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A Method for Choosing Concrete Forming Systems

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Abstract: Formwork systems, as the essential part of any concrete, have paralleled the improvement of concrete technology in the past decades. There is valuable information regarding the design within the context of a particular formwork system, but there is little guidance available on methods for choosing forming systems for an application. This paper describes the main types of the formwork systems that are widely available, considers their applications and advantages, and compares these systems within system perspective. Then it presents a basic method for deciding which forming system to use. Results of this study can be used as a decision making tool for the forming system selection to improve supply chain processes.

1 INTRODUCTION AND BACKGROUND

This section provides an overview on materials, methods, and techniques associated with concrete formwork. A forming system is a set of components designed to give shape and control to poured wet concrete in order to achieve the exact figure needed for the cured concrete. Concrete, the second largest commodity product in the world after water, has gone through significant changes in past decades and continues to develop. In many of today's civil works and construction projects, the predominant material employed is concrete. Concrete is also the most used man-made material in the world (Lomborg 2001). Just as concrete has advanced, so have concrete forming systems, and it is important that methods for selecting proper forming systems are available.

Due to the semi-liquid state that freshly mixed concrete acquires, it is incapable of retaining a solid shape. In order to elicit the distinctive building properties of concrete it is moulded by a formwork, also referred to as a shutter (Hurd 2005). According to Ilinoiu (2003), the basic components of a formwork system are the form panel - comprised of panel sheathing and panel frame, shoring members, and form accessories. Stick-built forms can be constructed onsite by workers or carpenters out of timber and plywood or moisture-resistant particleboard. Modular formwork, also known as prefab formwork or an engineered formwork system, is assembled from prefabricated modules. These modules often consist of steel, aluminum, pressure treated timber, or, in recent years, fibre reinforced polymer (FRP) and reusable plastic. Stick-built and modular formwork are often removed once the concrete is hardened, thus they do not contribute to the final structure afterward. Some formworks can be part of the finished structure aside from being a mould for concrete. They are often categorized into two groups: insulating concrete formwork and stay-in-place structural formwork systems. Insulating formwork, commonly made out of polystyrene foam, can provide support for wet concrete and insulation when the structure is finished.

Stay-in-place forms are usually prefabricated FRP hollow tubes which remain with the poured concrete to provide axial and shear reinforcement, as well as protection from adverse environmental effects.

According to Richardson (1977), a successful formwork must: "1) act as a temporary or permanent mould which controls the position and alignment of the concrete, 2) contain the complete mix without leakage or distortion caused by concrete pressures, construction loads and external forces, 3) provide the intended number of re-uses while maintaining a satisfactory standard of accuracy and surface finish, 4) be removed from the concrete without sustaining damage, 5) generate the critical geometry and face profile with the minimum amount of further labour being required to achieved the specified finish, 6) be capable of being worked by available labour and handled by the equipment available on site, 7) [and] where manufactured on site, the manufacture must be within the capability of those employed." According to Hurd (2005), other than miscalculations, there can be other reasons for formwork failure such as: "improper stripping and shore removal, inadequate bracing, vibration, unstable soil under mudsills, shoring not plumb, inadequate control of concrete placement, when formwork is not at fault (failure caused by other structural member), and lack of attention to formwork details"

Figure 1 provides the ontology for various formwork systems within methods and their components, and also illustrates some principles for this research. This paper identifies nine types of forming methods and systems. These methods are categorized by their method of application and type of material and equipment required. The following sections begin with a description of the existing construction practices and then recommend ways to best take advantage of the different formwork systems within a project's specifications, location, lifecycle, and so forth.

