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In recent decades, advances in formwork systems, which represent an essential component of any concrete placement, have paralleled significant improvements in concrete technology. While valuable information about the design of a particular formwork system is readily available, little guidance exists with respect to methods of choosing an appropriate forming system for a specific application. This paper describes applications of the main types of formwork systems and provides details about alternative formwork systems. This study mainly contributes to the development of previously unavailable model for facilitating and validating formwork decisions. A variety of project examples were considered based on field data and information provided by industrial partners. In particular, the emerging predominance of insulated concrete formwork for mid-rise residential structures is examined. The developed system can be used as a high-level decision support tool for the selection of forming systems.

KEYWORDS
formwork system; construction management; supply chain; concrete; modular; stick-built

Introduction and background

Concrete is the world's most commonly used manmade material and the second largest commodity product. Recent decades have seen significant changes in its composition and applications, which continue to develop. Concrete constitutes the predominant material in many of today's civil engineering and construction projects. Paralleling advances in the general use of concrete, the specific area of concrete forming systems has also improved. A forming system supplies the geometry and strength required by plastic concrete in order to achieve the exact form that the structural properties of the concrete must provide once it has cured. It is essential, now that forming systems options have multiplied, that builders understand methods for selecting the appropriate ones. Mainly, this study provides a robust decision model for selecting appropriate formwork systems. The proposed model will potentially enhance and facilitate the decision-making process. The study recommends this model after an iterative process of literature review in which the researchers concentrated on various concrete formwork systems, their applications, and the impact of the project on selection of forming methods. Next the researchers analysed their findings and results, both of which considered data and expert ideas from full-scale construction projects. Finally, the CII team spent more than a year developing a conceptual model and guidelines for the decision-making process in selecting a suitable formwork. This section provides an overview of the materials, methods, and techniques associated with concrete formwork.

In its plastic state, concrete does not yet retain a solid shape. In order to elicit the distinctive building properties of concrete, builders mould it using a formwork (also referred to as a shutter) (Hurd 2005). 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 reuses while maintaining a satisfactory standard of accuracy and surface finish; (4) be removable 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; and (7), where manufactured on-site, the manufacture must be within the capability of those employed.

Recent research has also determined that formwork systems must be sustainable (Jackson 2010). Mohammed

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et al. (2012) showed that the sustainability of the formwork system used significantly impacts that of the entire construction project. The construction industry considers sustainable building a high priority, so this aspect of the forming system becomes highly relevant.

Builders remove the formwork through a process called striking or stripping, during which the concrete cures or becomes sufficiently strong. They use bond preventatives to coat the formwork before placing it in order to ensure that the concrete does not adhere to the formwork as it sets. Typical bond preventives include oils, emulsions, chemical release agents, and waxes. Besides bond preventives, builders can apply various coatings to the form face in order to provide a decorative finish to the off-form concrete surface (CCAA 2006). In commercial and residential construction, builders often remove formworks of small and medium-sized walls and columns the day after concrete placement, while they leave in place formworks of slabs and beams for a minimum of seven days. In high-rise building projects, aluminium shoring systems support the slab formwork, and builders do not remove these until they have begun working on the slab at least three storeys above (Hurd 2005). Because coatings and the removal process are labour-intensive, they encourage the use of stay-in-place methods.

Builders exert two types of loadings onto horizontal formwork; these may be dead loads or live loads. Dead loads include the weight of fresh concrete, reinforcement, and the formwork itself. Live loads include the weight of workers and equipment, so engineers should design the formwork for a live load of no less than 244 kg/m^2 (Sandaker et al. 2011). When concrete is placed in a vertical form, it produces a horizontal pressure on the surface of the forms that is proportional to the density and depth of the concrete in its liquid or plastic state. As the concrete sets, it transitions from a liquid to a solid and generates a corresponding reduction in the horizontal pressure. The maximum lateral pressure produced on the form varies directly with the rate at which the forms are filled with concrete as well as the retarding effect of admixtures, and it varies inversely with the temperature of the concrete (Peurifoy et al. 2010). In order to avoid excessive vertical deflections during placement of concrete, builders must adequately support tall, vertical elements of formwork (if placed in a single lift) with additional tie rods or braces (CCAA 2006). If the engineers underestimate loadings – dead or live – those wrong decisions may cause collapse when the builders place concrete on the formwork. According to Hurd (2005), other than miscalculations, some additional reasons for formwork failure may include improper stripping and shore removal, inadequate bracing, or excessive vibration.

