ROLE OF FORMWORK SYSTEMS IN HIGH-RISE CONSTRUCTION

Hisham A. Abou Ibrahim\textsuperscript{1,2} and Farook R. Hamzeh\textsuperscript{1}
\textsuperscript{1}Department of Civil and Environmental Engineering, American University of Beirut, Lebanon.
\textsuperscript{2}hha131@mail.aub.edu

Abstract: The selection of formwork systems in high-rise buildings is often governed by their competence in optimizing concrete activities in an isolated manner, without relating this choice to the entire construction workflow. This paper studies the role of advanced formwork systems in high-rise construction and analyzes this role in shaping not only the progress of concrete activities, but the entire construction sequence. In this context, known research efforts do not address this important aspect in analyzing high-rise formwork technologies, and formwork selection is usually left to constructors’ experience, and corresponding organizational knowledge. Employing process models, the paper investigates advanced high-rise formwork technologies versus regular ones to better advice scholars and practitioners. Results highlight the importance of advanced high-rise formwork systems in streamlining the workflow of concrete and other downstream activities, allowing for better resource allocation, more waste reduction, smaller work batches, less inventory, and safer working environment.

1 INTRODUCTION

1.1 Background of High-Rise Building Construction

High-rise building projects encounter several challenges that affect the progress of their execution. Some of these challenges are related to project location where most skyscrapers are built in tight land lots in cities' business centers with serious limitations on space. This fact imposes high pressures on the supply chain management where on-time and smooth material delivery is of great importance. Other difficulties could be related to building design complexity, the technology used on site, labor availability and skills, the adequacy of the methods followed, and the capacity of planning professionals to foresee the dynamics of their site and proactively shape its progress. While multiple efforts targeted activity sequencing methods used in high-rise construction (Ranjbaran, 2007; Arditi et al., 2002; Thabet and Beliveau, 1994; Reda, 1990; Suhail and Neale, 1994), other researchers investigated the use of 4D modeling to graphically examine schedule progress on a 3D model where space clashes are detected and proactively solved to ensure smooth tasks handoff (Staub-French and Khanzode, 2007). However, none of the efforts linked the use of formwork systems to the workflow of activities. The choice of formwork systems is governed by several parameters (Gnida, 2010; Ciribini and Tramajoni, 2010), and cost considerations highly affect the final formwork selection especially that contractors try to minimize the cost of concrete activities in an isolated fashion without considering the indirect costs of the resulting schedule and related workflows affected by this choice.

To respond to the limitations of formwork selection procedures that focus solely on concrete construction sequence, this paper presents a comprehensive understanding of the effects of formwork selection that go beyond the execution of concrete elements and introduces to the industry a broader view of the
leading role formwork systems play in high-rise projects. In this regard, the paper: (1) compares advanced and regular high-rise formwork technologies, (2) highlights corresponding workflow changes, and (3) examines major enhancements on activities flow, production rates, inventory dynamics, and labor and material delivery to work areas.

1.2 Repetitive Construction in High Rise Buildings

High-Rise building construction is characterized by the repetition of multiple activities at different locations. Planners benefit from these repetitive tasks to maintain workflow continuity, decrease labor and equipment idle times, reduce hire and fire actions, and take advantage of the learning curve effects (Ranjbaran, 2007). However, these repetitive activities advance simultaneously in vertical and horizontal directions and may create spatial constraints that hinder the execution of work (Thabet and Beliveau, 1994). To account for these constraints, practitioners and researchers sought scheduling solutions to navigate the execution of tasks under these restrictions. Since the drawbacks of applying the CPM method to schedule repetitive tasks were investigated in several studies (Reda, 1990; Hegazy and Wassef, 2001), efforts targeted other scheduling techniques using the Line of Balance (LOB) method. LOB allows operations on site to continuously flow from one activity to another by balancing different tasks, resources, and space concurrently (Hegazy, 2002). While some researchers worked on combining both the CPM and LOB methods to enhance work scheduling in repetitive construction (Suhail and Neale, 1994), other researchers used 4D modeling techniques provided by BIM technologies to simulate the construction sequence and proactively account for possible on-site clashes (Staub-French and Khanzode, 2007).