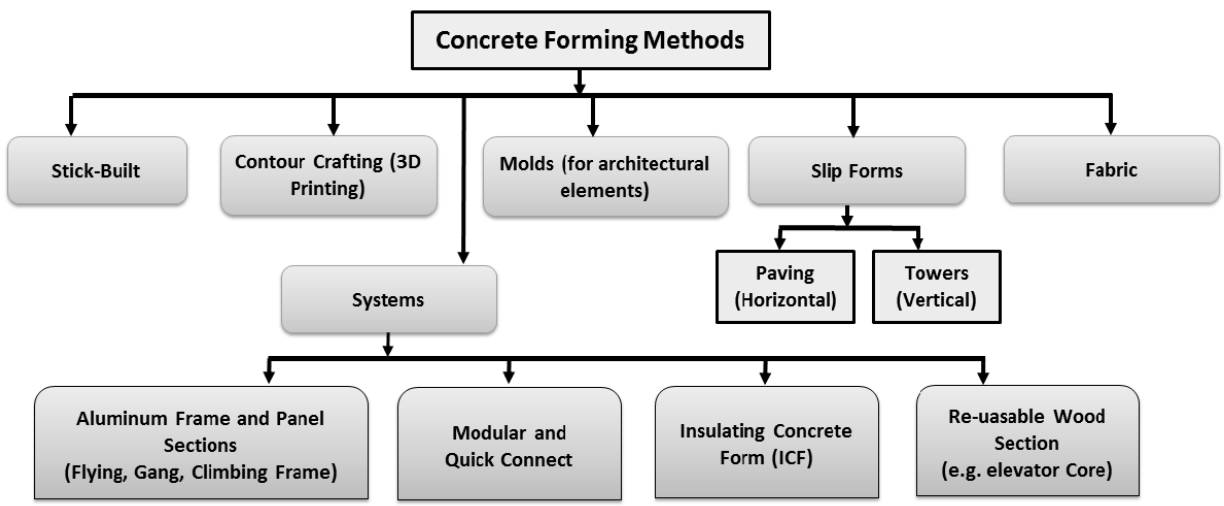


Figure 1: Concrete formwork systems

2 IMPACT OF PROJECT ON SELECTION OF FORMING METHODS

Formwork is an essential part of concrete equipment and is directly controlled by equipment management, supply chain management, and the work packaging system. Since all of these areas are overseen by project management, it is safe to say that formwork selection is indirectly related to project management (Figure 2). The impacts of project management consideration on the selection of forming systems can be summarized as follows; 1) availability of off-the-shelf, engineered, and bulk materials, 2) costs of ordering, stockpiling, managing, waste, transporting, re-using, etc. all of these materials, 3) degree of off-site versus on-site fabrication, 4) degree of re-use and cycling on-site, 5) training and skill requirements, 6) labor productivity associated with each system, 7) risks of sole-sourcing systems or materials, 8) opportunity for 3D BIM modeling and planning for formwork itself and the control this implies, 9) opportunity presented by different forming approaches for implementing lean construction principles, 10) finish quality created, and 11) acceptability within local design codes.

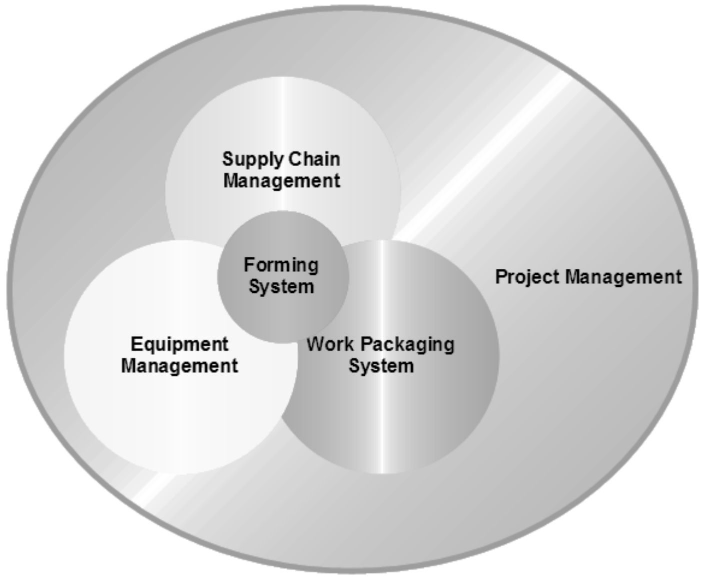


Figure 2: Relationship of formwork, project management, supply chain management, equipment management and work packaging system

