Comparative Analysis of Multi-Trade Prefabrication Construction Methods

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Abstract
This paper proposes a construction method for efficient application of multi-trade prefabrication (MTP). The currently most advanced prefabrication method, MTP was recently introduced in North America and Europe. However, there have been few reports and studies of MTP in Asia. This paper discusses MTP construction method application in a workshop and presents solutions to identified problems. MTP pilot test 1 was performed using combinations of conventional chain block and scissor lift. Productivity analysis indicated that on-site MTP construction increased an extra labor input which was 19.6% compared to the total labor input of the conventional method. Pilot test 2 used manual material lifts for on-site MTP construction. Labor input per MTP module was reduced to 75.8% of that required for pilot test 1, but the manual lifts extended overall construction time. Pilot test 3 used a proposed optimized stacker based lifting device. Labor input for on-site MTP construction was reduced to 47.0% of that for pilot test 1. These results will be the basis for development of best practices for future MTP construction and provide better understanding as well as directions for improving MTP construction.

Keywords: prefabrication; multi-trade prefabrication; modular construction; productivity

1. Introduction
The use of prefabrication to construct buildings faster and more efficiently is the most studied topic in the construction industry. The building information model (BIM), which has been gaining popularity recently, provides an opportunity to coordinate different building elements quickly, further strengthening prefabrication (Khanzode, 2011, McGraw Hill, 2013).

Application of the most advanced prefabrication method, known as multi-trade prefabrication (MTP), has been reported mainly in North America and Europe (Antillón et al., 2014, Colonna and Corrado, 2011). MTP can be used for multiple construction types and is expected to enhance schedule reduction and productivity improvement effects compared to single trade prefabrication. However, research on MTP construction methods to further increase productivity is limited. This study aims to provide solutions to improve MTP productivity.

This paper presents three pilot tests employing MTP for ceilings, one of the most complex building areas. Pilot test 1 used a combination of devices used in traditional construction sites. This test represents the first application of ceiling MTP in Korea. Pilot test 2 used manual lifting devices, and pilot test 3 used a proposed optimized lifting device based on problem analysis from the first two tests.

This paper proposes an improved design and construction method for MTP and presents the results of productivity analysis compared to conventional methods. Pilot test 3 applied the proposed improved MTP construction method and differences in construction productivity are compared to pilot test 1 outcomes.

2. Literature Review
Multi-trade prefabrication provides the opportunity to shorten project delivery schedules by converting on-site construction to factory production, increasing construction worker safety, providing a uniform working environment, and improving output quality. MTP can also reduce waste by minimizing mistakes as well as improving productivity (Fishking, 2011). Efforts to improve productivity are also being made in Asia, e.g. the Singapore Building Construction Authority (BCA) strongly encourages productivity improvement through prefabrication (BCA, 2015). However, MTP applications in Asia are mostly limited to modular buildings, which have restricted designs and unit bathrooms. Corridor rack-type MTP has not been reported in Asia.

The main reason for prefabrication is productivity increase (McGraw Hill, 2013). MTP has been reported to improve productivity by approximately 20% (Colonna and Corrado, 2011). However, another MTP
case report indicated that although the construction schedule can be shortened, additional labor input was required (Antillón et al., 2014). Some studies suggested that prefabrication increased vulnerability to errors and design changes in the construction phase, required higher level of management, and could not be economical due to the need for skilled workers (Pan et al., 2007, Lu, 2009).

Hoover et al. (2017) reported that although the prefabrication environment has improved over the past few years, more than 50% of contractors report that prefabrication is inefficient. Most studies have also concluded that the technology should be further developed for efficient application.

Although some MTP cases have been reported, research is sparse. Therefore, this study aimed to provide a method to increase MTP productivity, focused on improving on-site construction.

3. Research Method

This paper provides a preliminary study, pilot tests and productivity analysis for MTP (Fig.1.). The preliminary study consisted of introducing MTP design and construction methods during a workshop. Since there was no example MTP application in Korea, basic MTP implementation had to be discussed. Construction engineers for mechanical, engineering, and plumbing (MEP) trades and a general contractor conducted the workshop for approximately two months. This paper presents the basic MTP design and construction method derived from the workshop.

