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Making Formwork Design Lean

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Abstract: Traditional formwork design processes entail considerable waste, increasing non-value-adding manpower costs and operational time. The purpose of this research is to use lean thinking in formwork design so as to enhance design correctness and eliminate waste through establishing a Lean Formwork Design Process. In the design process, the concurrent design concept is adopted to provide a visual communication platform for design team members using Building Information Modeling (BIM). Industry Foundation Classes (IFC) are used as a protocol for sharing design artifacts. Design correctness is established to review and correct design errors, thus allowing for the construction of an organizational learning environment. Finally, the Lean Formwork Design Process is conceptualized using stock-flow diagrams. A real case is used to validate the applicability of the proposed approach. Application results show that the proposed method can enhance design correctness and reduce manpower waste and operational time in formwork engineering. This study is one of the first to apply lean thinking to improve practices in formwork design.

Keywords: Formwork design, concurrent design, building information modeling, design correctness, system dynamics.

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1. Introduction

Reinforced concrete is used to build 87% of the total floor area of residential structures (Peng, 1991). Formwork material and labor costs occupy approximately 15% total costs of constructing ordinary buildings and 33% of the total cost of reinforced concrete structures (Peng, 1992). Therefore, formwork engineering is a key success factor in construction projects (Santilli et al., 2011). Codes for formwork design have been formulated to ensure the quality of formwork engineering and to reduce construction accidents (TCCP, 2000; WHSQ, 2006). For example, the "Standard for Construction of Safety and Health Facilities" formulated by the Labor, Safety and Health Committee of Taiwan's Executive Yuan states that, "In order to prevent the collapse of formworks and thus protect workers, the construction design of formwork supports greater than 5 meters high and with an area greater than 100 square meters must be handled by a dedicated specialist" (IOSH, 2012). This regulation indicates the importance of quality formwork design. In addition, design problems contribute to the 40% rate of change orders in the construction phase (Chang et al., 2007), while 26% of project deficiencies (Josephson and Hammarlund, 1999) and 50% of house defects are due to design flaws (NEDO, 1998). Therefore, the design quality of formwork engineering affects construction quality and thus the progress of the project as a whole (Ko et al., 2011; Ko and Kuo, 2015).

Formwork design involves a variety of professional specialties (e.g., formwork assembly, scaffold, rebar, electromechanical equipment, concrete work, etc.) but, traditionally, formwork design is completed solely by the general contractor who may not be adequately proficient in all of these skills [Rosowsky et al., 1997; Chen and Shirole, 2006). Poor constructability caused by poor coordination, or by design changes in the construction phase, extends the construction period and increases costs Lee et al., 2009; Ko and Kuo, 2018).

Formwork consists of temporary or permanent molds into which concrete is poured. The process is inherently hazardous and formwork design places its top priority on safety (Piskoty et al., 2005; Lee et al., 2011), in part through conducting mechanical analysis, primarily focusing on lateral pressure on the formwork (Tchamba et al., 2008; Puente et al., 2010; Kwon et al., 2011). Formwork design also has to consider economic issues (Sutherland, 2005). Tam et al. (2005) and Abdelhamid et al. (2009) selected the most advantageous formwork systems for various projects according to the formwork characteristics. Mold moving, assembly, and cutting directly impacts labor costs and the number of required crane moves. Barakat and Altoubat (2009) and Benoist (2007) proposed methods to minimize mold requirements for reinforced concrete construction. Computer techniques are frequently used to optimize formwork design (Gregori et al., 2008; Gallego et al., 2011; Umit Dikmen and Sonmez, 2011). Although previous studies have focused on formwork mechanics and economics, a complete formwork design relies on a series of additional design activities, and previous studies have largely overlooked managerial processes to integrate these individual procedures.

The objective of this research is to develop a formwork design process to eliminate waste in formwork engineering. To achieve this goal, concurrent design concepts are adopted to reduce design error. Building Information Modeling (BIM) is used to visualize formwork design and a design correctness rate is proposed for developing an organizational learning environment. The proposed method's applicability is validated using system dynamics.

This paper is organized as follows. Section 2 introduces background information of the study, including explanations of formwork design requirements, lean manufacturing, concurrent design, building information modeling, and system dynamics. Current formwork design practice is then discussed in Section 3, followed by the development of a Lean Formwork Design Process in Section 4. Section 5 presents a real case to validate the applicability of the proposed method. Conclusions and direction for future research are provided in Section 6.

2. Background Information

2.1. Formwork Design Concept

Codes for formwork design have been formulated to ensure formwork quality and reduce construction accidents (TCCP, 2000; WHSQ, 2006). For example, construction regulations in Taiwan require that a dedicated specialist be assigned to manage formwork support and disassembly. Formwork construction, concrete pouring and other operations are all governed by shop drawings and plans. Loading upon the mold is limited by a permitted specification both before and after removing the formwork support. The regulations also require the load borne by a newly poured floor to be fully considered (IOSH, 2012). In summary, formwork operations are designed as a whole, the mold type is selected according to site conditions, and the formwork type, support type, soil state, fixing method, and conjunction method are comprehensively considered to avoid deformation or collapse.

2.2. Lean Manufacturing

Lean manufacturing is derived from the Toyota Production System (TPS) created by Toyota's founder Sakichi Toyoda. Toyoda learnt carpentry from his father and applied this skill to design and manufacture an automatic loom. This loom provided greater speed, but could automatically stop when it detected production errors and identify the error type, thus greatly reducing wastage through product defects. This emphasis on autonomation (jidoka) and quality control is the first pillar of the Toyota production system. Toyoda's son, Kiichiro Toyoda, later visited American supermarkets where he observed the just-in-time delivery of goods. He later applied this principle to manufacturing, providing each assembly station with the parts it requires as they are required. This approach became the production system's second pillar (Liker, 2003). Furthermore, all production processes in Toyota's factories are inter-related. Employee training is designed to avoid slowing down the production line Employees are trained to meet the organization's requirements, while management takes a personal interest in the well-being and equity of workers in support of the system's third pillar: "lean talent" (Liker and Meier, 2007). Fujio Cho, a former Toyota chairman, summarized these methods and created Toyota production system house, as shown in Fig. 1, to represent them. This diagram clearly and systematically describes how Toyoda trains people and puts the Toyota production system into practice to minimize inventories, enhance quality, and reduce waste (Liker and Meier, 2006).

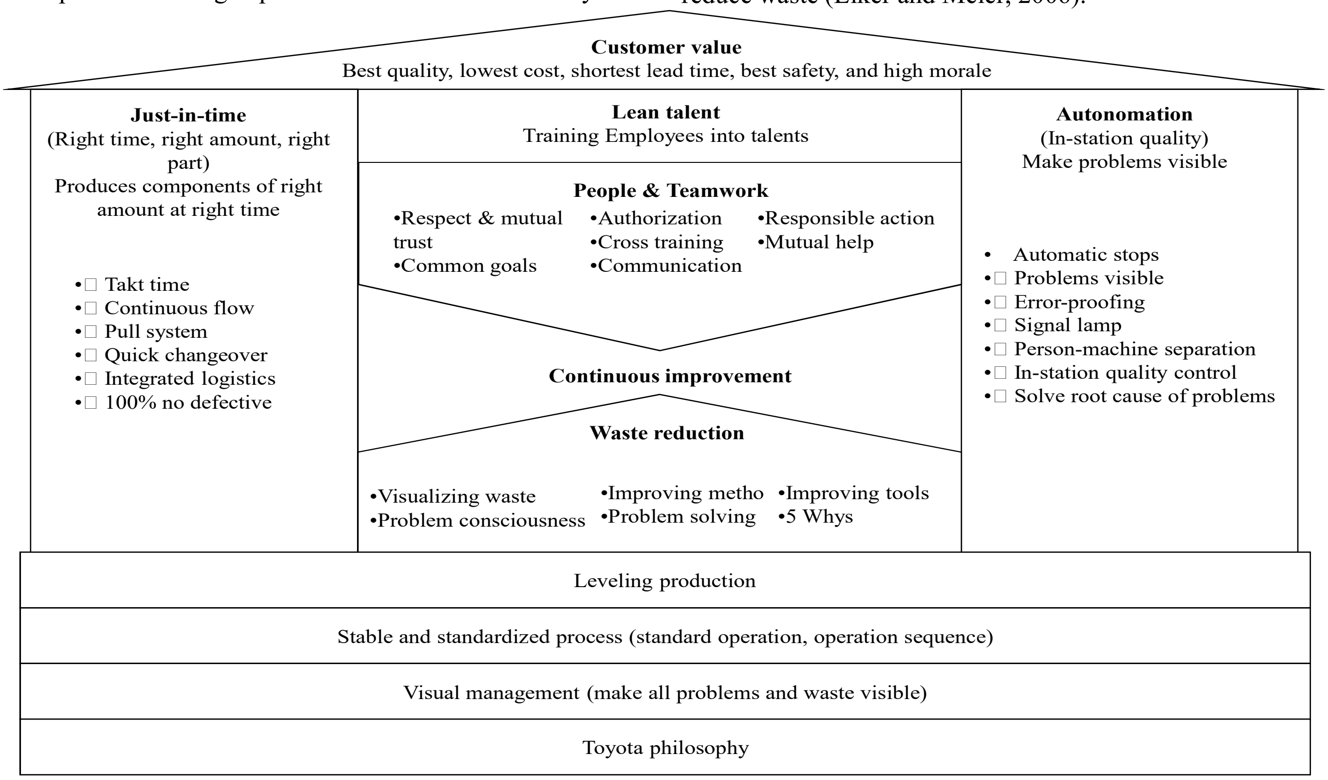

Fig. 1. Toyota production system house

2.3. Concurrent Design

Concurrent design originates from the concurrent engineering, which is defined by the Institute for Defense Analysis as follows (Winner et al., 1998):

"Concurrent engineering is a systematic approach to integrated, concurrent design of products and their related processes, including manufacturing and support. This approach is intended to cause the developers from the outset to consider all element of the product life cycle from concept through disposal including quality, cost, schedule, and user requirement."