1.3 Formwork Choice and Construction Workflows

The logic of work execution followed to satisfy building safety and integrity shapes the scheduling of involved activities. Structural works are the skeleton of every construction project and they set the pace to other downstream architectural and MEP activities. Hence, ensuring a continuous and on-time execution of structural framing is essential to keep the project on schedule. Assuming adequate availability of labor and material, the choice of formwork systems (e.g., the climbing technique) directly affects the progress of concrete works, and greatly influences the interlocking workflows of walls, shafts, and slabs where several tasks from different trades are involved. For instance, crane-lifted formwork used for core wall erection can congest the crane schedule and consequently delay the delivery of materials to other site zones. Whereas, self-climbing formwork release the crane schedule and can be reused for other critical activities. Another important factor that affects the progress of work is the resulting quality of cured concrete. Concrete repair consumes a significant amount of time and affects the speed and quality of finishing works that follow. In this regard, the quality of formwork system and the tolerance range it can provide is essential to ensure a smooth progress of work from one phase to another, and from one trade to another. Nonetheless, smaller tolerance ranges allow the incorporation of prefabrication and remote assembly that can boost construction speed.

1.4 Formwork Selection Parameters

Construction of high-rise buildings requires innovative formwork system technologies to overcome the limitations of space, budget, and time. However, many parameters affect the choice of formwork systems and are mainly divided into internal and external parameters as shown in Table 1 (Gnida, 2010). While internal parameters fall under designers and contractors control, external ones are affected by owner requirements, project milestones, project location, and corresponding local rules and regulations.
Table 1: Internal and external parameters governing the selection of formwork system (Gnida, 2010)

<table>
<thead>
<tr>
<th>Internal Parameters</th>
<th>External Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>Space</td>
</tr>
<tr>
<td>• Repetitive</td>
<td>• Constraint of Existing Road or Building</td>
</tr>
<tr>
<td>• Simple/complex</td>
<td>• Storage Area</td>
</tr>
<tr>
<td>• Changing Geometry</td>
<td>• Assembly Area</td>
</tr>
<tr>
<td>Concrete</td>
<td>Wind</td>
</tr>
<tr>
<td>• Rate of Pouring/Concrete Pressure</td>
<td>• Wind Load</td>
</tr>
<tr>
<td>• Concrete Finish</td>
<td></td>
</tr>
<tr>
<td>• Curing Time</td>
<td></td>
</tr>
<tr>
<td>Sequence of Work</td>
<td>Crane</td>
</tr>
<tr>
<td>• Cycle Time</td>
<td>• Capacity</td>
</tr>
<tr>
<td></td>
<td>• Availability</td>
</tr>
<tr>
<td></td>
<td>• Type</td>
</tr>
<tr>
<td></td>
<td>• Boom Reach</td>
</tr>
<tr>
<td>Formwork Choice</td>
<td>Safety</td>
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<tr>
<td>• Existing Formwork Material to be</td>
<td>• Special Requirements Needed</td>
</tr>
<tr>
<td>Reused</td>
<td></td>
</tr>
<tr>
<td>• Rental or Purchase</td>
<td></td>
</tr>
<tr>
<td>• Best Value for Current Project vs.</td>
<td></td>
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<tr>
<td>Flexibility for Future Projects</td>
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<tr>
<td>Construction Planning</td>
<td>Milestones</td>
</tr>
<tr>
<td></td>
<td>• Working Schedule/Shifts</td>
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<td></td>
<td>• Project Duration</td>
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<td></td>
<td>• Holidays</td>
</tr>
<tr>
<td>Local Rules and Regulations</td>
<td>Permits</td>
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<tr>
<td></td>
<td>• Restricted Noise</td>
</tr>
<tr>
<td></td>
<td>• Safety Requirements</td>
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</tbody>
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To account for these parameters, many contributions were made to improve the efficiency of formwork systems resulting in several types. Choosing the appropriate type of formwork depends on many factors including cost, time, quality, and safety. An overview of these types is summarized in Table 2. Other studies linked the selection of the formwork system to building height and weather conditions (Ciribini and Tramajoni, 2010). Figure 1 presents appropriate formwork options according to three height ranges in the case of good or bad weather conditions.

![Formwork choice diagram](image)

Figure 1: Formwork choice according to building height and weather conditions (Ciribini and Tramajoni, 2010)
Table 2: Formwork classification (Classification of Formwork, N.d.)