Recently emerging special concrete mixes tend to require specifically designed formworks. The most popular example is SCC (Self Consolidating Concrete), which needs to be placed in a watertight formwork with a higher lateral loading capacity. SCC was originally developed in Japan (Harvey 2009). SCC's unique properties make it an attractive option for usage in congested reinforcement placement areas (Lessard et al. 2003).

According to Ilinoiu (2006), 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, aluminium, pressure treated timber, or, in recent years, fibre reinforced polymer (FRP) and reusable plastic. Stick-built and modular formwork systems are often removed once the concrete is hardened and partially cured; thus they do not contribute to the final structure afterwards. 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. An example of stay-in-place formwork is prefabricated FRP hollow tubes technology which remains with the poured concrete to provide axial and shear reinforcement, as well as protection from adverse environmental effects.

This paper seeks to categorize previously developed forming systems by their method of application and type of material and equipment required in order to provide a method of selection based on these qualities. 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. 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.

Impact of project on selection of forming methods

Expert interviews conducted by Hanna et al. (1992) identified the key factors affecting the selection of

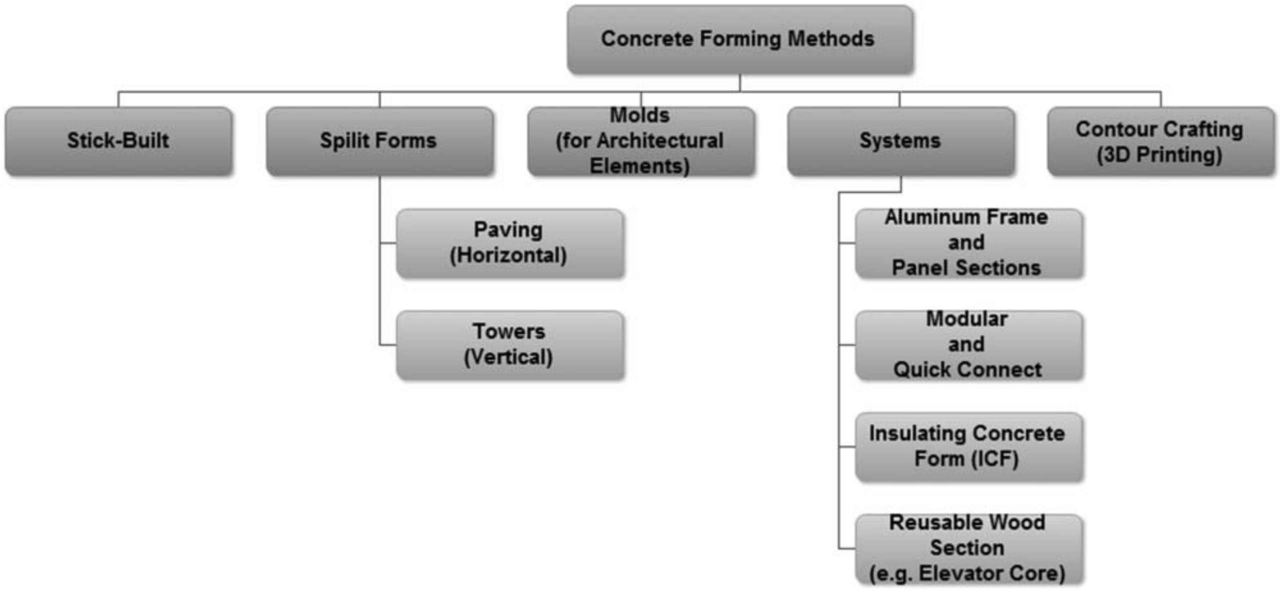

Figure 1. Concrete formwork systems.

forming systems. This research identifies formwork as an essential part of concrete placement equipment that is directly controlled by equipment management, supply chain management, and the work packaging system. The Construction Industry Institute (CII) expanded on those factors identified by Hanna et al. and arrived at the following list (Goodrum et al. 2012):

1. availability of off-the-shelf versus engineered versus bulk materials;
2. costs of ordering, stockpiling, managing, waste, transporting, reusing, etc., and all of these materials;
3. degree of off-site versus on-site fabrication;
4. degree of reuse/recycling on-site;
5. training and skill requirements;
6. labour productivity associated with each system;
7. risks of sole-sourcing systems or materials;
8. opportunity for 3D Building Information Modeling (BIM) modelling and planning for formwork itself (e.g. Peri Formwork Systems) and the control this implies;
9. opportunity presented by different forming approaches for implementing lean construction principles;
10. acceptable finish quality created; and
11. acceptable within local design codes.