Concurrent design is based mainly on information sharing and integrates all life cycle related departments to jointly review a product's design contents. Designers use computer-aided design systems to express their ideas in two or three-dimensional (2D or 3D) representations. Information is shared by unifying data formats on the server, thus allowing for design problems to be solved through online communication, and effectively reducing communication time requirements while improving enterprise competitiveness (Li and Shen, 2009). Facing fierce global competition, today's enterprises face challenges by high-mix-low-volume, limited cost and time. Enterprises lose market competitiveness if they fail to reduce production costs while reducing lead time. A general manufacturing process includes design concept formation, detailed design, structural analysis, manufacturing and sale. A problem in any links in this chain requires the production process to return to the previous step, or even return to the initial stages for design changes. Repetitive product design changes incur additional costs and reduce market competitiveness (Chung, 2010). These problems can be addressed by bringing together departments related to the project life cycle to jointly contribute to the design process. Problems identified in the product development process can thus be considered in the design phase, ensuring that resulting designs comply with the requirements of each phase. This can substantially reduce design changes, product R&D time, and costs, while improving quality and enterprise competitiveness (Aleisa et al., 2011).

2.4. Building Information Modeling

Building Information Modeling (BIM) can be seen as the process of generating and managing building data during the building's life cycle (Lee et al., 2006). In that BIM integrates building data and computer models. It can also be defined as a model-based technology linked with a database of project information. BIM includes the building's geometric shape, spatial relations, geographic information, component quantity and attributes, and data on relevant suppliers. Files required for connecting elements in space for communication such as engineering drawings, purchasing details, environmental conditions, delivery procedures, and building quality standards are also included (Azhar, 2011). Furthermore, BIM's Virtual Building Model provides architects, structural engineers, equipment designers, and consultant teams with an online platform for design communication and collaboration, allowing for the engineering design results to be delivered to the construction team for implementation. When the project is completed, the BIM can be handed over to owners or users for operations and maintenance. The use of BIM can avoid information loss while allowing design team members to add individual design information and receive design feedback (Peterson, 2011).

The establishment of BIM requires detailed information from design team members. In the construction phase, solving problems arising from design errors could take a few weeks. To avoid such issues, problems hidden in the design and construction phases should be brought to the surface as early as possible. Project members can be integrated through BIM, allowing them to collaborate on improving the design (Yan et al., 2011). Establishing BIM through cooperation may require significant changes within the enterprise. This technology allows for working boundary overlap between architects, engineers, and contractors, thus expanding the opportunity of technicians and engineers to participate in the design process (Knight et al., 2010). While earlier versions of BIM only provided tools for design and construction, the management of design and construction processes for modern projects has become more critical due to the advent of digital transmission. Thus more owners, engineering companies, builders, and subcontractors are now choosing BIM as a tool for design and coordination (Fazio et al, 2007; Arayici et al., 2011; Rüppel and Schatz, 2011; Ilozor anf Kelly, 2012).

2.5. System Dynamics

As developed by MIT's Jay W. Forrester, System Dynamics (SD), is an approach for understanding the behavior of complex systems (Forrester, 1961). SD stresses holistic consideration of the entire system, understanding structures within the system and their interaction through systematic thinking. SD uses computer simulations to display how system structure, policy, and delay affect the system's development and stability (De Marco et al., 2012). System Dynamics focuses on neither forecast nor single trend developments, but rather focuses on the causes behind complex changes, i.e. the fundamental mechanism of an entire dynamic operation (Senge, 1990). In recent years, SD applications can be found in diverse fields including construction, water resource management, the automotive industry, cash flow analysis, climate change tracking, and water supply system management (Alvanchi et al., 2011; Pastorino et al., 2011; Hassanzadeh et al., 2012).

The System Dynamics model consists primarily of four basic elements: stocks, flows, arrows, and auxiliary variables. These elements are explained using Vensim notations as follows (Eberlein and Peterson, 1992):

- Stocks

Stocks refer to the status of a system variable at a specific time. Stock values are the result produced by accumulating the net balance of inflows and outflows. In other words, they are the previously accumulated results in the system. Therefore, stocks can be viewed as the state variables of the system.

- Flows

Flows, also known as rates, indicate the change in a stock variable and represent the behavior at a given moment. Their values are mostly decided by the interaction between stock variables and auxiliary variables, and hence can be viewed as the system's control variables. Flows are directional, so flows that flow into a stock are called "inflows" while those flowing out of a stock are called "outflows."

- Auxiliary variables

Auxiliary variables, also known as converters, indicate an input value, or directly convert an input into an output.

- Arrows

Arrows, also known as connectors, represent the transmission of relevant information between stocks, flows, and auxiliary variables.

Stocks and flows are used for deducing system status, i.e., presenting element flows. Arrows and auxiliary variables can be used to deducing causal feedback loops, i.e. a representation of variable information flow. In Fig. 2, using population as an example, population is stocks, and births and deaths are flows (inflows and outflows, respectively). The birth and death rates are auxiliary variables. System Dynamics allow for the analysis of the dynamic relation between birth rate, population, and death rate.

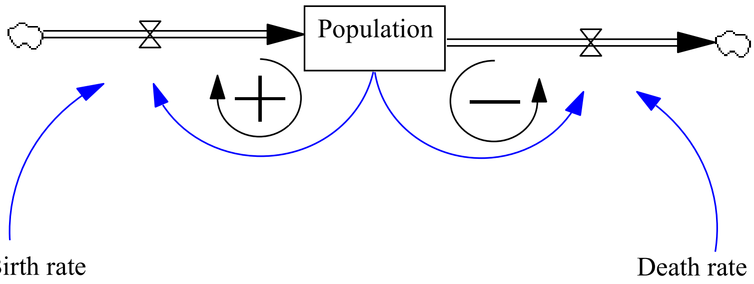

Fig. 2. Population stock-flow diagram

3. Formwork Design Practice

Current formwork design can be generally divided into preliminary and detailed design processes, as shown in Fig. 3. In general, formwork designs in the two phases are usually finished by the general contractor (GC). In preliminary design phase, the site manager draws the building system model according to the design drawing supplied by the architect. The formwork design and assembly schedule is also elaborated in this stage. The completed building system model is delivered to the structural engineer and the formwork subcontractor for formulating the formwork structure and assembly plan, respectively. The site manager integrates the results provided by the structural engineer and the formwork subcontractor to construct the preliminary formwork model. In the detailed design phase, the structural engineer establishes the detailed structure according to the preliminary formwork model. The model is endorsed once the mechanical behavior of formwork has been analyzed. The formwork subcontractor prepares the detailed shop drawing, molds, timbers, crew, and hardware fittings for mold assembly. The site manager finally integrates the formwork structural plan and the formwork construction plan to develop the formwork system model.

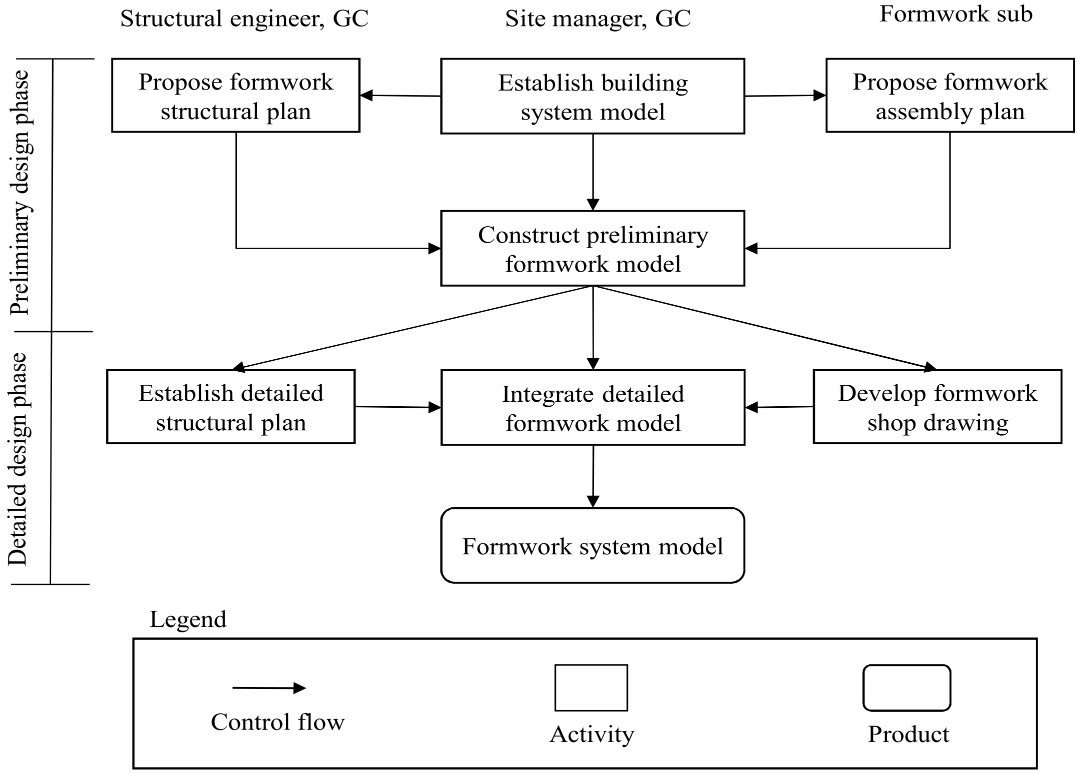

Fig. 3. Traditional formwork design process

During mold assembly, the site manager is responsible for coordinating the assembly schedule with various subcontractors (e.g., rebar, formwork, plumbing, and electricity). If design errors are found or molds cannot be assembled as designed, the GC (i.e., the site manager and structural engineer) is responsible for changing the design. The formwork subcontractor then revises the corresponding assembly plan and shop drawings in accordance with the revised design. This process is represented in Fig. 4 using current-state value stream mapping. According to the figure, problems for the current practice are explained as follows:

1. The structural engineers are unable to comment on the design until the site manager delivers the formwork design for mechanical analysis, thus depriving them of an opportunity to improve the design.