Equipment management is the process of monitoring, controlling, and improving the usage of formworks in construction projects by managing the inventory and maintenance of formwork materials and equipment in order to minimize, repair, and replacement costs. Christopher (1992) defines supply chain management (SCM) as "the network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer." According to Vrijhoef and Koskela (1999), "The principle roles of SCM are covered by the generic SCM methodology. The SCM offers general guidelines that can be used to analyze, reengineer, properly coordinate, and constantly improve virtually the complete formwork supply chain, resolving basic problems and the myopic control that have been plaguing the supply chain." A research team constituted by the Construction Industry Institute (1988) has recommended breaking projects down into manageable work packages in their report "Work Packaging for Project Control" and defined a work package as "a well-defined scope of work that terminates in a deliverable product(s) or completion of a service." By creating independent sub systems, each with their own constraints, schedule and goals, WPS allows the smallest aspect of a mega project to be managed independently.

The end goals are to minimize the cost risk and time required while increasing earned values of the project. In recent years, project management has utilized the work packaging system to monitor and gain better control the work flow (CII 2011). Research has been done on formwork selection methods but most of it concentrates on specific areas of construction projects and uses the case method extensively. For example, Shin et al. (2012) presented a model for form work selection based on boosted decision trees (BDTs) to assist decision makers in choosing a formwork method appropriate for tall building construction. Contradictorily, this research intends to provide a model for broad scope of construction projects.

3 FORMING SYSTEMS

After a brief introduction to the formwork systems, the different types of concrete forming systems are discussed in this section. Based on the historic overview, a new definition and taxonomy has been suggested to encompass all existing types of formwork systems. In general, the initial developments of formwork systems were motivated by a desire to reduce construction time and costs. Over the selection of a form work system, time is a critical factor including, time to set rebar and inserts within the form, stripping time, close-in time, and final disassembly time. Correspondingly, the amount of labor required for stripping, setting, pouring, and controlling the system; the amount of precision needed as far as plumbness and corner tolerances, ease of lifting, and the designer's intent should be considered as the important factors. (Hanna, 1999)

A different classification of formwork systems should be initially considered for selecting the best formwork system. A formwork can often be classified in accordance with its: size, material of fabrication, and method of assembly. It is also possible to categorize a formwork based on its intended usage, manufacturer, or workability. Because it is easier for construction practitioners to identify a formwork by reference to its size, material, and assembling technique, this method of selection is a more popular choice. In general, there are three main types of formwork systems: stick-built, modular, and prefab-custom units. These forming systems are summarized in the following sub-sections.

3.1 Stick Built Formwork

Formworks that are constructed on site by workers using available tools (such as: hammer, tape, circular saw, spirit level, etc.) are called stick-built formwork and often comprise of dimension lumbers, plywood panels, bolts, steel or aluminum bracing and angles, and nails. It is built in place for small beams, irregularly shaped slabs, or complex concrete details and anywhere else that the design of the structure is such that prefabricated panels cannot be adapted to the shape. It is also used when the formwork is built in place, used once and wrecked and the use of prefabricated panels cannot be economically justified (Ilinoiu, 2003).

Stick-built formwork is also known as the traditional formwork system. It has been in use for concrete construction since Roman times, though its usage has decreased slightly over the years in larger construction projects due to standardization of construction practices and increased usage of pre-cast members. The most common material in stick form, also known as ''traditional'' formwork is timber. It is used as bearers in soffit forms and as waling in wall forms. Timber has the advantage over all other materials because it can be easily cut, handled, and assembled on site, but it may not be the most economical option if a high finishing quality is required and a high degree of repetition is involved, In these cases the advantages of the metal and plastic forming types prevail (Peurifoy 2006; Brett 1988; Hanna 1995). Most materials used in stick-built formwork cannot be recovered after the construction project, thus the only method of financing is a one-time purchase. A high concentration of workmen and tools on site is often representative of the built in placed nature of stick form.