Pilot test 1 provided a case study for the MTP construction method and applied construction methods discussed in the workshop. The devices used for MTP construction were a combination of traditional devices (chain block and scissor lift). The second pilot test was conducted using the conventional manual material lift device. The third pilot test stage focused on improving the lifting device and provides a case study for modified MTP construction. Finally, we provide comparative MTP construction productivity.

3.1 Pilot Test Selection Criteria

Multi-trade prefabrication and contractor capability levels were considered, and the selection criteria for the three pilot tests (Table 1.) are as follows. Since it was not possible to ensure the same workers to be involved in all three pilot tests, we decided only the subcontractor and the same general contractor's subcontracting pool were to be involved.

- Construction difficulty:
  - Similar length of MTP module
  - More than four trades in the MTP module
  - Similar region of pilot site

- Worker skill level:
  - Same general contractor's subcontracting pool
  - No MTP construction experience

3.2 Data Collection

Labor input for MTP construction was measured by the minute for productivity analysis. The measurement scope was work after the MTP module was located on slab until full attachment to the upper ceiling.

Labor input for MTP construction was compared with that of the conventional method to investigate MTP productivity effects and identify MTP construction problems. The conventional method labor input was calculated from the Korea Estimation Standard (2015), which defines estimated labor input for unit quantity, for the same MEP quantity.
4. Preliminary Study

To introduce the MTP construction method, we describe the basic MTP design. The first thing required for MTP is a framing design for the MEP elements. The workshop identified the following approach. Since the pipe production unit in Korea is 6 m, the MTP module length was set to 6 m. If the length of a unit of the MTP module was determined to be less than 6 m, the pipe was segmented, and the additional cost for creating a joint in the pipe increased the total cost. The end of the MTP module was set as 500 mm from structural framing to prevent interference in MEP assembly. MTP module height excluded the girder height in the plenum space, minimizing the joint size by straightening the MEP component as much as possible. MTP module width was the width of the corridor excluding 50 mm at both sides to allow working space. Fig. 2. shows the prototype module reflecting the workshop discussions.

The next step was to determine how to construct the MTP module during the workshop. The most active discussion was whether to connect the MTP module at the plenum or slab level.

The construction process for connecting the MTP module at the plenum height is as follows. First, the MTP module is placed under the installation location. Then the module is lifted and connected to the upper slab. The raised module is then connected to already installed MTP module(s) by fine-tuning the module location attached to the upper slab. Module MEP elements are then assembled. The workshop defined this MTP construction method as sequential lifting, as shown in Fig. 3.

The construction process for the MTP module on the slab is as follows. First, multiple MTP modules are placed on the slab. In contrast to the sequential lifting method, each MTP module is connected to the MEP element joints. The connected modules are then lifted simultaneously and coupled to the upper slab. The workshop defined this MTP construction method as combinational lifting, as shown in Fig. 4.

The workshop decided to perform MTP construction using the combinational lifting method. Since the MTP module targets the corridor, one of the most complex sections of the building, MEP elements are complex. When combining MTP modules at the plenum level, bonding the lower MEP elements is relatively easy but bonding the upper MEP elements can be difficult. On the other hand, when the MTP module is bonded at the slab level, a scissor lift is not required to attach the MEP elements and the working time is expected to be shorter.

5. Pilot Tests

The pilot tests were conducted using the combinational lifting method determined at the workshop. There is little information about MTP construction methods and suitable lifting devices to finely adjust MTP module locations at the plenum level.

5.1 Pilot Test 1: Conventional Devices

A chain block was used to lift the MTP module. A scissor lift is generally used when constructing individual MEP elements in Korea, but an additional method was required to place the MTP module on the scissor lift to construct the combined MTP module. Therefore, the lifting process was divided into two
stages comprising lifting the MTP module above the height of the scissor lift using a chain block and then using the scissor lift.

Fig. 5 shows the entire construction sequence. First, the fixture used to attach the chain block to the upper slab was installed. A number of MTP modules were then placed on the slab and each module was connected. The chain block was attached to the fixture on the upper slab to lift the connected MTP modules. The connected MTP modules were lifted above the scissor lift height and the MTP module mounted on the scissor lift. The combined module was moved to the correct location and work was completed by bonding the module to the upper slab.