2. While the formwork assembly plan is produced by the formwork subcontractor, mold assembly may involve other subcontractors (e.g., scaffolding, rebar, wiring, and plumbing). Working alone, the formwork subcontractor would have considerable difficulty formulating a perfect plan. Errors in the plan can lead to poor constructability in that design errors may influence construction delivery, therefore increasing costs and reducing quality.

3. Current formwork design drawings are mostly 2D graphs. However, formwork, wiring, plumbing, and rebar operations overlapped to a certain degree. The use of 2D diagrams increases the difficulty of finding conflicts, thus increasing the possibility of change orders.

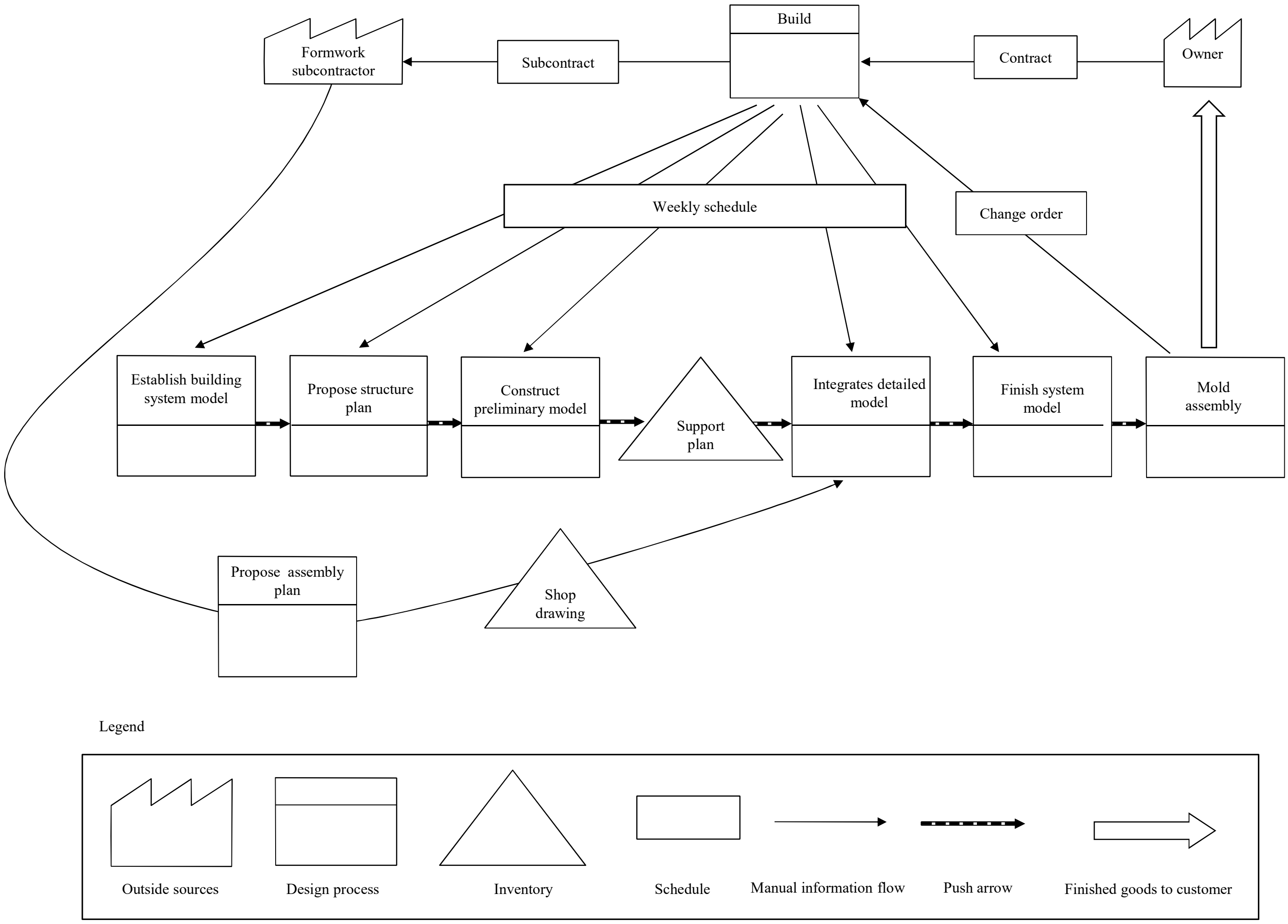

Fig. 4. Current-state formwork design value stream mapping

4. Lean Formwork Design Process

4.1. Design Schema

Traditional formwork design is expressed in 2D drawings, which present difficulties in describing 3D space. Moreover, curvature surfaces are difficult to understand in a 2D environment. Computer-aided 3D drawing software makes it relatively easy to represent real world objects, and the resulting digital files can be exchanged through data transfer protocols. Using this method for formwork design could help improve understanding and communication between design team members.

This paper adopts Toyota's philosophy of continuous improvement to eliminate waste in formwork design. To eliminate waste resulting from a design error, specifications of formwork pillars, walls, beams, slabs, staircases, and constructability are verified prior to release for mold assembly. The design schema is displayed in Fig. 5. In the figure, concurrent design practices are conducted through the project. Turnkey contracts are adapted to relieve design errors and improve constructability. After understanding the owner's requirements, the GC assists the formwork subcontractor in formulating the formwork design. Design artifacts are documented and used in online collaboration via the IFC_2x3(*ifc) standards. All participants can use BIM applications such as GraphiSoft ArchiCAD or Autodesk Revit to identify problems or conflicts in the formwork model. Finally, the design process is represented using stock-flow diagrams and System Dynamics is used to simulate and analyze the improvement program. This approach gradually reduces formwork-related waste in the project life cycle, thus increasing customer satisfaction.

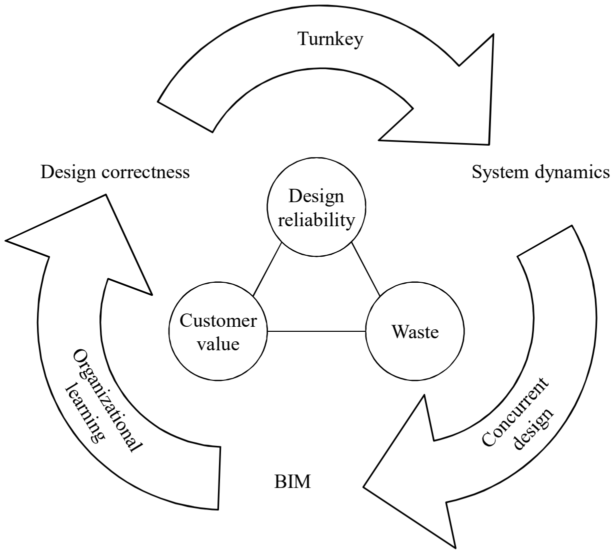

Fig. 5. Structure of design process

4.2. Design Value

The value of formwork design lies in correctly completing the formwork design in accordance with customer requirements. This study improves design value through raising the design correctness rate which, as defined in this study, is an indicator for used in reviewing whether the design contents comply with requirements from project participants.

This study applies the concept of concurrent design in the formwork planning phase. The site manager brings together the formwork subcontractor and other subcontractors responsible for formwork engineering in the project level. As far as requirements of project participants are concerned, the formwork subcontractors, structural engineers, and related subcontractors (e.g., scaffold, rebar, electromechanical, and concrete engineering) can be integrated. The purpose of allowing project participants to take part in the initial formwork planning and design is to bring out formwork engineering issues as early as possible, and to solve problems that may occur in the construction phase at an earlier time.

4.3. Value Stream Analysis

A product cannot generate value until it has been manufactured. Wastage occurs when poor design reduces product value or market competitiveness (Ohno, 1998). In other words, poor design is itself a waste that results in change orders and defective products. Molds which cannot be assembled based on shop drawings are a common problem during the construction phase (Jarkas, 2010; Williams et al., 2011). The Lean Formwork Design Process is a production flow for enhancing customer value. During production, value stream mapping is used to analyze non-value-adding activity, followed by improvements to gradually improve customer value. Problems hidden in the framework design drawings, can result in waste through change orders and rework in the construction phase. The general contractor helps the formwork subcontractor carry out the concurrent design. Moreover, the formwork subcontractor appropriately uses organizational learning to continuously analyze the design stream value so as to enhance the formwork design value.

4.4. Design Flow

Traditional formwork engineering is outsourced in the form of labor and materials. Formwork is traditionally designed by the general contractor and then delivered to the formwork subcontractor for assembly. However, if the formwork subcontractor does not participate in the design process, problems such as design errors and poor constructability will be encountered in the construction phase. To smooth the design process, this paper uses turnkey, concurrent design, and organizational learning to enhance design value. Turnkey formwork engineering involves the general contractor subcontracting both formwork design and assembly to a formwork subcontractor. Concurrent design involves the design team members collaborating on design documents. Organizational learning is adopted primarily to increase design reliability through feedback on design correctness.