<table>
<thead>
<tr>
<th>Classification Category</th>
<th>Details</th>
</tr>
</thead>
</table>
| **Size**                | • Small-Sized: operated manually  
                          | • Large-Sized: crane facilities are required in the operation, or self-climbing |
| **System vs. Location of Use** | • Traditional timber form /Aluminum form: irregular frame structure  
                                   | • Gang form /Climb form /Jump form: core wall  
                                   | • Table form: slabs  
                                   | • Tunnel form: repeated regular section |
| **Construction Materials** | Timber:  
             | • Adaptable to complex shape.  
             | • Labor intensive  
             | • Environmentally unfriendly  
             | • Low initial cost  
             | • Most popular  
             | Steel:  
             | • Sections: Hot rolled or Cold formed  
             | • Heavy weight  
             | • Suitable for large-sized panels  
             | Aluminum:  
             | • Stiff and light weight  
             | • Excellent finish  
             | • High material and labor cost |
| **Nature of Operation** | • Manually Operated  
             | • Self-Lifted  
             | • Crane-Lifted  
             | • Gantry/Traveling/ Tunnel Type Systems |

1.5 Formwork Safety and Work Environment

Safety is a major challenge in every construction project especially in high-rise construction. Labor falls from heights are considered to be the major cause of accidents encountered and the most serious ones (Hinze and Russel, 1995; Huang and Hinze, 2003). Different studies targeted the work environment and investigated different safety procedures (Mohamed, 2002; Cecen and Sertyesilisik, 2013), and researchers as well as industry leaders are continuously developing tools and methods to enhance safety standards. Work environment is also affected by other factors that contribute to labor productivity and construction progress. Noise, for instance, is a major contributor to work stress and fatigue. Noise is created by the use of machines, equipment, and space congestion and can cause hearing problems for workers on site (Barkokébas et al., 2012). Methods to reduce noise were suggested by Barkokébas et al., and techniques can be inspired by their study in order to control noise production and transmission. Height is also considered as an additional risk in high-rise construction. Height changes affect workers’ perception of danger and could disturb their response in hazardous situations (Hsu et al., 2008). In this regard, safety measures were incorporated into the design of formwork systems in order to enhance the safety on site.

To respond to the limitations of formwork selection procedures that consider the optimization of concrete works in isolation, this paper presents a comprehensive analysis of advanced and regular formwork technologies and highlights their role in shaping the progress of concrete and non-concrete activities. Addressing the role of formwork systems in leading construction workflows in high-rise projects is a novel approach that allows researchers and practitioners to link the choice of formwork system to construction workflows on one hand, and to logistics planning, inventory dynamics, crane schedule, labor and material delivery and safety procedures on the other. The following sections examine advanced and regular formwork technologies, link the formwork choice to activities sequence, and investigate major related differences.
2 METHODOLOGY

The paper compares advanced and regular formwork systems to underline major differences, and employs a process model to describe construction activities and their interdependent relations in both cases. It also examines the resulting differences in construction sequence and flow from a scheduling perspective, to finally highlight the major enhancement the advanced systems present on inventory size and dynamics, crane availability for non-concrete activities and labor and material delivery to work zones.

![Research methodology diagram](image)

Figure 2: Research methodology

3 FRAMEWORK DEVELOPMENT

3.1 Advanced and Regular Formwork Comparison

3.1.1 Core wall Formwork

Advanced as most regular core wall formwork technologies used are self-climbing systems, lifted using hydraulic jacking mechanisms independent of any external crane or lifting equipment, and are available as single or double jump formwork assemblies (Figure 3). As the name implies, the double jump system jumps two floors at a time leading to significant reduction of cycle time; the work to be done is halved. For instance, steel fixing activities have to be done only once every two floors, and the same concept applies to concrete pouring as two consecutive floors are poured together. Other time-consuming activities such as surveying operations, formwork alignment, and reinforcement inspections are also optimized to boost core wall construction speed. Therefore, as the number of cycles is largely decreased, the construction time undergoes substantial drops. Moreover, the single jump system has also been proven to reduce the cycle time to three or four days per floor (Naylor, 2006) considering that the formwork is totally isolated from external weather conditions by cladded screens and a top deck free from mass constraints. This provides workers with a safe and adequate working environment.

![Advanced core wall formwork](image)

Figure 3: Advanced core wall formwork (Double-Jump System, n.d.)

In addition to time savings, the advanced core wall system also impacts cost savings. By merging two floors into one cycle, or one concrete pour, steel reinforcement splicing (or coupling) will only be done on every second floor. Thus, the number of splices (or couplers) is reduced which implies key cost savings on material. Furthermore, the advanced system ensures that building service elevators are made operational as early as possible. In this regard, lifts of the building are used to transfer material and labor
early on during the execution phase, thus decreasing demand on external hoists and tower cranes and boosting production (Glasby, 2009).