One of the major problems was that there was no proper lifting device and there were several lifting steps in the MTP construction process. Lifting was separated into four steps: installing a chain block fixture, attaching the chain block to the fixture, lifting using the chain block, and lifting using a scissor lift.

We compared the MTP productivity with that of the conventional method, as shown in Fig. 6. (Jang and Lee 2018). Fifteen MTP modules were used for four floors. The Korean government estimation standard was set as the baseline for the labor input required for the conventional method. The number of labor inputs to complete off-site MTP manufacturing decreased to 93.9% compared to the conventional method.

Only 67.7% of conventional labor input was required to attach each MEP element to the structural framing. As off-site module construction becomes more popular, productivity can be expected to increase. However, with the change to MTP, 26.3% of conventional labor input was added to the structural framing work, and 19.6% of conventional labor input was added to install the MTP module on-site. Therefore, the total labor input for MTP construction was 113.5% of the conventional method. These results indicate that simple MTP application will not achieve productivity improvements. It is also easy to understand why many contractors in the FMI survey (Hoover et al., 2017) responded that development of related technology is required to ensure efficient prefabrication. MTP process and productivity can be improved in various ways, but this study focused on MTP on-site construction.

5.2 Pilot Test 2: Manual Material Lift

The traditional equipment for on-site construction in Korea is scissor lifts and forklifts. The biggest advantage of a scissor lift is that it can be used for lifting materials and for lifting workers to upper levels.
It is also relatively lightweight and low volume, so there is no problem with ride hoisting and sharing devices with other MEP installation work. However, the MTP module needs to be lifted from the slab to the height of the scissor lift. Since the weight of one MTP module is 500–1000 kg, it is difficult to lift by hand. Therefore, another lifting device is required, such as the chain blocks used in pilot test 1.

The counter balance forklift is commonly used to move materials for various trades, including MEP materials, on the construction site. However, forklifts are so heavy they are constrained to hoisting and were not considered suitable for navigating between MTP modules located in a narrow corridor space.

Therefore pilot test 2 was performed using a manual material lift for MTP construction, as shown in Fig.7. Manual material lifts are not suitable for raising workers like a scissor lift, and are only suitable to lift relatively small weights of about 350 kg. They are mainly used for lifting, such as for duct members, which have relatively small weight per volume.

Fig.8. shows the process to construct the MTP module using manual material lifts. First, the MTP module is placed on the material lift supports. Since the lift fork lengths are shorter than the MTP module width, at least three manual material lifts must be used to lift one MTP module, therefore at least six manual lifts are needed for the sequential lifting method for two combined MTP modules.

Hence, although the manual material lift weighed less than 200 kg and was easy to handle in the field, the disadvantage of short lifting forks and allowable load meant the number of lifts to be increased.

5.3 Pilot Test 3: Optimized Device

The main problem identified in pilot test 1 was the lack of a suitable lifting device. Consequently, the lifting process was divided into several stages, requiring an extra 19.6% of conventional labor input for the on-site construction phase (Fig.6.). Accordingly, this study sought to reduce the percentage of labor input in the on-site construction phase by improving the lifting device.

This study proposes utilizing a stacker device, which is commonly used in logistics management. Issues considered at the MTP workshop and pilot test 1 are summarized and the functions of the lifting device presented.

The lifting device should be capable of lifting vertically to the slab level. Since the MTP module weighs more than 500 kg, it must include motorized lifting for work efficiency, and should be capable of bearing more than the MTP weight.

The process of construction using the chain block (Fig.5.) showed that the MEP module tilts during lifting. Therefore, The MTP lifting device should be capable of fine angle adjustment because several MEP elements must be connected.

The Korean Estimation construction standard (Ministry of Land Infrastructure and Transport, 2011) states that pipe joints should be within 2 mm for connection. Therefore, the lifting device should include a side shift function to move the MTP module. Current forklifts and stackers can adjust their direction at the operator's position but cannot move horizontally. Therefore, this study proposes changing stacker wheels to move in four directions.

However, changing the wheels to enable 4-way movement does not free the lifting device from movement constraints. Current forklifts and stackers can only change direction at the location of the operator's steering wheel. Therefore, we added a ring and pulling device to apply force to the front wheel.