When the formwork subcontractor uses concurrent design for formwork design, the general contractor helps the subcontractor integrate the design team including owners and other formwork related subcontractors to ensure design results comply with the requirements of the owner and other third parties. The design process consists of preliminary design and detailed design phases, as shown in Fig. 6.

4.4.1. Preliminary design

The main purpose in this phase is to correctly mark the building on the drawing. The BIM is prepared by the general contractor. The formwork subcontractor designs the prototype of the formwork system. Structural engineers analyze the mechanical behavior of the formwork structure.

- Establish the building system BIM model: The general contractor establishes the building system BIM according to design drawings supplied by the architect. Schedules of formwork design and assembly are also made at this stage. The developed building system BIM model is turned over to the structural engineer and the formwork subcontractor in IFC format.

- Propose formwork structural plan: The structural engineer is entrusted by the formwork subcontractor to analyze the mechanical behavior of the concrete structure. The preliminary formwork structural plan, including a seismic-resistant structural scheme, external load analysis, and material allowable stress analysis.

- Propose a formwork assembly plan: According to BIM system offered by the general contractor, the formwork subcontractor designs the preliminary formwork assembly plan, including the prototype formwork structure, support structure, conjunction of structural materials, and materials estimates.

- Evaluate preliminary design correctness: Design correctness in the preliminary design phase is evaluated using Table 1. The formwork team (i.e., the general contractor, formwork subcontractor, and structural engineers) jointly review and discuss the design contents shown in Table 1. In case any design contents are not described in detail, the responsible designer is required to provide a complete explanation that can be understood by all team members, regardless of professional specialty. Any incorrect or improper designs are returned to relevant designer for further modification. The next design phase cannot be carried out until all design contents, including modifications, meet the customer's requirements. Rather than specific figures for grade evaluation, Table 1 uses "Yes" and "No" to evaluate the correctness of the design contents. This table allows the construction and design team members to learn and work to identify and solve problems early in the process.

- Integrate preliminary formwork system model: Results achieved in the preliminary design phase are collected and sorted into files as required by the construction plan, including a formwork assembly plan and a formwork structural plan.

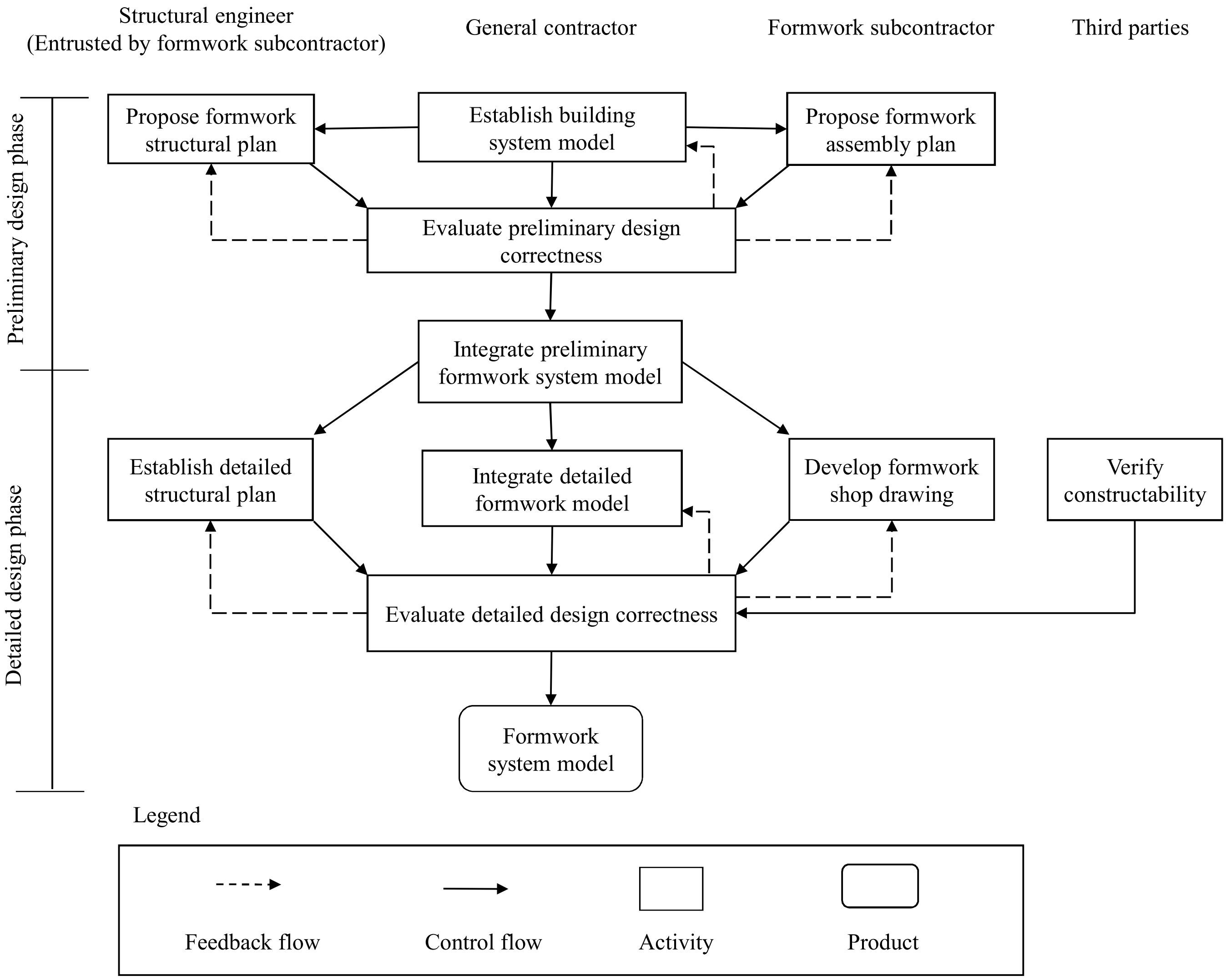

Fig. 6. Lean formwork design process

4.4.2. Detailed design

The main purpose in this phase is to develop shop drawings and a 3D formwork system. Feedback on design correctness allows for the incremental improvement of the formwork system.

- Integrate detailed formwork model: The preliminary formwork system is represented in 3D. Structural and equipment details are shown on BIM. In this phase, the general contractor decides the groundbreaking time, monthly and weekly assembly schedules, and coordination time of third parties.

- Establish a detailed structural plan: In this step the detailed formwork seismic-resistant structure, detailed structural drawings, and the material specifications are prepared.
- Develop formwork shop drawings: Detailed formwork shop drawings, detailed conjunction drawings, mold quantities, support material quantities, hardware fitting quantities, and formwork layouts are developed.
- Verify constructability: The third parties verify the constructability of the proposals. With the aid of concurrent design, the constructability can be verified before mold assembly.

Table 1. Preliminary design correctness evaluation

Evaluation item		Evaluation results	General contractor		Structural engineer		Formwork subcontractor	
			Yes	No	Yes	No	Yes	No
General contractor	**Building system model**							
	Assembly schedule							
	Design conflicts	**Concrete engineering**						
		Scaffold engineering						
		Electromechanical engineering						
		Rebar engineering						
		Other						
Structural engineer	**Seismic-resistant structural scheme**							
	External loading analysis	**Vertical loading**						
		Side force						
		Horizontal force						
	Material allowable stress analysis	**Steel**						
		Timber						
		Accessories						
Formwork subcontractor	**Formwork structure**	**Foundation formwork design**						
		Wall formwork design						
		Pillar formwork design						
		Beam formwork design						
		Slab formwork design						
		Staircase formwork design						
		Special formwork design						
	Support structure	**Timber support**						
		Steel tube support						
		Shaped steel supports						
	Conjunction design							
	Materials estimates							

- Evaluate detailed design correctness: Formwork design team members, Architectural/Engineering (A/E), and related subcontractors jointly evaluate the design results. Detailed structural plans, detailed formwork models, and formwork shop drawings are continuously improved until 100% design correctness has been achieved. A detailed design correctness check list is presented in Table 2.

The general contractor integrates the data and information developed in the two design phases to develop a formwork system model. The formwork subcontractor cannot conduct the assembly until groundbreaking, when the completed formwork system model is confirmed by the general contractor.

Table 2. Detailed design correctness evaluation

Evaluation items		Evaluation results	Structural engineer		Formwork subcontractor		A/E		Third parties	
			Yes	No	Yes	No	Yes	No	Yes	No
General contractor	**Detailed formwork plan**									
	Detailed formwork support plan									
	Monthly and weekly schedule									
Structural engineer	**Seismic-resistant structure**									
	Formwork structure	**Shop drawing**								
		Support configuration								
	Material specifications									
Formwork subcontractor	**Formwork shop drawing**	**Foundation**								
		Wall								
		Pillar								
		Beam								
		Slab								
		Staircase								
		Special formwork								
	Detailed conjunction									
	Mold quantity									
	Support material quantity									
	Hardware fitting quantity									
	Layout plan									
Third parties	**Constructability**									

4.5. Pull design

This research adopts Ballard's (2000) Last Planner to pull the design process so as to increase design flow stability. As shown in Fig. 7, in the traditional formwork design process, formwork planning is carried out immediately after the general contractor determines the project target. Working items are confirmed before producing the assembly schedule. The scheduled working items are completed based on available resources, and uncompleted work can only be finished when additional resources are provided. However, the traditional planning system often cannot complete the formwork design according to the predetermined design schedule. To allow for the successful execution of scheduled items, the Last Planner is added to the formwork design to control design progress, as shown in Fig. 8. When generating the formwork design schedule, the Last Planner evaluates the current design status, and "pulls" the qualified work items (i.e. those items ready for execution) into the design schedule. If failure of certain preconditions results in scheduled design items failing to be included, backlog operations can be implemented in advance to maintain smooth design progress and prevent rushing caused by work item delays. When executing the design plan, the resources necessary for the specific future work items should be prepared ahead. In case a work item cannot be finished within the specified time, the root causes of the delay should be discussed.