Upon choosing a formwork system, project management devises a monitoring system to establish a statistical relationship between the progress of the project and the performance of the chosen formworks. The end goals are to minimize cost, risk, and time while increasing the 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; Safa 2013; Safa et al. 2014). There have been several studies on formwork selection methods, but most of them concentrate on the specific areas of construction projects and use the case method extensively. For example, Shin et al. (2012) presented a model for formwork 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 a broad scope of construction projects.

Introduction to modular and other formwork systems

The selection of an appropriate forming system requires the knowledge and awareness of all common formwork applications; therefore, this section introduces and generally discusses the different types of concrete forming systems. 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 formwork system, time is a critical factor, including time to set rebar and inserts within the form, stripping time, close-in time, and final disassembly. Correspondingly, the amount of labour required for stripping, setting, placing, 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 other important factors (Hanna 1999). Designers and vendors are aware of the need to keep in touch with the technological advancements in any material's fields in order to develop creative innovations that are required to maintain quality and economy in the face of new formwork challenges. However, the trend today is leaning toward prefabrication, assembly in large units, fast erection by mechanical means, and reuse of formwork (Hanna 1999).

A different classification of formwork systems should initially be considered for selecting the best formwork system. 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 assembly 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.

Stick-built formwork

Formworks which are constructed on-site by workers using available tools (such as hammers, drills, circular saws, spirit levels, etc.) are called stick-built formwork and often comprise dimension lumbers, plywood panels, bolts, steel or aluminium bracing and angles, and nails. A stick-built forming system 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 so that the use of prefabricated panels cannot be economically justified (Ilinoiu 2006).

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 finish quality is required and a high degree of repetition is involved, where the advantages of the metal and plastic types prevail (Brett 1988; Hanna 2007; Peurifoy et al. 2010). 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. High concentration of workmen and tools on-site is often representative of the built-in-place 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 2006, p. 47–54).

Modular formwork

Modular formwork systems represent a new method of formwork construction, which is becoming popular in large-scale construction projects. Modular formwork requires less skilled labour when compared to traditional methods of formwork construction. It also allows for faster erection and stripping, as well as 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. The study also highlights how 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, aluminium (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 form, and special-purpose/custom-made forms. Unlike stick formwork systems, modification to modular forms cannot be done on-site and they are not easily modified without damaging their structural integrity. Their main advantage is that they can be reused many times at a reasonable cost. As a result, modular forms have seen increasing use on construction projects in both Canada and the United States in efforts to save material and labour costs through the efficiency of mass production. 'Their flexibility in financing means that the forms may be purchased, rented or sometimes rented with an option to purchase' (Hurd 2005, p. 2–47).

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 labelled 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 prefab-custom unit systems may be deformed during operation and also may be hard to manoeuvre in terms of safety, where the elements become large. Examples (subcategories) of the mentioned main pre-fab formwork systems are summarized as follows: (1) Euro-form: this is a modular form, mainly used when the building plan is standardized; (2) gang-form: the enlarged, but simplified forms are assembled with lumber and aluminum panel framing, and dismantled. It is applied to wall forms; (3) flying-form: this is a floor form, with a form board, a joist, a beam-joist, and a support manufactured and built up as one unit; (4) climbing-form: a form for wall finishes work; and (5) slip-form: vertically, horizontally, and continuously structured, without construction joists, by moving the form continuously.

In high-rise, tower, chimney construction, a special-purpose modular formwork called a climbing formwork is used. 'Climbing formwork is a method of casting a concrete wall in known vertical lift heights (approx. 1m) using the same forms in a repetitive fashion to obtain maximum usage from a minimum number of panels' (Ilinoiu 2006, p. 2–47). Although the panel systems were developed primarily for wall forming, many of them are adaptable to slab forming, and smaller ones have been successfully used in forming beams (Hurd 2005).