Finally, additional steps were required to make fine adjustments. When using a forklift or stacker, a ladder or scissor lift is normally employed to lift material and workers when some work is needed at the top. Therefore, we added steps to both sides of the device to minimize the need for these additional devices. Fig.9. shows the final device as proposed in this study.
6. Productivity Analysis and Discussion

We analyzed MTP productivity for the three pilot tests, including labor input and construction time. Pilot test 1 performed MTP construction through a combination of chain block and scissor lift. It took 22.4 person days to construct 15 modules, i.e., 1.49 person days per module. Construction of each MTP module took 1.64 hours, and MTP construction time was the shortest component. Utilization of the chain block required additional preparatory work before MTP lifting, but since this made it possible to install up to four modules at a time, installation time was shortest among the three methods.

Pilot test 2 required 27.2 person days, i.e., 1.13 person days per module, 75.8% of pilot test 1. It took 2.41 hours, the longest time, to install each MTP module. Additional activities were reduced, but the manual material lift was too slow, and multiple workers were required to perform the task simultaneously, increasing overall time.

Pilot test 3 was performed using the optimized stacker and required 7.07-person days labor, i.e., 0.79 person days per MTP module. In terms of labor input, this test required 47.0% of that required in pilot test 1. However, MEP construction required 103.9% of pilot test 1 labor.

Table 2. summarizes the productivity measures. Thus, it was more efficient to use the optimized stacker based device for MTP construction. However, considering the cost and time required to modify the equipment, pilot tests 1 or 2 could also be effective. In addition, chain blocks, scissor lifts, and manual lifts can be used for other tasks at the construction site, saving equipment replacement. If MTP application is expanded the optimized stacker based device may be more efficient for large numbers of MTP applications. Although this study covers a limited set of cases, the process of deriving improvements is intuitive rather than purely scientific. Since MTP application is in its infancy, these findings will significantly contribute to the Asian construction industry. Through similar MTP studies, we expect that MTP construction will gradually become a more efficient construction option.

7. Conclusion

This paper presents an improved method for MTP construction, which is considered the most advanced form of prefabrication. Prefabrication is expected to increase building speed and improve contractor productivity. However, technology development is required for smooth prefabrication application (Hoover et al., 2017). The advanced prefabrication method, MTP, is considered new and unfamiliar, and it is necessary to develop the technology from various perspectives.

This study investigated productivity impact by improving the lifting device through three pilot tests. Pilot test 1 used a combination of chain blocks and scissor lift, which are commonly used in traditional construction. Overall labor input increased to 113.5% of the conventional method. Although only 93.9% of labor inputs were required for MTP production off-site, an extra 19.6% labor input was required for on-site construction. Hence, MTP alone cannot ensure productivity increase, and can only be achieved when relevant construction methods are also improved.

Pilot test 2 used manual material lifts. Although labor input for on-site MTP construction was reduced to 75.8% of pilot test 1, construction time was longer.

Pilot test 3 used a proposed optimized stacker based device for on-site MTP construction. Labor input was reduced to 47.0% of pilot test 1.
This study provides a strategy for MTP construction productivity improvement. Further studies regarding device optimization will improve MTP productivity. This study also provides better understanding and knowledge of MTP construction and contributes to the research development of best practices to employ advanced MTP construction methods.

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Table 2. Modified Construction Method Labor Inputs

| Lifting method          | Pilot test 1 | Pilot test 2 | Pilot test 3 |
|-------------------------|--------------|--------------|--------------|
| Lifting unit capacity   |              |              |              |
| Number of modules       | 15           | 24           | 9            |
| Total labor input       | 22.4         | 27.2         | 7.07         |
| (person day)            |              |              |              |
| Productivity            | 1.49         | 1.13         | 0.79         |
| (person day per module) |              |              |              |
| Total construction time | 24.6         | 57.8         | 19.7         |
| (h)                     |              |              |              |
| Time per module         | 1.64         | 2.41         | 2.19         |
| construction (hour)     |              |              |              |
| Expected total labor    | 113.5%       | 108.8%       | 104.3%       |
| input compared to       |              | (expected)   | (expected)   |
| conventional method     |              |              |              |