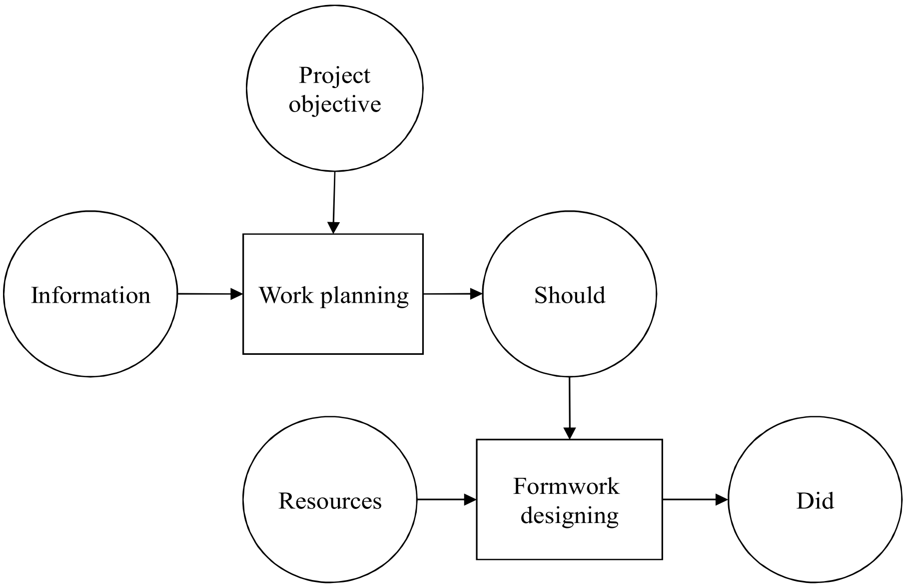

Fig. 7. Push formwork planning system

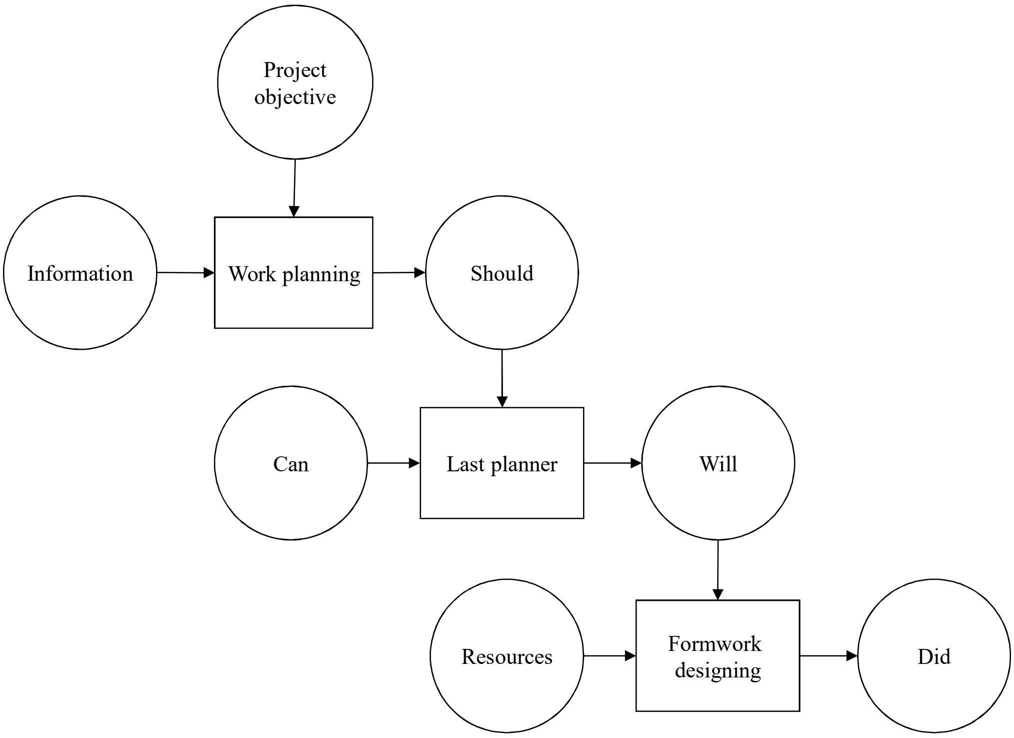

Fig. 8. Pull formwork planning system

4. 6. Pursuing Perfection

Pull manufacturing and concurrent design are used to pull work items within the system to ensure that the formwork system design meets the owner's requirements. Designers and owners work jointly in the design process, and this improved process is drawn into the future-state map.

4.6.1. Preliminary design

The main purpose in this phase is to correctly mark the existing building on the shop drawing. The general contractor delivers the building system BIM to the formwork subcontractor and structural engineers through the Electronic Information Flow platform. They then bring forward the formwork assembly plan and structural plan for the provided BIM. Items for completion in the formwork design plan need to be checked in the preliminary correctness table. Because formwork design and planning work differ from manufacturing processes (i.e., the processed work pieces cannot be sent to the next work station through the belt), the supermarket pull system is used to pull the upstream supplier and downstream customer, as shown in Fig. 9. A production card is used as a signal to start production, and a withdrawal card is a purchase order for receiving items. The supermarket notation opens on the left, which corresponds to the supplier. During review of the preliminary design correctness, incomplete and unclear items must be returned to the responsible designer for modification. The withdrawal card also can be used to pull designs to enable the upstream supplier to make improvements in the information sent from the downstream supplier. Finally, the general contractor integrates the detailed formwork model to pull the preliminary design correctness to complete the formwork design.

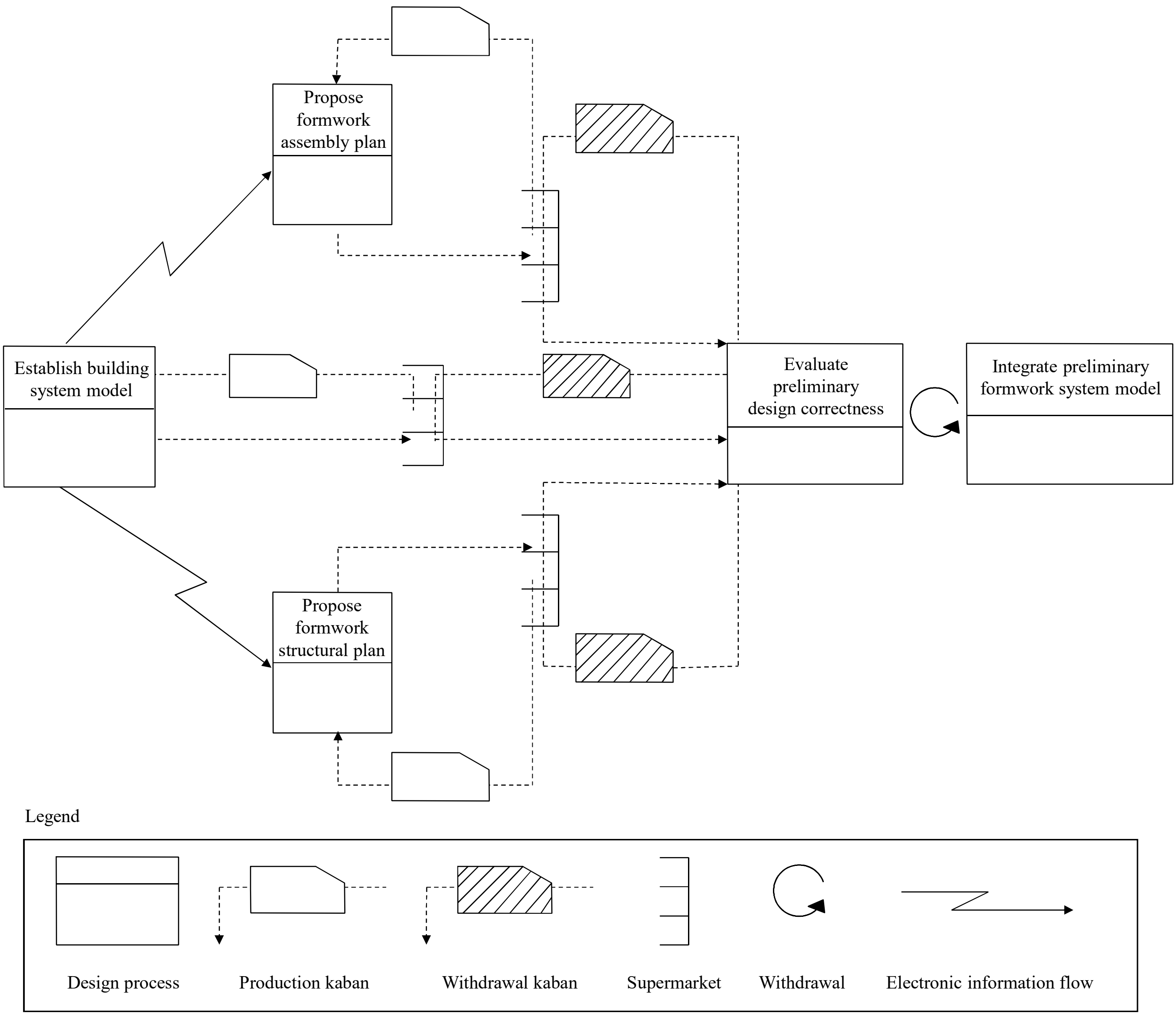

Fig. 9. Preliminary design future-state map

4.6.2. Detailed design

This phase focuses on completing shop drawings and the formwork BIM system. The completed formwork system model is used to satisfy the general contractor's requirements. Design mistakes and conflicts can be reduced through increased design correctness, which improves design reliability. The process executed in the detailed design phase is shown in Fig. 10. In the figure, the general contractor uses the electronic information flow to transfer BIM, and the formwork system model pulls the detailed design correctness evaluation. As a result, design operations can be pulled in this phase.

