
	1	2	3	4	5	6			1	2	3	4	5	6		
Consider the condition of ground																
The consideration of ground condition	5	4	4	4	4	4	4.17	9	5	2	2	3	4	2	3.00	8
Recall the list of available resources																
The perception of available resources especially the machine base plates	4	4	3	4	4	4	3.83	14	5	2	0	3	5	2	2.83	9
Consider the required resources based on the actual situation																
The perception of required resources in terms of type, size, and quantity in order to set up the machine	5	4	4	4	5	4	4.33	4	5	2	0	3	5	2	2.83	9
The resource identification	5	3	3	4	5	3	3.83	14	5	2	2	4	5	2	3.33	7

Table 7.49 The importance and reduction of knowledge and skill requirements for the mobile crane operator in step C (Cont.)

Knowledge and skill requirements for the mobile crane operator in step C	**Importance**								**Reduction**							
	Expert						**Average**	**Rank**	**Expert**						**Average**	**Rank**
	1	**2**	**3**	**4**	**5**	**6**			**1**	**2**	**3**	**4**	**5**	**6**		
Compare the required resources and the available resources																
The comparison between required resources and the available resources	5	4	3	5	5	3	4.17	9	5	1	2	4	4	1	2.83	9
If the required resources are not complete, reconsider the working location																
The perception of required resources	4	4	3	5	5	3	4.00	12	5	0	2	4	5	1	2.83	9
The perception of available resources	4	4	3	5	5	3	4.00	12	5	0	2	4	5	1	2.83	9
Cooperate with the workers																
The communication using hand signals	5	5	4	5	5	5	4.83	1	5	1	0	2	5	0	2.17	15
Move the related resources to the location																
The resource identification	4	4	3	4	4	3	3.67	17	5	0	0	3	5	1	2.33	14
The operation of mobile crane to lift and move resources	5	5	3	4	5	4	4.33	4	0	0	0	3	3	0	1.00	17

Table 7.49 The importance and reduction of knowledge and skill requirements for the mobile crane operator in step C (Cont.)

Knowledge and skill requirements for the mobile crane operator in step C	**Importance**								**Reduction**							
	Expert						**Average**	**Rank**	**Expert**						**Average**	**Rank**
	1	**2**	**3**	**4**	**5**	**6**			**1**	**2**	**3**	**4**	**5**	**6**		
Move the machine to the location																
Mobile crane operation to move and set up the machine	5	4	3	5	5	4	4.33	4	0	0	0	3	4	1	1.33	16

Table 7.50 The importance and reduction of knowledge and skill requirements for the workers in step C

Knowledge and skill requirements for the workers in step C	**Importance**								**Reduction**							
	Expert						**Average**	**Rank**	**Expert**						**Average**	**Rank**
	1	**2**	**3**	**4**	**5**	**6**			**1**	**2**	**3**	**4**	**5**	**6**		
Cooperate with the mobile crane operator																
The communication using hand signals	5	5	4	5	5	5	4.83	1	5	0	0	2	5	0	2.00	1
Support the related resource moving																
The resource identification, especially the machine base plates	4	3	3	4	4	4	3.67	4	5	0	0	3	4	0	2.00	1
The use of cable, shackles, and hooks for resource hooking and unhooking	4	4	4	5	5	5	4.50	2	5	0	0	2	5	0	2.00	1
Support the machine moving																
The communication using hand signals	5	3	4	5	5	5	4.50	2	5	0	0	2	5	0	2.00	1

Table 7.51 The importance and reduction of knowledge and skill requirements for the inspector in step D

Knowledge and skill requirements for the inspector in step D	Importance								Reduction							
	Expert						Average	Rank	Expert						Average	Rank
	1	2	3	4	5	6			1	2	3	4	5	6		
Perceive the list of prefabricated members																
The perception of installed prefabricated members in a structure	5	5	4	5	5	3	4.50	1	5	4	4	4	5	2	4.00	2
Identify a prefabricated member																
The prefabricated member identification	5	5	4	5	5	3	4.50	1	5	4	4	4	5	2	4.00	2
Perceive the quality terms of a prefabricated member from the checklists or specifications																
The selection of checklist or specification	5	4	4	5	5	3	4.33	4	5	1	4	4	5	2	3.50	6

Table 7.51 The importance and reduction of knowledge and skill requirements for the inspector in step D (Cont.)