Traveling form construction is based on reusable forms mounted on movable frames or scaffolding called travellers. After the concrete of one section of the structure has cured sufficiently, the forms are released and moved along the structure to the next section to be concreted (Hurd 2005). Table formwork is used when casting large repetitive floor slabs in high-rise structures. Their main objective is to reduce the time factor in erecting, striking, and re-erecting slab formwork by creating a system of formwork which can be struck as an entire unit, removed, hoisted, and repositioned without any dismantling (Ilinoiu 2006).

Slipform-type operations which tend towards extrusion have been used for casting walls, safety barriers, kerbs, and horizontal structural components. The main requirements of slipforming are a high degree of uniformity of concrete mix control, maintenance of a suitable degree of workability with cohesion, and early strength gain (Richardson 1977).

> The technique of slipform consists of constructing a wall-shaped form of reduced height (1.00–1.20 m or even 2.00 m, in exceptional circumstances) at the base of the structure to be built. This form is constructed rigidly and precisely, is not fixed to the floor and is suspended either from several lifting devices supported on metal rods of 25–50 mm, or from members resting on the foundation or on hardened concrete, by means of wooden or metal yokes (frames). Once the form has been filled with fresh concrete and curing has started, the form is gradually raised by the lifting devices on which it is suspended, the form progressing along the tie rods or supporting members by manual, hydraulic, pneumatic or mechanical devices. (Dinescu 1984, p. 47–53)

For heavy civil works such as bridges, sea walls, or repetitive floor systems, shell roofs, tunnel linings, culverts, and segmented or multiple domes, travelling forms are most suitable for slipforming.

ICF forming system

Insulating concrete form (ICF) or permanently insulated formwork (PIF) has grown over recent years. In residential construction, recent years have seen a rise in ICF 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), the system can be used to develop a wall with high thermal resistance, with R-values typically above R-17. If it is observed visually, structures constructed using ICF can be indistinguishable from conventional formwork. Besides its insulating capability, ICFs have proved to be an excellent soundproofing material and can reduce heating, ventilation and air conditioning (HVAC) operating costs. The foam modules are dry-stacked, fastened together using plastic ties, added with rebar, and filled with concrete. The construction progress is relatively easy to learn and follow because of the lightweight and highly modifiable nature of the system. Similar to stay-in-place FRP formwork, ICF protects the concrete from adverse environmental effects, physical damage, and provides 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 placed 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. (Encyclopedia of Alternative Energy 2015)

Contour crafting (3D printing)

This section addresses a promising new technology that may significantly affect the concrete work process in the future. Contour crafting (CC) could be considered as a layered fabrication technology and potential future method for automated construction. This technology uses computer control to exploit the superior surface-forming capability of trowelling to create smooth and accurate planar and free-form surfaces. Some of the important advantages of using this system are better surface quality, higher fabrication speed, and a wider choice of materials (Khoshnevis et al. 2001).

The environmental impact of CC is also remarkable because a significant amount of various harmful emissions and solid waste are generated from construction on-site or in manufacturing plants. In terms of resource consumption, more than 40% of all raw materials used globally are consumed in the construction industry. The contour crafting machines can be fully electric and hence emission free; moreover, accuracy of the contour crafting could result in little material waste. The CC method has the potential of completing the construction of an entire building in a few hours. This time saving also results in efficiency of construction logistics (transportation) system and also environment (Khoshnevis 2004).

Decision model

An effective decision-making model facilitates good judgement. The proposed model gives a structured and effective pattern for selecting the best formwork system for a specific construction project. The model proposed here relies on expert input (Construction Industry Institute members) gathered during a one-year research project. The researchers designed the model so that it can be updated later with statistical data from several construction projects. They define the proposed system by the following nine steps:

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 structures, 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 labour
   - 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 and so precluding modular approach.
   - e.g. labour is scarce, so stick-built is too slow to meet schedule constrains and thus is precluded;
3. Review technically feasible options using project conditions checklist for identification of precluding conditions within sustainability of the formwork;
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 labour 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; and
9. Choose combination of work packages and their associated forming systems which results in lowest total project cost (a manual or automated optimization).