Fig. 11 integrates the future-state map of the Lean Formwork Design Process. The owner contracts general contractor to undertake the project. The general contractor outsources the formwork engineering to the formwork subcontractor. The formwork subcontractor then designs the formwork plan, and assigns the structural engineers to analyze the formwork mechanical behavior. The Lean Formwork Design Process is developed to allow the general contractor, formwork subcontractor, structural engineers, Architectural/Engineering team, and related third parties to jointly participate in the design process. A feedback/modification loop is designed into each design phase, thus reducing design errors and the risk of change orders during the construction phase. Furthermore, the introduction of the pull process helps smooth the design process.

5. Application and Verification

5.1. Case Study

A real case is used to validate the feasibility of the proposed approach. The formwork design process is improved using the proposed Lean Formwork Design Process. Finally System Dynamics is applied to analyze the effectiveness of the proposed method. The case is a 2185 square meter reinforced concrete structure in Taiwan with one basement and four stories, built using the traditional formwork design method. The general contractor develops the building system model required for formwork engineering. The formwork structural plan is prepared by the structural engineers. The general contractor formulates the preliminary formwork models. The structural engineers analyze the mechanical behavior of the formwork support system. The formwork subcontractor is responsible for the formwork assembly plan. The general contractor then integrates these artifacts into a formwork system model which is finally used by the formwork subcontractor to assemble the molds.

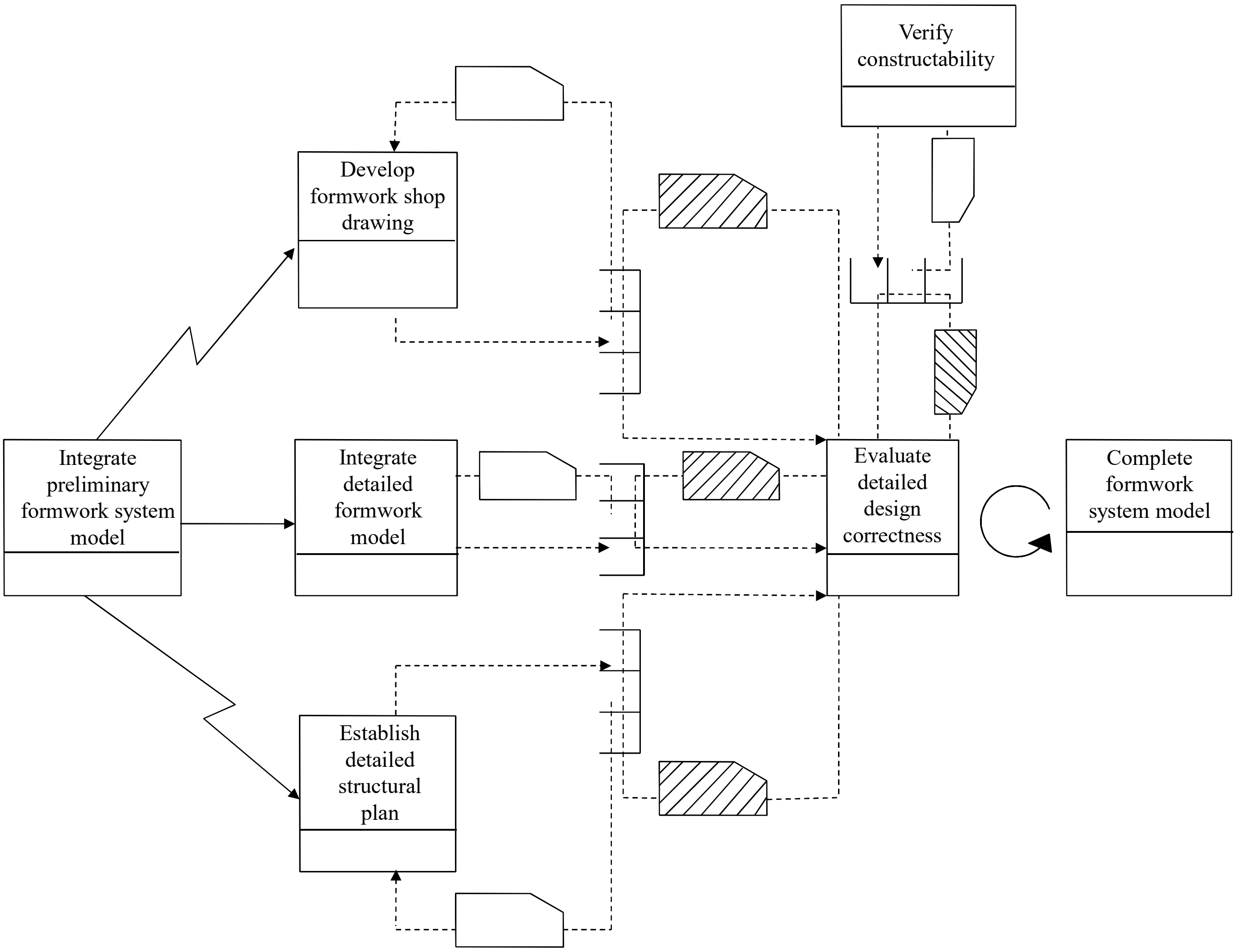

Fig. 10. Detailed design future-state map

5.2. Formwork Building Information Modeling

The Lean Formwork Design Process is applied to improve the formwork design process, using BIM as a platform for information sharing and communication. The formwork subcontractor leads the formwork design with assistance from the general contractor who coordinates the requirements and prerequisite work of the formwork-related subcontractors prior to mold assembly. To ensure effective communication between design stakeholders, BIM is used to design the formwork. BIM 3D models enable the formwork assembly team to understand the building system. Formwork related stakeholders can jointly participate in the design process, contributing their specialized knowledge to the design drawings, thus enhancing design quality. BIM is applied as follows. First the mold assembly positions of both beams and pillars are set. Drawings are then converted into a 3D model. Design results can be transferred to other designers and third parties through IFC protocol. These IFC files can be saved and opened through BIM software, like ArchiCAD and Autodesk Revit. For example, the graphic file IFC_2x3(*ifc) can be drawn and saved in ArchiCAD and then imported into Autodesk Revit or, vice-versa, Autodesk Revit can be used for drawing a 3D graph, which is then exported in IFC_2x3(*ifc), and imported into ArchiCAD. Fig. 12 illustrates the BIM formwork design process, using two pillars and one wall as an example.

5.3. System Dynamics Analysis

The effectiveness of the proposed Lean Formwork Design Process is analyzed using System Dynamics. The process shown in Fig. 6 is converted into stock-flow diagrams so as to show the influence and information flow in the design system. Fig. 13 shows the stock-flow diagram of the preliminary design. The correctness rate of the preliminary design is set as a stock (TYPE Constant). The inflows are assembly plan correctness, building system model correctness, and structural plan correctness. The auxiliary variable is a modification number.

Detailed design can begin when preliminary design correctness rate reaches 100%. The detailed design correctness rate is set as the stock. The inflows are shown in Fig. 14. The auxiliary variables are detailed modification numbers and the correctness rate of the integrated preliminary formwork model.

- Preliminary design system

Table 1 shows the proportion of preliminary design items evaluated by the general contractor, formwork subcontractor, and structural engineers. The total number of evaluation items is 26, of which seven are evaluated by the general contractor, accounting to 26.9 % (7/26). The formwork subcontractor accounts for 46.2% and structural engineers for 26.9%. These proportions are set as weights, expressed using the Eq. (1). In general, the correctness rate of an architect-provided building system model is about 70%, which can be increased by 30% after each modification (Chung, 2010), as expressed by Eq. (2). The correctness rates of the formwork assembly plan, formwork structural plan, and system model can be increased by 30% in each modification, as represented in Eq. (3).

MIN (0.269 * Building system model correctness rate + 0.462 * Formwork assembly plan correctness rate + 0.269 * Formwork structural plan correctness rate, 100) (1)

MIN (70 + 30 * Preliminary modification numbers, 100) (2)

MIN (Building system model correctness rate + 30 * Preliminary modification numbers, 100) (3)

Fig. 15 shows the preliminary design correctness rate analyzed using System Dynamics. The design correctness reaches 100% with one time modification lasting about a week. Once no errors are found in the preliminary design, the next phase of the detailed design system is carried out.