### 3.1.2 Floor Formwork

The selection of horizontal formwork is governed by several parameters as mentioned in Table 1. Yet, practitioners try to benefit from the repetitive nature of slab construction by standardizing formwork size and material and maximizing the number of formwork reuse. In this context, table forms are widely used on high-rise projects to decrease formwork setup time and slab cycle time to match that of core walls. However, regular table forms are crane dependent and obstruct the crane schedule every time they are moved from one floor to another.

Advanced formwork technologies provide innovative perimeter systems which combine construction and safety screens requirements. A self-climbing system is used to form vertical elements such as columns and walls independent of floor slab construction. The system jacking points are above floor slab giving clear access for slab formwork, reinforcement, and pouring below the system. The key advantage of the perimeter system is the accelerated construction of columns and slabs that progress independently. The system can also provide lifting services to move slab table forms internally without any use of tower cranes which are consequently released for other critical activities resulting in a faster overall construction process. Figure 4 shows the perimeter system where the columns are two floors ahead of slab construction, and pouring activities are taking place below the system's platform.

![Figure 4: Advanced self-climbing perimeter system (Double-Jump System, n.d.)](image)

### 3.2 Construction Process Mapping

To examine the role of formwork in shaping construction workflows, two process maps, depicted in Figures 6 and 7, were developed to trace the differences in construction sequence between advanced and regular formwork systems. The trailing platform hanging from the advanced core wall formwork (Figure 5) allows internal lift specialists to start fixing lift rails and necessary accessories early on in the project, thus undergoing the same cycle as the core wall cycle. Whereas, elevator related tasks would not start until finishing core wall construction in the case of regular forms. Accordingly, service elevators can be made functional before final core wall erection and can be used to hoist labor and material for finishing crews.

![Figure 5: Schematic Representation of the Attached Trailing Platform](image)
Figure 6: Construction Process Map Using Advanced Formwork Systems

On the other hand, the advanced perimeter system allows columns and slabs to progress independently, with defined Start to Start and Finish to Finish lag times to allow for the system to be assembled and disassembled as presented in Figure 6. Using regular formwork, floor construction follows successive cycles of columns erection and slab construction with a Finish to Start relation as shown in Figure 7.

Figure 7: Construction Process Map Using Regular Formwork Systems
3.3 Schedule Optimization and Workflow Improvements

Advanced formwork systems allow project managers to optimize the project schedule. The trailing platform plays a major role in opening downstream work early in the project and benefitting from the available core wall shaft areas which are usually wasted work spaces in regular formwork technologies as conveyed through Figure 9. The early engagement of elevator crews reduces corresponding material batches where required accessories can be delivered to site on demand without storing large inventories. On the other hand, the independent progress of columns and slabs helps streamline both activities together and reduce the risk of one process delaying the other as is the case of using regular formwork. It also boosts production of both activities due to learning curve effects. Higher availability of tower crane for non-concrete activities when using advanced systems, along with making building service elevators functional at core mid-height, can increase material and labor delivery rates to work zones, thus increasing production rates of non-concrete activities as presented Figure 8. Nonetheless, core wall labors could be relocated to other activities once the core wall is erected, therefore decreasing total labor costs and allowing for more flexibility in resource allocation.

Figure 8: Schematic LOB Schedule Using Advanced Formwork

Figure 9: Schematic LOB Schedule Using Regular Formwork
4 DISCUSSION AND CONCLUSION

Formwork systems play a vital role in leading high-rise construction, and technological advancements are pushing the limits of formwork industry to new perspectives allowing it to surpass traditional constructability constraints. The role of formwork systems in high-rise projects goes beyond erecting concrete elements to set the pace of construction processes at different fronts. Innovative features provided by advanced formwork technologies play a major role in streamlining concrete and non-concrete activities where downstream tasks are more sensitive to formwork pace. For example, this applies to the case of elevator related activities that undergo the same core wall cycle and to column and slab-related activities that follow the advanced perimeter pace. Advanced systems also impact logistics planning as faster labor and material delivery rates are achievable due to crane schedule release and the use of building service elevators early on in the project. Faster material delivery is an important step towards decreasing material batch sizes, where required material can be smoothly delivered to work areas based on site demand instead of having large inventories in laydown areas which may not always be available.

Advanced formwork systems provide innovative solutions for today’s complex high-rise developments, and open the doors for greater improvements in construction methods. Future studies can link the use of advanced systems to the implementation of lean ideals on high-rise projects, such as waste reduction, Takt time calculation, and the use of pull systems and Kanban cards.

References