For defining the application in step 1, the project managers (decision makers) require experience and robust knowledge of different forming systems and access to information including design, performance, and specification. They should then analyse various forming methods to ensure that the potential selected systems are technically feasible and economically justifiable. Managers perform this process by reviewing their options using a project conditions checklist to identify precluding conditions within the sustainability of the formwork. Decision makers should consider the factors identified by Hanna (expanded by the CII), as mentioned in the previous section, in implementing these steps. Since experts have always expressed concern over their inability to estimate costs accurately, it becomes critical in the decision-making process that managers select an appropriate cost model. The following section provides an overview of cost estimation models. In virtually every case, project managers find difficulty in gathering data about local cost and labour productivity; they may overcome this challenge by hiring a consultant and local experts.

Cost model for estimating

As mentioned in steps 5–7, one of the main factors in selecting an appropriate formwork system within a project is calculating the cost of formwork systems.

Formwork constitutes the largest cost component for most construction projects. For example, in a typical high-rise reinforced concrete building, formwork costs account for 40–60% of the cost of the concrete structural frame and almost 10% of the total construction project cost. Of the total cost of the formwork, labour represents a large portion, so project managers can significantly reduce the cost of the formwork, and thereby the cost of the total project, by reducing labour costs as much as possible Using a formwork system is labour intensive and the significant cost saving could be reached by reducing labour costs as a large proportion of the cost of formwork is associated with formwork labour costs (Hanna 1999; Sung et al. 2003).

This study presents straightforward cost models that contain a small number of items and uses them to estimate the cost of the formwork systems. Cost-estimation models for this study can be classified into four main categories: a standard consumables-oriented model, a rental and cycling-oriented model, a capital plant-oriented model, and a pre-assembly-oriented model.

1. The *standard consumables-oriented model* is based on long-standing empirical estimating functions. This model is appropriate for the stick-built, foam block, fabric, and other similar forming systems. *Total cost = [materials purchase cost per* m^2 *(consumable) + labour cost per* m^2 *+ equipment cost per* m^2*] *[area* m^2*]*
2. The *rental and cycling-oriented model* is based on an equipment perspective. This model is appropriate for modular, climbing form, and flying. *Total cost = [((materials rental cost per month/number of cycles per month)/*m^2*) +assembly cost per* m^2 *+ labour cost per* m^2 *for cycling + labour cost per* m^2 *for assembly + equipment cost per* m^2 *(crane mostly)] *[area* m^2*]*
3. The *capital plant-oriented model* is based on capital plant investment and automation. This model is appropriate for slip forming and 3D printing. *Total cost = set-up of plant + [operating cost of capital plant per* m^3 *+ extra cost per* m^3 *of special properties concrete required + consumable materials cost per* m^3 *+ labour cost per* m^3*] ** m^3
4. The *pre-assembly-oriented model* assumes that materials are assembled into reusable form that is disposed of after a number of cycles. *Total cost = assembly or manufacture cost of form + [(labour cost per cycle + material cost (e.g. coating for forms) per cycle + equipment cost (e.g. crane) per cycle) * cycles]*

Henceforward, the study looks at an application of the decision model.

Analysis

This section inspects the cost and productivity of applying modular, ICF, and stick-form forming systems. It begins by addressing the archetypical problem of deciding between modular versus stick-built forming systems for building construction. 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 care is always taken in choosing the most suitable option to optimize the project outcome. Further, this section examines the effect of labour rates on the cost of using modular and stick-built formwork. It then describes and explicates why there is a growth in using insulated concrete forming based on the advantages and disadvantages of applying the ICF system.

Modular formwork

The use of modular formwork in construction has a number of benefits over traditional or stick-built formwork systems in large-scale construction projects. 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 labour to build more complex formwork systems exists, as only basic labour 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 reuse of construction equipment are present. However, the use of modular formwork is unfavourable when the construction project is small in size, or there is a high level of customization and specialized or detailed design. Moreover, when a limited amount of space is available for mobilization of equipment, modular formwork can be a challenge.

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 re-employment is specified differently from one country to another. For example, Taiwan often uses wooden formwork systems in reinforced concrete construction. Wooden formwork can be used

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 aluminium 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
Labour requirements	Less skilled labour is required	–
Lifecycle of formwork	Formwork systems can be reused between 40 and 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 labour to fix	Difficult to allow for architecturally designed surfaces, without additional formwork systems or stick-built formwork additions

approximately three to five times; the number of usages and quality are mainly affected by three factors: working attitudes, efficiency, and the stripping process (Ling 2000).

In general, modular formwork can be favoured in some circumstances, outlined in Tables 1 and 2, which compare the advantages and disadvantages of modular and stick-built formwork.