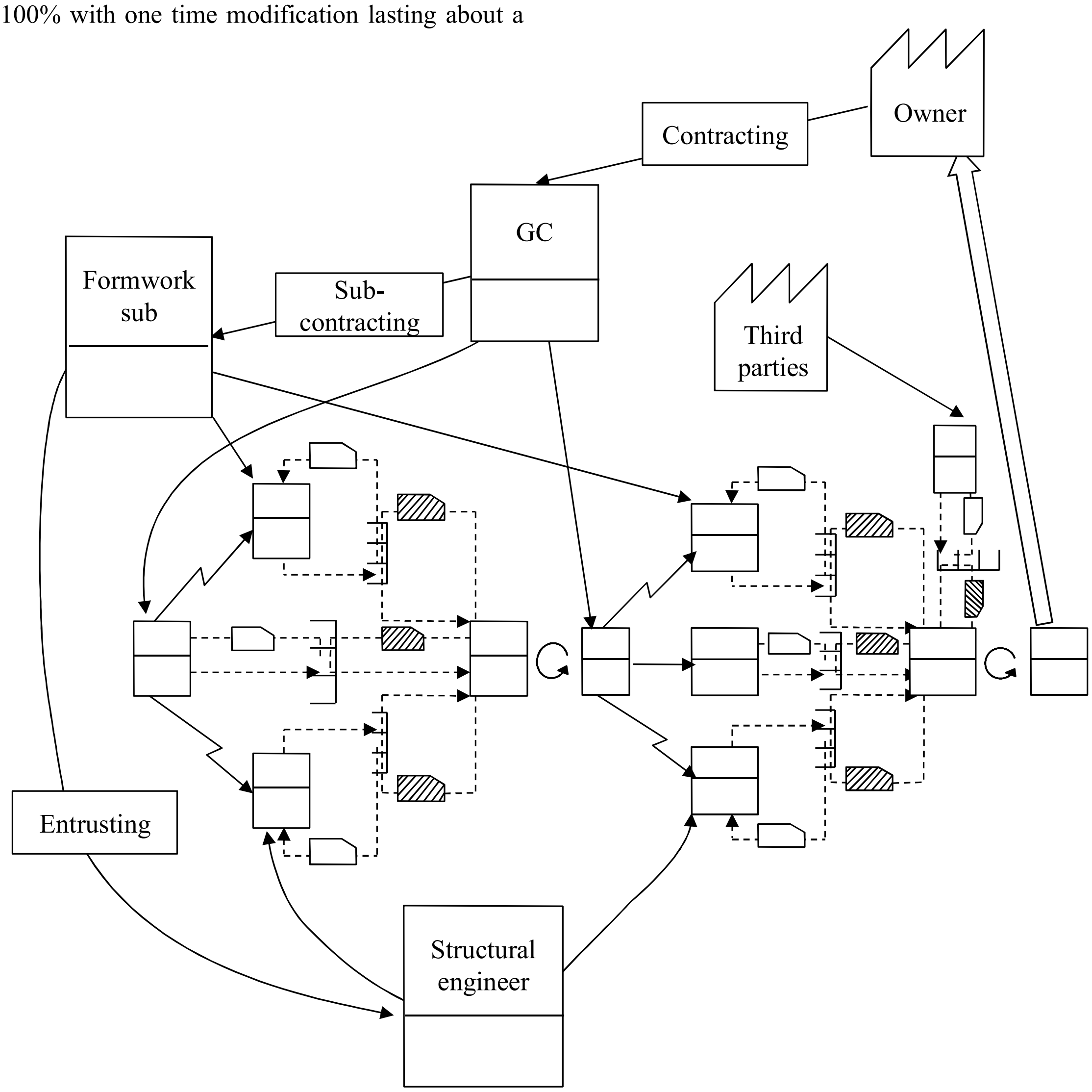

Fig. 11. Future-state map of the lean formwork design process

- Detailed design system

In this phase, the formwork-related subcontractors are invited to verify the constructability of the designed formwork system. A total of 21 evaluation items are summarized in Table 2. The general contractor is reasonable for 14.3% of the work items (3 of 21), while the formwork subcontractor accounts for 57.1%, structural engineers for 23.8%, and other subcontractors for the remaining 4.8%. Using Eq. (4), these proportions are set as the weightings to represent the detailed design system, shown in Fig. 14. The correctness rates of the detailed formwork model, shop drawings, and structural plan can be improved by 40% with each modification, as expressed in Eq. (5). The influence of constructability of detailed design correctness is formulated in Eq. (6).

MIN (0.143 * Detailed model correctness rate + 0.571 * Shop drawing correctness rate + 0.238 * Detailed structural plan correctness rate + 0.048 * Constructability, 100) (4)

MIN (Integrated preliminary formwork model correctness rate + 40 * Modification numbers, 100) (5)

MIN (Modification numbers * 40, 100) (6)

Fig. 16 shows the detailed design correctness rate as analyzed by System Dynamics. In the organizational learning environment, the detailed design correctness rate reaches 97.12% in the first modification. However, under the influence of the constructability review, the rate reaches 99.04% by the second week, and 100% correctness can be achieved in the third modification.