Knowledge and skill requirements for the inspector in step D	**Importance**								**Reduction**							
	Expert						**Average**	**Rank**	**Expert**						**Average**	**Rank**
	1	**2**	**3**	**4**	**5**	**6**			**1**	**2**	**3**	**4**	**5**	**6**		
Inspect a prefabricated member																
The perception of quality checklist or specification for each prefabricated member	4	4	5	5	4	4	4.33	4	5	3	4	4	5	3	4.00	2
The understanding of quality terms	4	4	4	5	5	4	4.33	4	5	1	3	4	5	2	3.33	8
The interpretation of construction drawings	5	5	4	5	5	3	4.50	1	5	1	0	4	5	3	3.00	10
The use of measurement tools	4	4	4	5	5	3	4.17	8	5	1	0	4	3	1	2.33	11
The inspection by following the quality terms	4	4	4	5	5	3	4.17	8	5	1	4	4	4	2	3.33	8
Record the inspection results																
The data collection	5	5	4	5	4	3	4.33	4	5	4	5	5	5	4	4.67	1
Make a decision to stop inspection																
The perception of installed- and inspected prefabricated members	4	4	3	4	5	3	3.83	11	5	4	4	4	5	2	4.00	2
The decision making	5	4	3	5	5	3	4.17	8	3	4	4	4	5	1	3.50	6

Table 7.52 Summary of evaluation in terms of knowledge and skill importance

Average evaluate scale in terms of importance			Number of knowledge and skill	Percentage
From	To	Meaning		
4.50	5.00	Very important	46	43.81%
3.50	4.49	Important	59	56.19%
2.50	3.49	Neither important or unimportant	-	-
1.50	2.49	Unimportant	-	-
1.00	1.49	Very unimportant	-	-
Total			105	100%

Table 7.53 Summary of evaluation in terms of knowledge and skill requirement reduction using the automation approach

Average evaluate scale in terms of Reduction			Number of knowledge and skill	Percentage
From	To	Meaning		
4.50	5.00	Excellent	2	1.90%
3.50	4.49	Above average	49	46.67%
2.50	3.49	Average	27	25.71%
1.50	2.49	Below average	23	21.90%
0.50	1.49	Extremely poor	4	3.81%
0.00	0.49	None	-	-
Total			105	100%