Cost comparison

The cost for each of the proposed slab formwork systems includes both the cost of the materials needed for each system, and the labour costs associated with installing each particular system. In order to obtain an accurate analysis of the installation cost of any formwork system, the labour and material costs should be priced separately. In pricing the labour costs for the slab formwork system, a rate of how many hours it takes to install a square foot of formwork is established for each particular system. Once this is determined, the total area, in square metres, of slab formwork required for the project is calculated from the construction drawings and then multiplied by the installation rate to get the total number of hours required to install each system. After the total number of hours to construct each system is ascertained, the total labour cost for each formwork system is calculated by multiplying the total hours with the average hourly labour wage rate. As for pricing the material costs of each formwork system, the cost per square metre for each formwork system was obtained through correspondence with the manufacturers of the formwork systems considered (June 2010). Once this cost rate is obtained, the total cost of each slab and wall formwork system is calculated by multiplying the cost rate with the area of wall and slab formwork required. For a typical set of rates, a complete cost breakdown of each of the proposed modular slab formwork systems and also stick-build system is required. It should be noted that rates will vary by supplier, rental agency, region of the country, economic cycle, units of modular formwork used, etc.

Combining the material and labour costs of each modular slab formwork system, it is determined that Mevadec and PERI Multiflex systems are relatively costly formwork systems. Also, the PERI Skydeck and Alumalite Table Form systems have comparable total costs; however the PERI Skydeck is the less expensive of the two and as a result is the least expensive modular slab

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 labour 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
Labour requirements	Smaller projects require only a small, specialized crew of carpenters	High skilled labour 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 labour is often required to fix imperfections. Also natural features of wood must be considered

Table 3. A 'typical' cost breakdown of each slab formwork system for a single set-up or tear-down cycle.

Slab formwork cost breakdown							
		Labour cost ($/m^2)					
Formwork system	Man hours (hr/m^2)	Hou	Tor	Buff	LA	Chi	Material cost ($/m^2)
Mevadec	0.028	0.93	1.18	1.36	1.67	1.99	5.11
Alumalite	0.037	1.24	1.57	1.81	2.23	2.66	4.46
Peri Skydeck	0.028	0.93	1.18	1.36	1.67	1.99	4.83
Peri Multiflex	0.046	1.55	1.96	2.26	2.79	3.32	4.46
Stick-built	0.053	1.77	2.24	2.58	3.18	3.78	2.32

formwork system considered. Table 3 also shows that the stick-built system is the cheapest, with respect to initial cost, in comparison to modular slab formwork systems.

It should be noted that these tables are prepared based only on one set-up/tear-down. Tables 1 and 2 show how the modular formwork systems can be reused between 40 and 100 times, depending on materials, jobsite, climate, and usage, but the stick-build materials can generally be used 4–8 times. Taking into account the degree of repetition which is directly related to the design of a building, the use of modular formwork systems is therefore highly recommended in repetitive situations, since labour rates for cycling of set-up sections are typically relatively substantially lower.

Making the decision to choose the best formwork option clearly depends on the characteristics of projects. A US Midwest construction firm specializing in concrete works provided general information (February 2011) that could be a good basis for understanding selection of formwork systems. Figure 2 shows the total installation costs of using modular formwork systems in comparison to stick-built for the Houston and Chicago labour markets

In Figure 3, a high-rise building, consisting of 60 storeys of office space (4600 m^2 per storey) is considered. The figure shows slab formwork costs of a modular system compared to a stick-built system in Houston and Chicago. The breakeven point indicates the number of storeys at which the total cost for the modular and stick-built are equal. The plots show that as the number of storeys increases, the total formwork cost by using the modular option reduces substantially. For example, a project in Houston where the number of storeys is between 8 and 10, using a modular formwork system is the best option. A project located in Chicago, where the number of storeys is either four or five, yields greater savings by using modular (the labour rate in Chicago is approximately twice that in Houston). In mega-projects, the savings are more significant compared to a typical project such as the example above. As the plots indicate, the labour 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 labour savings of the modular system do not outweigh the much higher material costs. When modular formwork is owned, however, sometimes it will be used regardless.

The effects of labour rates and the cost of different formwork systems 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 labour, and availability of plant and equipment.

Insulated concrete formwork

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 they 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 economical alternative to other forming methods due to an increase in producers and available technologies that has increased competition and reduced costs.