A special case of stick-built formwork is permanent formwork. In certain circumstances, formwork is left permanently in place because of the difficulty and cost of removing it once the concrete has been cast. Other times, it is used as both formwork and outer cladding especially in the construction of in-situ reinforced concrete walls. The external face or cladding is supported by the conventional internal face formwork that can, in certain circumstances, overcome the external support problems often encountered. "This method is, however, generally limited to thin small modular facing materials" (insulating board, gypsum board, precast stone or concrete), the size of which is governed by the supporting capacity of the internal formwork" (Ilinoiu 2003).

3.2 Modular Formwork

Modular formwork systems represent a new method of formwork construction. This forming system is becoming popular in large scale construction projects. Modular formwork requires less skilled labor when compared to traditional methods of formwork construction, allows for faster erection as well as stripping, and has a much longer expected lifecycle usage rate. Modular formwork systems are also versatile and have the ability to fast-track projects when standardized members are used, such as in high-rise construction projects. Modular formwork systems have evolved to help meet the demands of the construction companies and their clients by improving supply chain processes.

Modular forms are manufactured from more durable materials than those used in stick forms. The materials include, but are not restricted to: steel, aluminum (alloys 6061-T6 and 6063-T6), plywood, fibre, and composite. Modular forms comprise of: panel, pan and domes, void and duct, column (often made of FRP to be used once), stay-in-place forms, and special purpose/custom-made forms. Unlike stick formwork systems, modification to modular forms cannot be done on site and are not easily modified without damaging their structural integrity. Traditional wall formwork (panel form) consists of standard sized (600 – 1200 mm width X 600 – 2400 mm height) steel-framed panels tied together over their backs with horizontal members called wales that provide resistance to the horizontal pressure of fresh concrete. Their main advantage is that they are can be reused many times at a convenient cost. "Their flexibility in financing means that the forms may be purchased, rented or sometimes rented with an option to purchase" (Hurd 2005). As a result, modular forms have seen increasing use on construction projects in both Canada and the United State in efforts of saving material and labour costs through the efficiency of mass production.

3.3 Prefabricated Custom Formwork

Another type of formwork system is the prefab-custom unit. This system is classed between stick-built and modular formwork systems. Prefabricated formwork is often labeled as modular formwork which is made with the help of heavy machinery in a factory setting and can be assembled on-site to create the desired mould for concrete. This combination system can be used in many different kinds of projects and is usually prepared for specific usages. The prefab-custom unit system includes both modular and stick-built elements that may be used for elevator shafts, spillways, etc. However, the elements of the prefab-custom unit system may be deformed during operation and also may be hard to maneuver in terms of safety, where the elements become large.

Examples (subcategories) of the mentioned main pre-fab formwork systems, based on their characteristics, include euro-form, gang form, flying form (table form), climbing form, slip form, tunnel form, and traveling form. A euro-form is a modular form, mainly used when the building plan is standardized. Gang-forms are enlarged, but simplified forms for walls assembled with lumber and STD framing, and dismantled. A flying-form is a floor form, with a form board, a joist, a beam-joist, and a support manufactured and built up as one unit. A Climbing-form is a form for wall finishes work that is fabricated as one unit, lifted at a time, and installed. Slip-forms are vertically, horizontally and continuously structured, without construction joists, and are applied by moving the form continuously as concrete is poured and cured. The traveling form method of construction is based on reusable forms mounted on movable frames or scaffolding called travelers.

3.4 ICF forming system

This section provides an overview of the insulating concrete form (ICF). ICF or PIF (permanently insulated formwork) has grown over recent years. If it is observed visually, structures constructed using ICF can be indistinguishable from conventional concrete ones (Figure 3).