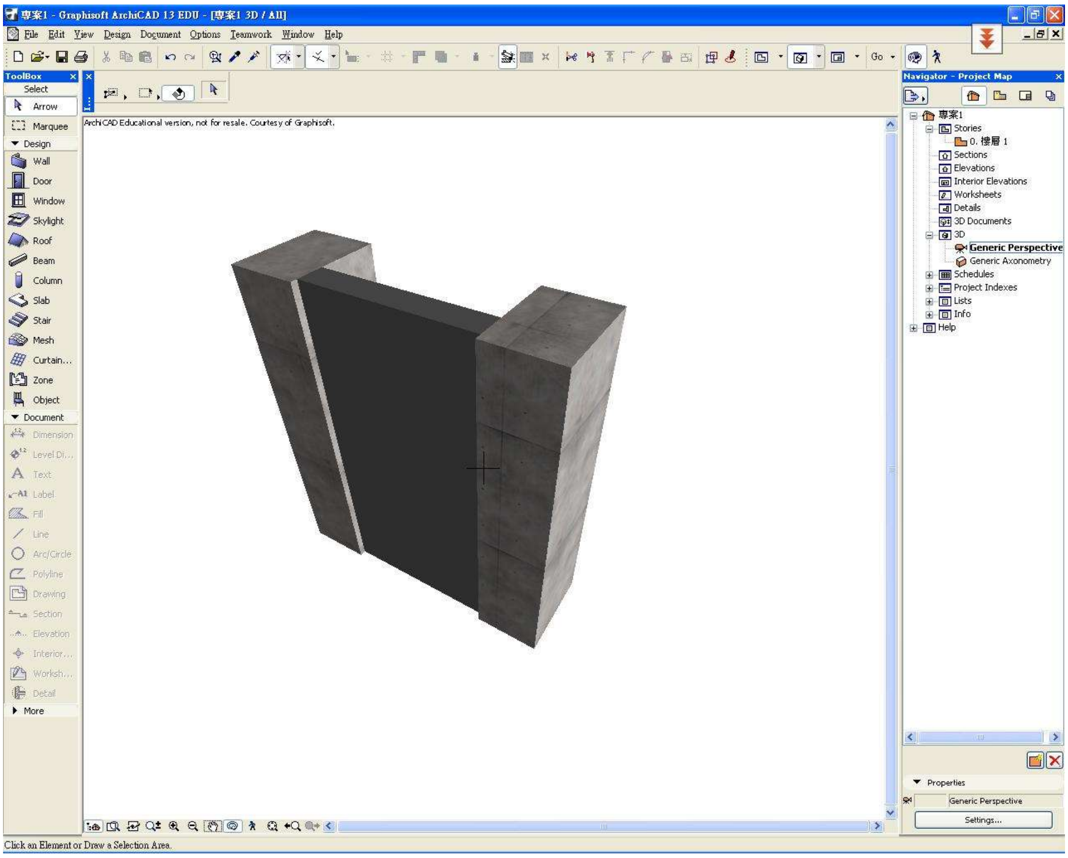

Fig. 12. BIM formwork design

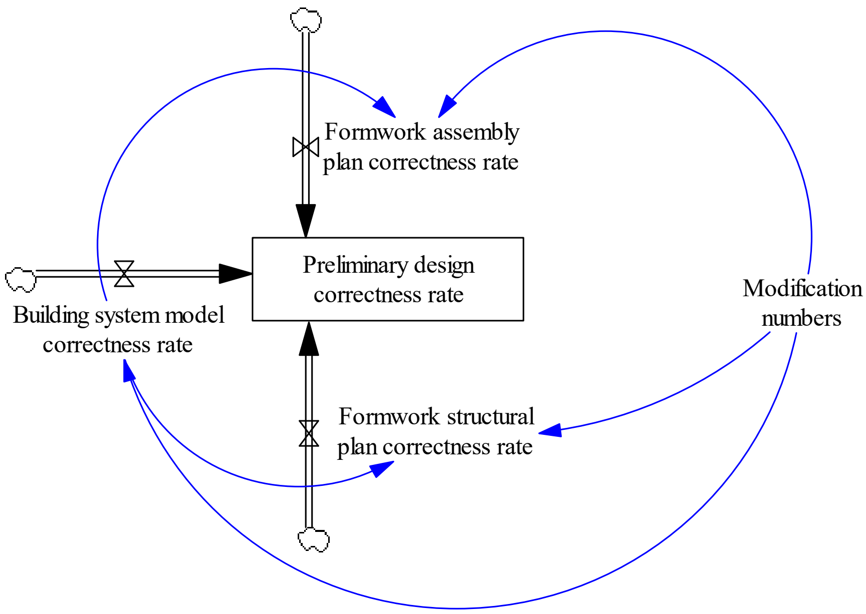

Fig. 13. Preliminary design stock-flow diagram

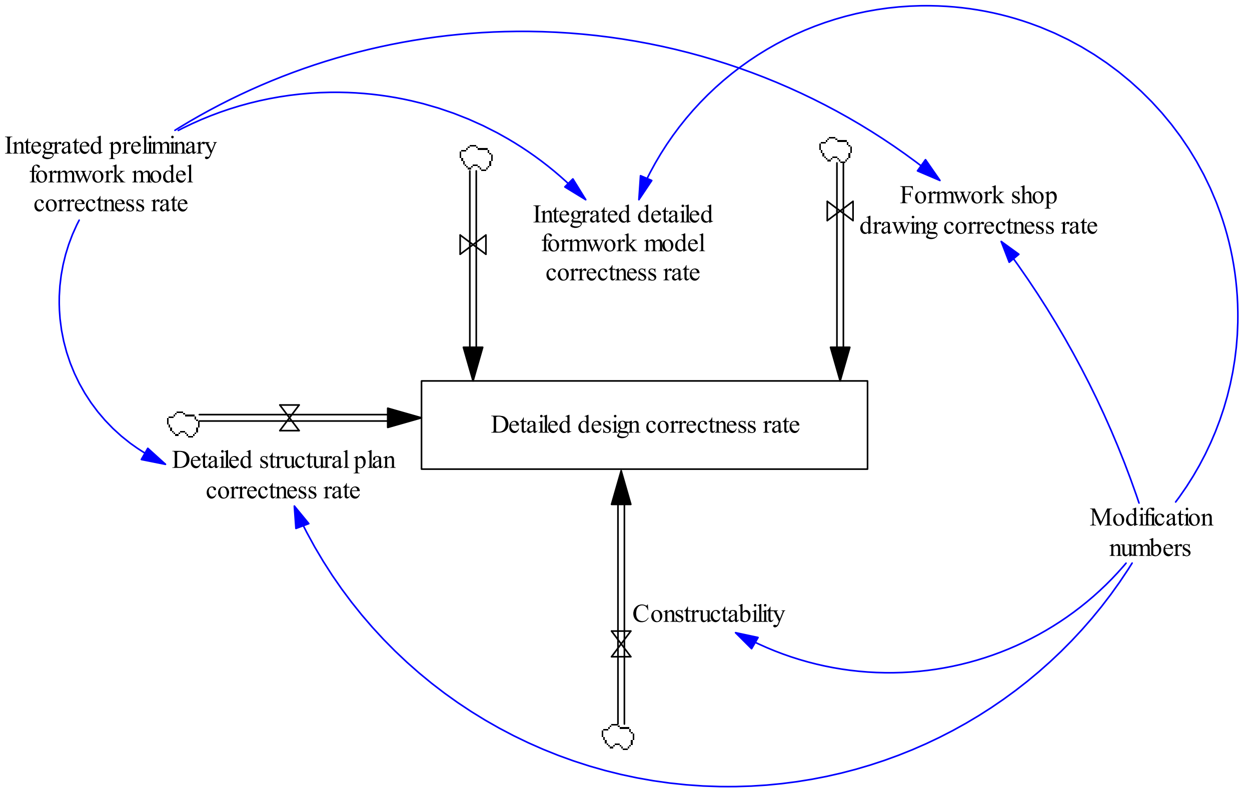

Fig. 14. Detailed design stock-flow diagram

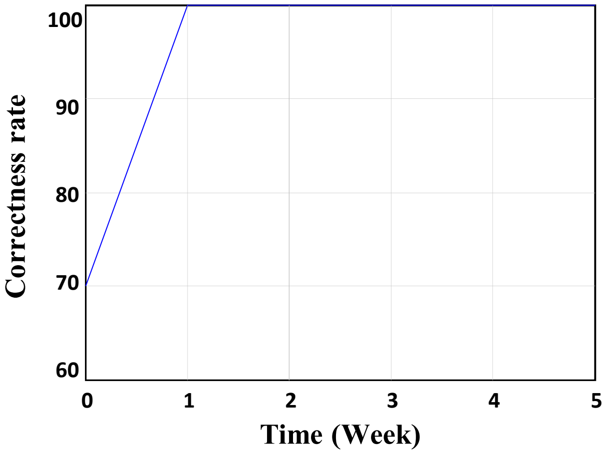

Fig. 15. Preliminary design correctness rate

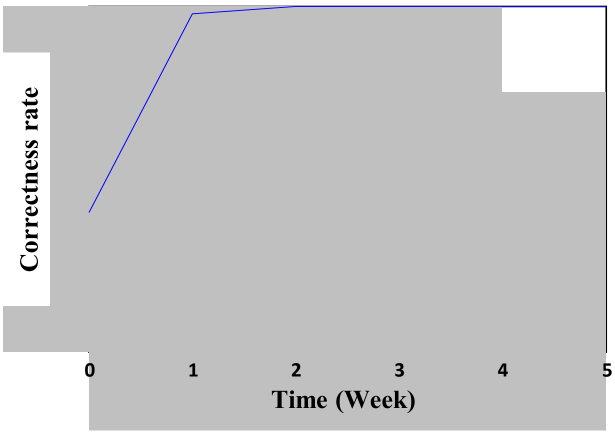

Fig. 16. Detailed design correctness rate

5.4. Waste Analysis

Poor design frequently results in change orders and waste, such as rework during construction (Anastasopoulos et al., 2010; Aleisa, 2011). Waste caused by design error is analyzed to help understand the influence of design error on the construction phase. To save time, when design errors are found in the formwork assembly, most formwork subcontractors respond by modifying assembly method or adding other materials on site, rather than by making change orders. Thus, increasing formwork design correctness can reduce waste in the assembly and processing of formwork.

Table 3. Formwork assembly and processing operations

Operation	Description	Time proportion
Measure	Measure size of required formwork	6.8%
Walk	Walk and inspect formworks	13.5%
Find	Find required materials for formworks	22.1%
Pull	Pull out nails from formwork	3.8%
Cut	Cut required materials	2.3%
Pass	Pass formworks to workers	9%
Wait	Wait while materials are located	7.9%
Nail	Nail molds to appropriate positions	31.8%
Mend	Mend gaps between molds	3.6%

Design weight in this study represents the proportion of tasks devoted to design-specific activities in the design phase, and design weights are calculated from Fig. 6, Table 1, and Table 2. For example, in the preliminary design phase shown in Fig. 6, the major design work for the formwork subcontractor is to propose a formwork assembly plan. Referring to Table 1, the formwork subcontractor accounts for 26.9% (7/26) of the evaluation items, thus the design weight for proposing the formwork assembly plan in the preliminary design phase is 26.9%. This method can be used to obtain the design weights for the lean formwork design activity shown in Fig. 6. The building system model is established by the general contractor, and occupies 26.9% of the evaluation items. The structural engineers are responsible for proposing a formwork structural plan, accounting for 46.2% (12/26) of the items in the preliminary design evaluation table (Table 1). Design weights for detailed design phase can be calculated using the same method.

Table 4. Poor design influence

Design phase	Design activity	Design weight, %	Assembly and processing design weight, %	Design-affected manpower, laborers	Design-affected value time, hours
Preliminary	Propose formwork assembly plan	26.9	15.3	21.5	171.7
	Establish building system model	26.9	15.3	21.5	171.7
	Propose formwork structural plan	46.2	26.2	36.9	295.0
Detailed	Integrate detailed formwork model	14.3	8.1	11.4	91.3
	Establish detailed structural model	23.8	13.5	19.0	151.9
	Develop formwork shop drawings	57.1	32.4	45.6	364.5
	Verify constructability	4.8	2.7	3.8	30.6

Formwork operations are analyzed to measure waste produced by poor design. In this study, formwork assembly and processing are divided into nine operations, i.e., “measure,” “walk,” “find,” “pull,” “cut,” “pass,” “wait,” nail,” and “mend.” Proportions of formwork operational time, as shown in Table 3, are adopted from (Peng, 1998).

The value-adding activities in formwork assembly and processing include “measure,” “pull,” “cut,” “pass,” “nail,” and “mend.” The proportion of value-adding activities accounts for 56.8% of operational time. Multiplying design weights obtains the design weight of the formwork assembly and processing. These weights represent the proportion of design activity results in formwork assembly and processing activity. For example, the proportion of proposing formwork assembly plan is 15.3 % (i.e., 26.9% * 56.8%).

The design weight of formwork assembly and processing multiplies the manpower (140.5 laborers) by value-adding time (1124 hours), to respectively obtain the "design-affected manpower" and "design-affected value time". Note that this research investigates the manpower (140.5 laborers) and value-adding time (1124 hours) at the construction site. In the activity of proposing the formwork assembly plan, the design-affected manpower is 21.5 (i.e., 15.3% * 140.5) and the design-affected value time is 171.7 hours (i.e., 15.3% * 1124). The influence of poor design is summarized in Table 4.

The formwork system in this case study was designed using traditional methods without examining design correctness or any mechanism for organizational learning. However, in building projects, the cost of rework due to design error can be as high as 35% (BRE, 1981; Hammarlund and Josephson, 1991, Choo, 2008), which implies that errors may account for up to 35% of the formwork system design, and that up to 35% of manpower used in mold assembly may be wasted. The proposed Lean Formwork Design Process can eliminate unnecessary waste in formwork assembly and processing, including 7.53 (i.e., 21.5 * 35%) laborers and 60.01 (i.e., 171.7 * 35%) working hours.

6. Conclusions

To reduce waste originating in formwork design, three methods are adopted to develop the Lean Formwork Design Process. The concurrent design method is used to reduce design errors. A visual communication platform is established through IFC and BIM. Turnkey contracts are used to enhance collaboration between members of the formwork design and assembly teams. Furthermore, to establish an organizational learning environment, a design correctness ratio is developed to gradually improve design correctness and constructability through co-review and modification. Finally, feasibility of the Lean Formwork Design Process is validated using System Dynamics on a real building project.

In current practice, formwork design and assembly are carried out respectively by the general contractor and formwork subcontractor, which results in formwork design becoming a mere formality. This research considers design correctness and constructability while designing the formwork. In addition, through the concurrent design, design team members can collaborate to help stakeholders identify problems early on, therefore enhancing design correctness. The proposed Lean Formwork Design Process feeds back information on problems to the responsible designer through design correctness evaluation. Design correctness is gradually enhanced through repetitive review and modification. The design and construction teams jointly participate in the design phase, resulting in more complete and accurate design drawings.

Analysis in this study shows that the application of the Lean Formwork Design Process can protect a project from the impact of change orders while reducing labor and operational time wastage. Future research could further analyze cost reductions due to design correctness, and could also focus on applying this process to improve different types of design activities.

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