Insulated concrete forming systems provide formwork for concrete in a different way than other forming systems by remaining 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.

ICF wall systems are difficult to compare to traditional forming methods such as stick-built or modular formwork because of their unique placement process and function. Unlike traditional wall forming systems, where the rebar placement and forming placement can be considered as separate work packages, rebar placement is

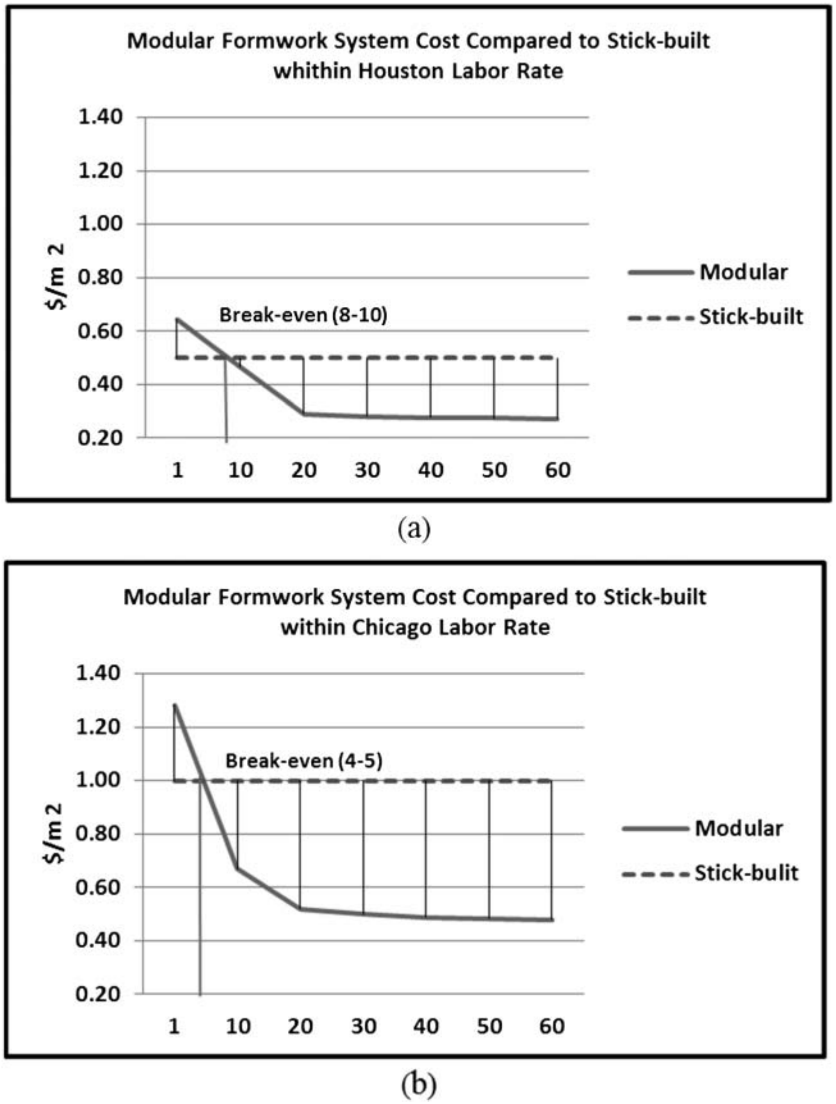

Figure 2. Project ($/m2) of the slab formwork system versus number of cycles within Houston labour rate (a) and Chicago labour rate (b).

largely integrated in the placement of the ICF system. During installation, rebar is placed on the plastic webbing of each course of ICF block as the wall is built. Services installed in the wall may also need to be installed during the formwork installation. Additionally, in order to compare material costs the entire wall system must be considered. According to industry estimates, the full cost of using ICF for concrete wall construction is $205 per square metre of wall, which is higher than the cost of using stick or modular forming systems. This is largely due to the fact that ICF are a leave-in-place formwork and cannot be removed and reused. By remaining in place, the insulated concrete formwork also creates the insulation and air vapour barrier for the exterior of the building. Therefore, in order to properly compare the cost of ICF to other types of forming systems, the cost of the insulation and AV barriers must also be accounted for. These costs vary significantly depending on location and desired type and level of insulation, but can largely account for the extra cost of ICF.