Figure 3: Polystyrene foam formwork block (Waterloo, 2011)

In residential construction, recent years have seen the rise in insulating concrete form application. This formwork system allows the insulation to be built into the walls as part of the structure. According to the United States Department of Energy (2011), it can create walls that have a high thermal resistance, with R-values typically above R-17. Besides its insulating capability, ICFs have proved to be an excellent sound proofing material and reduce HVAC operating cost. The foam modules are dry-stacked, fastened together using plastic ties, added with rebar, and filled with concrete. The construction process is relatively easy to learn and follow because of the lightweight and highly modifiable natures of the system. Similar to stay-in-place FRP formwork, ICF protects the concrete from adverse environmental effects and physical damages and adds some structural support. "There are three basic types of ICF systems that use either foam board or foam blocks. A flat system yields a continuous thickness of concrete, like a conventionally poured wall. A grid system creates walls using a waffle pattern—the concrete is thicker at some points than others. A post-and-beam system consists of discrete horizontal and vertical columns of concrete, which are completely encapsulated in foam insulation" (DOE 2011).

4 DECISION METHOD

The decision making model helps to make good judgments. The proposed model gives a structured and effective pattern for selecting the best formwork system for a specific construction project. The following nine steps fit all the parts of making a decision together.

1) Define application (design, performance, specification, etc.)
    - e.g. for concrete paving slip form, stick-built, and pre-assembly (pre-cast)
    - e.g. for small office building structure, foam block, and modular are appropriate
2) Identify technically feasible forming methods for application
    - e.g. foam lock system precluded because of unavailability of appropriately trained labor
    - e.g. prevalent design shapes unavailable in modular systems so modular precluded
    - e.g. required contracting of re-bar assembly, formwork, and concrete placement to different subcontractors precludes lean-construction balancing of flow thus making modular cycling low thus precluding modular approach.
    - e.g. labor is scarce, so stick-built is too slow to meet schedule constrains and thus is precluded
    - Review technically feasible options using project conditions checklist for identification of precluding conditions
    - Select appropriate cost model for each forming system that is still technically feasible and not precluded due to project conditions
    - Gather local cost and labor productivity data
    - Divide concrete work into appropriate packages
    - Conduct total cost comparisons using each forming cost model and system for each work package
    - Iterate through steps 7 and 8 using appropriate work package variations
    - Choose combination of work packages and their associated forming systems which results in least total project cost (a manual or automated optimization)
3) Review technically feasible options using project conditions checklist for identification of precluding conditions
4) Select appropriate cost model for each forming system that is still technically feasible and not precluded due to project conditions
5) Gather local cost and labor productivity data
6) Divide concrete work into appropriate packages
7) Conduct total cost comparisons using each forming cost model and system for each work package
8) Iterate through steps 7 and 8 using appropriate work package variations
9) Choose combination of work packages and their associated forming systems which results in least total project cost (a manual or automated optimization)

Thenceforward, the example of application of the decision model is discussed.

5 ANALYSIS

This section addresses an archetypical problem of deciding between modular versus stick-built forming systems for building construction. Then it describes and explicates why there is a growth in using insulated concrete forming systems. In theory, stick-built and modular formworks can be used interchangeably for any concrete structures in a construction project. However, in practice, due to their unique advantages and disadvantages, as well as different production times and costs, great consideration is always taken in choosing the most suitable option to optimize the project outcome. In developed countries, such as Canada and the United States, the trend today is toward increasing the use of modular forms, assembly in large units, erection by mechanical means, and continuing reuse of the forms (Hurd 2005). In other parts of the world where the labour cost is relatively low, stick form still dominates the construction scene.