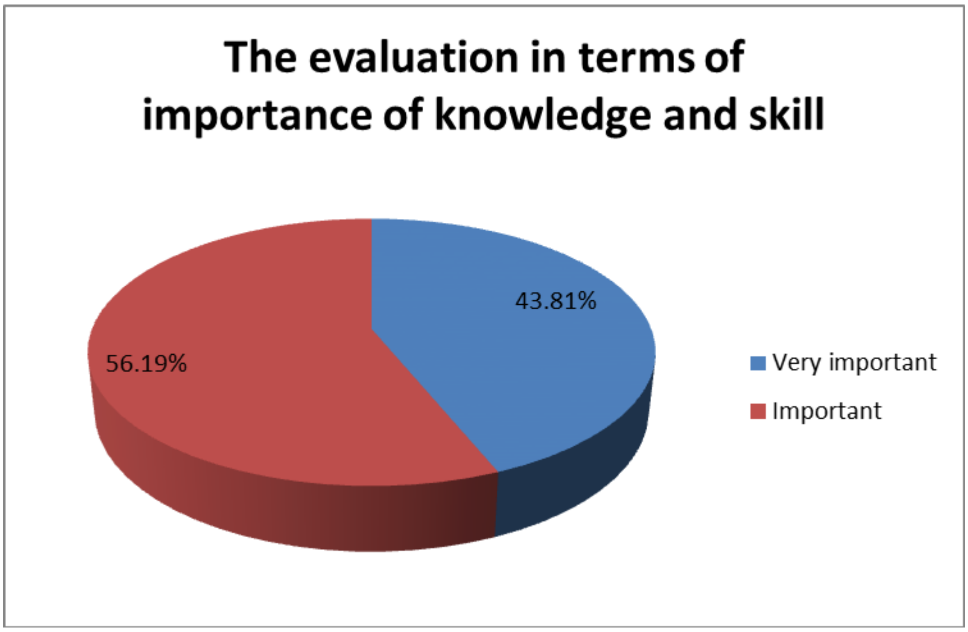

Figure 7.65 Evaluation in terms of knowledge and skill importance

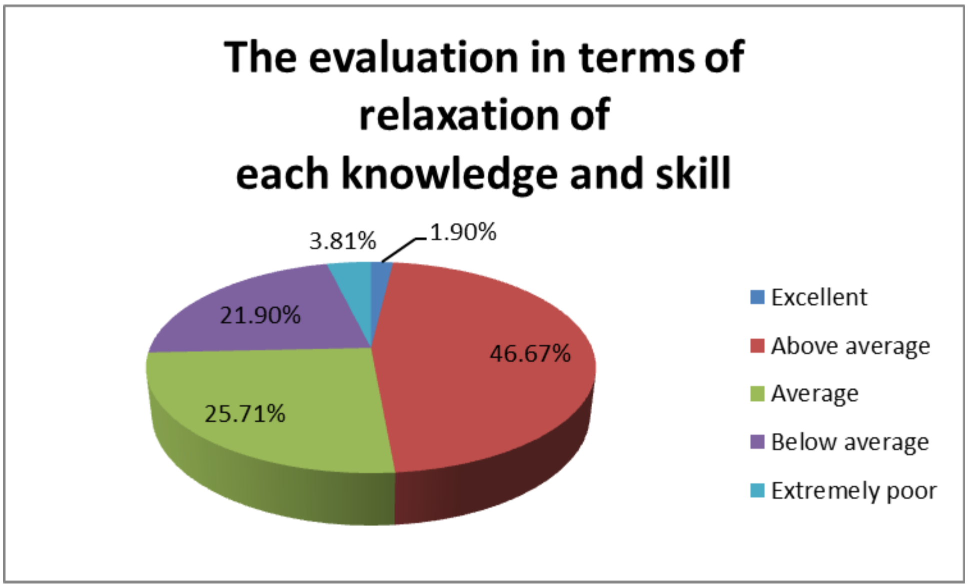

Figure 7.66 Evaluation in terms of knowledge and skill requirement reduction

7.4.6 The evaluation of automation approach

After the demonstration, the experts evaluated the automation approach in terms of the usage. The results are shown in Table 7.54.

All of issues were evaluated in the range of "above average", which the average scale was between 3.50 and 4.49. In addition, an expert recommended that the information should be linked between the manufacturing process, stock process, and installation process, including the rejected members from transportation and the installation process. This will support the manufacturing work to perceive the current condition of their work.

Table 7.54 The evaluation of automation approach usage

Evaluation of automation approach	**Expert**						**Average**	**Rank**
	1	**2**	**3**	**4**	**5**	**6**		
Ease of use	5	4	4	3	5	4	4.17	2
Ease of carry while working	4	4	4	2	5	5	4.00	3
Working procedure	5	4	3	4	4	4	4.00	3
Adequate information	4	3	3	4	5	3	3.67	6
Display and format of information	4	4	4	3	5	4	4.00	3
Speed of processing	4	4	4	4	5	1	3.67	6
Improving speed of construction	5	4	2	3	5	2	3.50	8
Mistake reduction	5	4	4	4	5	4	4.33	1

7.5 Conclusion

In this chapter, three phases of evaluation were performed. These include evaluation by the prefabricated member model, evaluation at the construction site, and evaluation by the experts.

Firstly, the automation approach was evaluated using the prefabricated member model. The 10 samplers installed the model in three rounds. Each round was a random situation and composed of an installation by the conventional method and an installation by the automation approach. Then, the results in terms of installation duration and installation mistakes were compared. The improvement in terms of installation duration was in the range of 15.69% to 64.66%, while the improvement in terms of the number of mistakes was in the range of 50% to 100%. Both of the improvements were statistically tested by paired sample test with 95% confidence interval of difference.

At the construction site, an evaluation was performed through collecting the data of installation by the conventional method and by the automation approach. The installations of 56 members from 78 members of the first floor wall were observed. After the implementation of the automation approach, the working duration per panel of swing back, find and hook, swing, and install were improved. The total working duration per panel was improved by 16.71%. In terms of the installation mistakes, the mistake in the installation process using conventional method was 5% of the installed members and 4.65% of the total installation duration. After the implementation of automation approach, none of mistakes occurred. However, the mistake improvement was not significant in terms of statistics.