Insulated concrete forming systems are being used to construct multiple mid- to high-rise residential buildings in the Waterloo, Ontario area. Most of these buildings are being constructed with ICF structural walls and foundation walls. The slab systems are hollow core precast concrete, and any additional horizontal structural elements are built using steel beam sections. An example of an exterior wall section formed with ICF is shown in Figure 3.

The project shown was building a 663 m^2 typical floor plate and a wall area per floor of 463 m^2 with a 20-person team in 50 working hours during a winter build. This value was projected to decrease to 45 hours for a fair weather build. At this rate the full wall system was

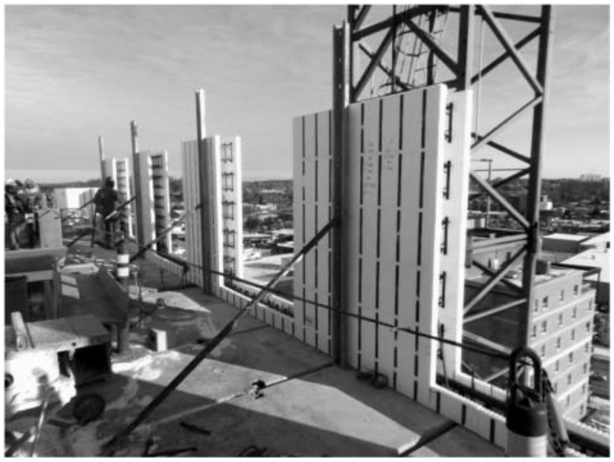

Figure 3. Insulated formwork installation.

being placed at 0.5 square metres per work hour. This value includes the set-up, concrete placement, and bracing removal. Table 5 shows estimated placement and stripping rates for ICF compared to the stick form and modular wall forming systems as well as the cycling rate for modular and stick forming. The rates for stick and modular forming are based on research conducted by Dadi et al. (2012).

It should be noted that these values are subject to various installation conditions and may vary. Also, the placement of the ICF forms includes the time taken to place rebar in the formwork. This is unlike the rates for the stick-form and modular, which are strictly rates for placing the forming system. The productivity of placing ICF benefits greatly from the fact that little stripping, around 5% of the total installation time, is required after concrete placement. In terms of total work hours required for wall placement and stripping, the ICF system performs similarly to traditional methods. However, when repetitive elements are present and forms can be cycled and reused, then using ICF forms becomes much less productive than modular or stick-built forms. It follows from this data that the ICF system is best applied in situations where repetitive cycling cannot be achieved. In addition, the extra cost of forming must be justified by the requirement of higher levels of energy and sound insulation in the formed walls.

Table 5. Vertical forming labour rates.

	ICF (m^2/work hour)	Stick-form (m^2/work hour)	Modular (m^2/work hour)
Installation	0.54	0.84	0.84
Stripping	10.29	1.86	1.77
Total	0.51	0.58	0.57
Cycling	N/A	0.84	1.44

Conclusion and recommendations

Because it can significantly influence cost and duration, builders absolutely must select an appropriate formwork system in order to successfully complete a construction project. Project management can include formwork under the headings of equipment management, supply chain management, and work packaging systems. To assist decision makers, this research provides a decision model based on the advantages and disadvantages of the newest formwork systems versus traditional systems. The study analysed stick-built, modular, and insulated concrete forming systems. The researchers determined that their reusability makes modular systems the best choice in applications with high amounts of repetition. They also found that builders can place insulated concrete forming systems at rates similar to those associated with other methods, and these methods may be cost-effective in situations in which the extra cost can be justified by the requirement for insulation. However, in applications with a high degree of repetition, they are not as effective as modular systems. The nature of the project also plays a major role in the selection process. Decisions about formwork ultimately depend on the assessment of experts with years of practical experience. The proposed model is substantially more comprehensive than other selection methods. Newer formwork technologies, however, which could potentially, substantially alter the way in which concrete is placed, may require further research.

Table 4. The pros and cons of using insulated concrete formwork.

	Pros	Cons
Formwork assembly	The lightweight formwork is easily portable and little 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 or repetitive areas
Labour requirements	The entire system can be constructed by a small team of workers	A learning curve for the installation of each system is expected
Lifecycle of formwork	The formwork remains in place as part of the building 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	Does not allow for a clean concrete finish and can be bulky where insulation is not required

Disclosure statement

No potential conflict of interest was reported by the authors.

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