Some national building codes allow the reuse of lumber and plywood in stick form. The number of times of reemployment is specified differently from one country to another. For example, Taiwan often uses wooden formwork systems in reinforced concrete construction. Seven days after the pouring of reinforced concrete, the wooden formwork can be torn apart. The wooden formwork can be used approximately three to five times. The number of usages and the quality are mainly affected by three factors, working attitudes, efficiency, and stripping process (Ling 2000).

The use of modular formwork in construction has a number of benefits over traditional or stick built formwork systems in large-scale construction projects. The benefits include, but are not limited to the following: 1) the erection time is usually shortened; 2) standardized and simple installation procedures require less skilled labor; 3) the prefabricated form sets can be reused multiple times within and between projects, improving cost-effectiveness; 4) the higher strength of the form should allow for faster pouring tasks; and 5) the smooth surface of a modular form reduces the need for additional finishing work after the form stripping. In general, modular formwork can be favored in some circumstances which are outlined in Table 1 and 2, which compare the advantages and disadvantages of modular and stick-built formwork.

Table 1 - The Pros and Cons of Using Modular Formwork

	Pros	**Cons**
Formwork Assembly	Formwork is quickly and easily constructed and stripped, especially when there are standardized members or sections	Smaller projects may not benefit greatly from the faster assembly of modular formwork systems
Materials Required	Prefabricated components are procured from a supplier. Components are typically fabricated from aluminum and plastic	Prefabricated components have high initial costs and smaller projects cannot typically justify these costs
Erection Time	Formwork is quickly assembled and can allow for a dramatic reduction in formwork build-up time	Erection time can be lengthened for complex formwork and if construction is done in tight spaces
Labor requirements	Less skilled labor is required	-
Lifecycle of Formwork	Formwork systems can be re-used between 40-100 times, depending on materials, jobsite, climate, usage, etc.	In smaller projects, limited ability to reach a system's expected lifecycle unless a contractor uses the same system on various projects
Finished Surface	The resulting finished surface is smooth, flat, and generally free of imperfections, reducing additional labor to fix	Difficult to allow for architecturally designed surfaces, without additional formwork systems or stick built formwork additions.

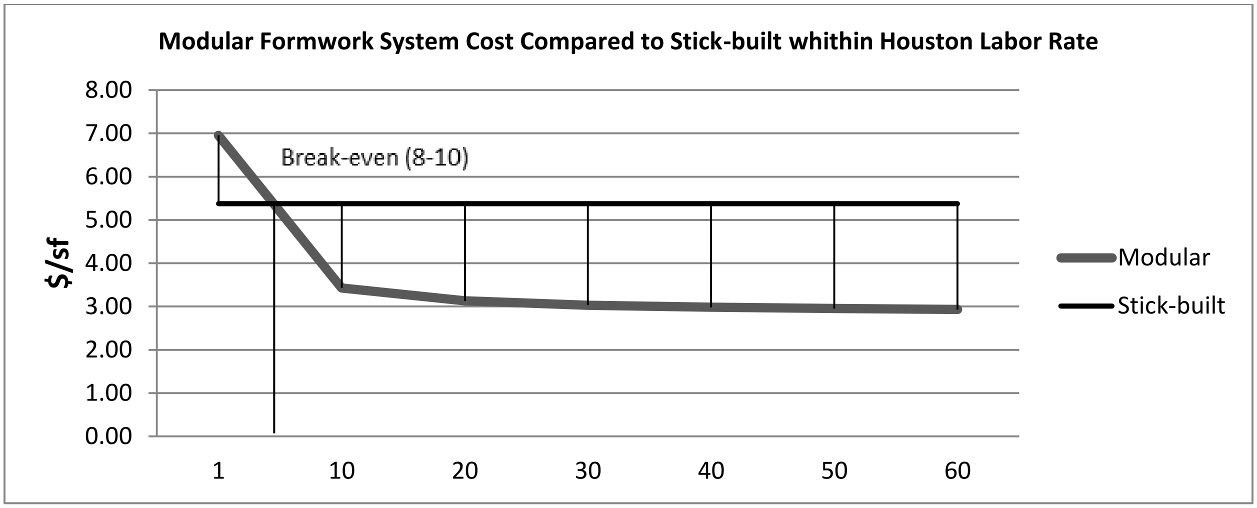
Table 2 - The Pros and Cons of Using Stick-Built Formwork