The evaluation by the experts focused on the suitability of the work breakdown structure, the importance of each step in the installation process, the completeness of knowledge and skill requirements in each step, the importance of knowledge and skill for each person in each step, the reduction of knowledge requirements using the automation approach, and the evaluation of automation approach.

For the suitability of the work breakdown structure, the experts all agreed with the proposed work breakdown structure of the installation process. The three main steps, including checking the availability of other resources, were evaluated as the most important for the installation duration. While the deciding the work location of the mobile crane was evaluated as the least important step for the installation duration. Experts evaluated the three main steps, including deciding the work location of the mobile crane as the highest three ranks, which affect installation mistakes. The steps of checking the availability of other resources and the inspection of installed prefabricated members were evaluated as the least important for installation mistakes. For the completeness of knowledge and skill requirements in each step, most of the installation steps were evaluated at least “complete” scale. In terms of knowledge and skill importance in each installation step, all requirements were evaluated as very important and important by 43.81% and 56.19% respectively. The knowledge and skill requirement reduction using the automation approach was evaluated as excellent, above average, average, below average, and extremely poor by 1.90%, 46.67%, 25.71%, 21.90%, 3.81%, and 1.90% respectively. Experts evaluated the automation approach in terms of the usage at least “above average” for all issues.

Chapter 8
Conclusion

In the last chapter, the subject matters of this research are concluded and divided into six parts: (1) the requirements of knowledge and skill in each installation step, (2) the automation approach, (3) discussion, (4) research contributions, (5) adaptation for the other constructions, and (6) future works.

This research employed the eight steps of methodology in as follows: (1) primary site survey, (2) literature reviews, (3) data collection, (4) current practice analysis, (5) analysis of knowledge and skill requirements, (6) automation approach development, (7) evaluation, and (8) research summarisation and discussion. The data was collected from the installation processes of prefabricated members at six construction projects, which performed the prefabricated housing construction. All projects are located at Bangkok metropolitan and nearby areas.

8.1 The requirements of knowledge and skill in each installation step

The knowledge and skill requirements depend on the roles and responsibilities of each person and the work processes. In addition, the changes and mistakes in the work process increase the knowledge and skill requirements in order to perceive the changes or mistakes and select the countermeasures in a timely manner. The work process was broken down into a detailed work breakdown structure and the action flow was created. The knowledge requirements in each action were analysed from the physical work or movements and the related data and information.

Using the prefabricated member installation as a case study, the requirements of knowledge in each installation step were revealed in this research. The installation process was broken down into three main steps and four supplementary steps. The main steps included (1) checking the available prefabricated members, (2) making a decision for an installation process, and (3) installing the prefabricated members. While the supplementary steps were (A) checking the availability of available resources, (B) comparing the required resources and the available resources, (C) deciding the work location of the mobile crane, and (D) the inspection of installed prefabricated members. Therefore, the knowledge and skill requirements of each person in each step were summarised.

In the knowledge and skill requirements, the requirements can be categorised into 2 types, i.e., (1) the knowledge, and (2) the knowledge and skill. The examples of knowledge are the perception of prefabricated members or combination in the structure, the consideration of effect from resource unavailability to the installation process, the perception of a prefabricated member, which will be lifted and installed, and the perception of installation specification. For the knowledge and skill, the examples are the interpretation of construction drawing, the prefabricated member identification, the installation sequence generation, and the usage of materials.

8.2 The automation approach

The automation approach was developed based on the work process and the knowledge and skill requirements of each person. In addition, because the changes and mistakes affect the knowledge and skill requirements, the automation approach was designed to perceive the changes and process the data and information for countermeasure the changes and mistakes.

In this research, the case study is installation process of prefabricated member. Thus, the work process composed of three main steps and four supplementary steps. The automation approach consists of a PDA with RFID reader and laptop computer. The PDA with RFID reader is assigned to the foreman and inspector, while laptop computer is assigned to the mobile crane operator and located in the cabin of the machine.

The automation approach is comprised of user interfaces, five modules, and a database. The user interfaces are for the foremen, mobile crane operators, and inspectors. Each user interface is assigned to cooperate with other modules, input data, and display information.