	Pros	Cons
Formwork Construction	Can be quickly constructed for smaller projects by a small crew. Assembly can be done in tight spaces.	As projects get larger, the amount of labor and time required to build the required formwork systems increases substantially.
Materials Required	Only basic materials are required for formwork construction, which are readily available and inexpensive to procure	Potential for wasted material and increased costs for procurement on larger projects
Erection Time	Can be quickly assembled for smaller projects, repairs, and detailed concrete placing	The total erection time can be substantially higher, potentially delaying the project.
Labor requirements	Smaller projects require only a small, specialized crew of carpenters.	High skilled labor requirements for specialized work on larger projects.
Lifecycle of Formwork	Low procurement and disposal costs.	Formwork can generally be used 4-8 times
Finished Surface	Formwork can allow for complex geometry, architectural details, and unique/non-standardized design elements	Surface may be rough due to poor construction or quality of materials, and additional labor is often required to fix imperfections. Also natural feature of wood must be considered

Modular formwork can be favoured in large-scale construction processes, such as high-rise construction, where there is a high degree of standardization and/or repetition in the construction of the facility. It is also favourable where a shortage of high-skilled labor to build more complex formwork systems exists, as only basic labor requirements are necessary to set up modular formwork systems, where fast-tracking of a project is required and there is limited time available to build formwork systems, and where environmental incentives for reduced waste or re-use of construction equipment are present. However, the use of modular formwork is unfavorable when the construction project is small in size, or there is a high amount of customization and specialized or detail design. Moreover, when a limited amount of space is available for mobilization of equipment, modular formwork can be a challenge.

Making the decision to choose the best formwork option clearly depends on the characteristics of the project. A RT-252 member provided general information (Feb, 2011) that could be a good basis for understanding selection of formwork systems. Figure 4 shows a total installation costs of using modular formwork systems in comparison to stick built for the Houston and Chicago labor markets. In Figure 4, a high-rise building consisting of 60 stories of office space (50,000 sf per story) is considered. The figure shows slab formwork costs for a modular system compared to a stick-built system in Houston and Chicago. The breakeven point indicates the number of stories at which the total cost for both the modular and stick-built methods are equal. The plots show that as the number of stories increases, the total formwork cost of using the modular option reduces substantially. For example, a project in Houston where the number of stories is between 8 and 10 stories, using a modular formwork system is the best option. A project located in Chicago, where the number of stories is either 4 or 5, yields greater savings by using modular (the labor rate in Chicago approximately is twice as Houston). In mega-projects, the savings are more significant compared to a typical project such as the example above. As the plots indicate the labor rates will affect the project cost and therefore the formwork system type used. Also, in small projects, the stick-built system should be utilized since the labor savings of the modular system do not outweigh the much higher material costs. When modular formwork is owned sometimes it will be used regardless.

The effects of labor rates and the cost of different formworks are generally discussed above, although a number of factors are involved in this decision making process. The formwork selection criteria include, but are not limited to: specification of concrete (quality), number of cycles, degree of repetition, speed of production, relative costs (such as maintenance), building form and location, on-site inventory and transport system, availability of labor, and availability of plant and equipment .



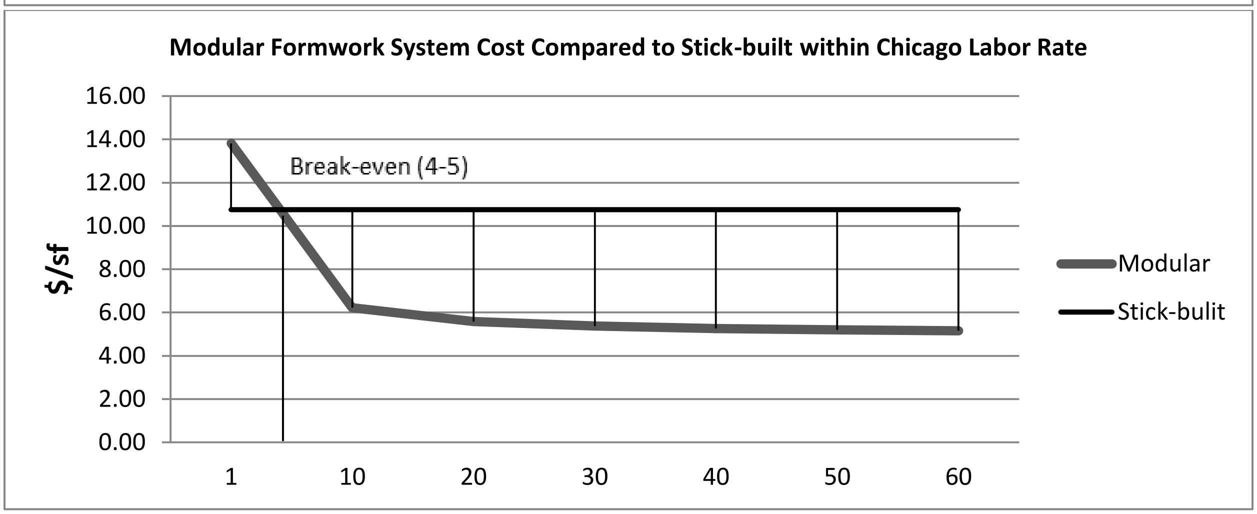


Figure 4: Project ($/sf) of the Slab Formwork System versus Number of Cycles

ICFs provide formwork for concrete in a different way than other forming systems by remaining as part of the final product. This characteristic allows ICFs to possess some unique characteristics. The advantages and disadvantages of ICFs are outlined in Table 4.

Table 4 - The Pros and Cons of Using Insulated Concrete Formwork

	Pros	**Cons**
Formwork Assembly	The lightweight formwork is easily portable and no stripping of the formwork is required	Each proprietary system may be slightly different to construct.
Materials Required	Forming materials are prefabricated and are composed of lightweight foam and plastics.	Material stock is critical because there is no reuse.
Erection Time	Allows for quick assembly of smaller and complicated projects.	May result in longer erection times than other systems for large areas.
Labor requirements	The entire system can be constructed by a small team of unskilled labour.	A learning curve for the installation of each system is expected.
Lifecycle of Formwork	The formwork remains in place as part of the wall insulation system.	This forming system only allows for a one time use.
Finished Surface	The insulation system for the concrete is incorporated into the wall, which eliminates further insulation work.	Since the formwork remains in place, the finish surface is the foam or plastic finish of the formwork itself.

Insulated concrete formwork has seen a dramatic increase in popularity over the last few decades since its inception in the early 1970s. Insulated concrete forms were widely used as a method of residential subgrade concrete installation due to the insulation and moisture resistance properties it can offer. However, the system began to replace wooden framing for residential superstructure as an energy efficient and more structurally resilient alternative. This caused an increase in its use among low rise commercial construction, which eventually spread into other areas of construction (Lyman, 2007). As a result, ICFs have become an economically justifiable alternative to other forming methods due to an increase in producers and available technologies that has increased competition and reduced costs.

6 CONCLUSION AND RECOMMENDATIONS

The proper selection for a formwork system is crucial to the success of a construction project's completion. The selected formwork system can significantly influence the project's cost and duration. This research provides a decision model based on the advantages and disadvantages of the newest formwork systems versus traditional systems to help decision makers. The nature of the project also plays a major role in the selection process. Ultimately, this decision depends on the experts' assessments based on their years of practical experience. The proposed model is substantially more comprehensive than the other selection methods; however, further research is required.

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