The five modules include the (1) general information module, which provides static information such as project details, personnel details, and resource requirements, (2) specific information module, which provides the dynamic information specific to the current conditions and installation sequence, (3) actual condition recording module, which is utilised to check the available resources, and record the actual executions, (4) alternative generating module, which generates the installation sequence, checks the completeness of resources, and generates the alternative work methods with expected results, and (5) quality assurance and control module, which provides the inspection checklists and records the inspection results. The database stores data and other related information and knowledge.

8.3 Discussion

The automation approach was evaluated using the prefabricated member model to control the related factors and for safety reasons. The 10 samplers installed the model in three rounds. Each round was conducted in random situations and composed of an installation by conventional method and by automation approach. Then, the results in terms of installation duration and installation mistakes were compared. The improvement in terms of the installation duration was in the range of 15.69% to 64.66%, while the improvement in terms of the number of mistakes was in the range of 50% to 100%. Both of the improvements were statistically tested by paired sample test with 95% confidence interval of difference. However, in the evaluated using the prefabricated member model, the installation mistakes occurred while the sampler was using the automation approach. The reason is confusing in perspective figure, which illustrate the location of installed prefabricated member.

The automation approach was implemented at the construction site. The installation process of the first floor wall was selected as a case study. In this phase, both of the installations by conventional method and automation approach were observed. When comparing the installation duration per panel by conventional method and automation approach, the working duration per panel of swing back, find and hook, swing, and install were improved. The total working duration per panel was improved by 16.71%. In terms of installation mistakes, the mistake in the installation process by conventional method accounted for 5% of the installed members and 4.65% of the total installation duration. After the implementation of the developed framework, none of the mistakes occurred. However, the mistake improvement was not significant in terms of statistics.

From the evaluation by experts, the reduction of knowledge requirements using the automation approach was evaluated as excellent, above average, average, below average, and extremely poor by 1.90%, 46.67%, 25.71%, 21.90%, 3.81%, and 1.90% respectively. The experts also evaluated the automation approach in terms of the usage. All the issues were evaluated in the range of “above average”.

However, using the proposed automation approach, most of the knowledge and skill requirements were replaced or reduced by the system, the personnel still require knowledge and skills for some actions. For example, the knowledge and skill to interpret the perspective figure, which represent the installed location of prefabricated member, and the skills for the physical works. In addition, the knowledge for using laptop computer or PDA is added up by using the automation approach and must be trained to the personnel.

8.4 Research contributions

From this research, the contributions can be summarised into three parts as follows: (1) the knowledge and skill, which are required in the installation process of prefabricated members. These requirements may be used for the training or the requirement reduction. This contribution includes methodology to analyse the knowledge and skill requirements, (2) the automation approach, which aims to reduce the knowledge and skill requirements. This approach gives the indirect effects to improve the productivity and reduce the number of mistakes. Both of them affect the efficiency and effectiveness of prefabricated construction, and (3) the new idea for raising the automation degree in the construction process. The automation approach reduces the dependency of the personnel's knowledge and skill and increases the automation degree in the construction process. Thus, the gap of automation degree between the manufacturing process and construction process will be bridged.

8.5 Adaptation for the other construction methods

The automation approach was designed and developed based on the installation process of prefabricated construction. However, the system can be adapted for other types of construction. The system supports the work of personnel, especially the work concerning installation based work, the repetitive work, and sequential work characteristics. An example is the formwork installation as shown in Figure 8.1 and Figure 8.2.

Figure 8.1 Formwork installation

Figure 8.2 Formwork installation

8.6 Future works

The automation approach will be implemented for testing with the actual size model as shown in Figure 8.3. The test aims to acquire the results of using the system under controlled factors and the actual dimensions.

Figure 8.3 Actual size model

In the future, the automation approach should be improved to cover the upstream and downstream processes of the prefabricated member installation. The upstream processes include the manufacturing process and transportation process. While the downstream processes consists of the maintenance process and customer service. The expansion can use the data and information already inputted into the system. This expansion aims to reduce the requirements of knowledge and skill in the upstream and downstream processes.

By this expansion, the processes of prefabricated construction will be changed from the human driven to the more automation level process. The working of personnel will be controlled by the system, which knowledge and information are provided by certified personnel. Then, the work will be operated based on the same standardisation.

Moreover, the return of investment will be more and more from the expansion using the current infrastructure of automation approach.

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Vitae

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