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Exploiting digitalization for the coordination of required changes to improve engineer-to-order materials flow management

Materials flow
management

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Abstract

Purpose – The dynamic nature and complexity of construction projects make it challenging to ensure that the engineer-to-order (ETO) materials supplied onsite match changing needs. The quick and efficient communication of required changes in material fabrication, delivery and use, due to changes in the design and construction schedules, is needed to address the challenges. This study aims to provide a novel integrated management framework with its embedded informatics to help major stakeholders efficiently absorb agility during communication to deal with required changes and improve workflows.

Design/methodology/approach – An integrated management framework is developed that integrates the milestones in look-ahead plans and structured iterative processes for major supply chain stakeholders to quickly disseminate information emanating from changes in design, schedules, production and transportation. A prototype system is devised including the informatics to support the framework, which consists of BIM-RFID functional modules and a central database and uses a client-server architecture. The usefulness of the prototype is illustrated using a construction of part of a fictive but realistic high-rise building.

Findings – The integrated management framework with the informatics provides major stakeholders with the ability to coordinate their activities efficiently and stimulate their agility (measured by process time) in planning and controlling material information. Although only a fictive example was used, it is shown that the use of the system is likely to result in a substantial reduction in the time required to deal with required changes when delivering ETO materials onsite (by 18% in the example).

Research limitations/implications – The functionalities of the prototype system can be easily scaled up to coordinate changes in the design and scheduling of other types of materials. More functional developments are needed to show the extent of the possible improvement for entire construction projects. Future work should focus on investigating the possible improvements for other types and sizes of construction projects, and eventually in real-world construction projects.

Practical implications – By fitting the look-ahead plans into structured iterative processes through digital data sharing, stakeholders increased their capability to quickly capture required change information and resolve associated problems. This is particularly useful for the management of ETO supply chain processes, where prefabricated elements such as ductwork, plumbing, and mechanical systems typically have to be modified because of last-minute design and schedule changes.

Originality/value – Unlike traditional information technology (IT) based supply chain management practices, this research is characterized by a process-centered management framework that provides explicit

decision points over iterative planning processes for major stakeholders to manage material information. The iterations through digital data sharing allow stakeholders to quickly respond to last-minute changes on site, which fundamentally achieves workflow agility in the construction supply chain context.

Keywords Agility, IT/integration/implementation, BIM integration, Look-ahead plan, Change management, Supply chain processes

Paper type Research paper

1. Introduction

In most construction projects, material elements that need to be designed, engineered and fabricated to meet customer specifications are viewed as engineer-to-order (ETO) products. These ETO material elements, such as the structural steel columns and prefabricated mechanical systems, are often characterized by design complexity and manufacturing process variability, which are often the main causes of change orders and rework during construction processes (Mello *et al.*, 2015; Ji and AbouRizk, 2018). These characteristics also bring great challenges to the coordination of the material flows processes [1] or their supply chain processes (Boston Consulting Group, 2016; McKinsey and Company, 2016; KPMG International, 2018). A lack of coordination of material flow processes further results in incorrect material deliveries and material delays, which inevitably leads to over 50% of project delays and cost overruns (Caldas *et al.*, 2015; Liu and Lu, 2018). Therefore, ensuring good coordination of material flow processes by reducing the impact of required changes and process variability is essential to successful project deliveries.

Coordination, in the context of construction material flow processes, is a managerial function responsible for aligning the decisions of major stakeholders (i.e. designer/engineers, supplier and contractor) to deal with the required changes (Chen *et al.*, 2020b). Massive coordination efforts are needed in current practices for design and schedule changes to ensure the ETO components are designed and delivered as required. By nature, construction projects involve a network of stakeholders with different roles and responsibilities. The stakeholders usually work in geospatially distributed teams composed of independent firms, leading to a high degree of misunderstanding and conflict when required changes in material design and scheduling have to be coordinated. Much literature in construction supply chains describes an industry that uses *ad hoc* solutions to solve such challenges on a project-by-project basis.

To reduce *ad hoc* coordination, an integrated management system for supply chain coordination can enable more efficient interactions between contractors and suppliers. A framework for such an integrated management system should consider two emerging requirements. First, an integrated management system should make use of emerging information and communication technologies for the supply chain. Specific examples include building information modeling (BIM) (Eastman *et al.*, 2018; Wu *et al.*, 2020), radio frequency identification (RFID) (Altaf *et al.*, 2018), quick response (QR) codes (Hu *et al.*, 2018), ultra-wideband (Tomasi *et al.*, 2015), Bluetooth low energy (Moses *et al.*, 2016), near-field communication technologies (Fernandez-Llatas *et al.*, 2015), indoor global positioning systems (GPSs) (Xu *et al.*, 2019) and laser scanning and photogrammetry (Nahangi and Haas, 2016) or the integration of these technologies. Most of their use cases emphasize improving indoor positioning accuracy, shipping location accuracy and tracking installation progress, mostly in prefabricated projects. The primary advantage of these technologies is the real-time extraction of information to represent real-time delivery status and material installation status.

Second, an integrated management system should consider existing management practices for supply chain coordination. For example, supply chain agility, a concept of flexible manufacturing systems, enables contractors and suppliers to sense and enact change in response to varying demands (Parthasarthy and Sethi, 1992; Dallasega *et al.*, 2019). Supply chain agility requires increased visibility of the information on the dynamic scheduling and changing material demands to improve the responsiveness in coordinating material flow processes. It also requires a just-in-time delivery system where the time can be adjusted quickly to control the real-time material deliveries and reduce waste. The concept of agility also intertwines often with lean principles. For example, look-ahead plans are useful to improve construction workflows (as used in the Last Planner System). They could help multiple stakeholders capture changes early before they are reported too late for timely resolution (Ballard, 2000). They are useful to stimulate agile supply chain processes and reduce the rework because of late changes.

However, current management practices based on those information communication technologies have not fundamentally resolved the coordination complexities because they have lacked a process-based perspective to guide the coordination activities. Thus, stakeholders remain unclear when and what to do with the information updates over different supply chain stages. To fix this problem, this paper proposes an integrated management framework to replace *ad hoc* coordination activities with structured and agile workflows. Even though agile management and applications of BIM and RFID are common in current practices, unlike those, the proposed framework is characterized by a process-centered mechanism, integrating the milestones (i.e. decision points) in look-ahead plans and structured iterative processes in a construction supply chain context. The framework aims to bring the agility to a new level that allows major supply chain stakeholders to quickly disseminate information emanating from changes in design, schedules, production and transportation of materials.

From a theory point of view, the framework contributes to agile principles by co-applying the look-ahead plans and standard practice of agile steps. This new management framework is also considered as an essential informatics work to support the work in Chen *et al.* (2020a). Chen *et al.* (2020a) have previously only emphasized the basic units of look-ahead planning processes (i.e. macro components needed to set up the processes) to support material coordination, and the management framework in this paper provides detailed informatics of functional modules to fit agility into the look-ahead planning processes in a context of resolving design and schedule changes.

The remainder of the paper is structured as follows. Section 2 provides the context for this work concerning ETO supply chain coordination and agile management about various technological advancements as well as an explanation of the research gap. Section 3 describes the proposed integrated management framework including the main supply chain stages and roles of stakeholders. Section 4 presents how the framework is functionally demonstrated using a prototype system that is designed with BIM, RFID and a central database. Section 5 illustrates an example of the functional demonstration of the framework using a construction of part of a fictive but realistic high-rise building. Section 6 discusses the potential and limitations of the framework. The conclusion and proposals for future work are provided in Section 7.

2. Literature review

The state-of-the-art in each is synthesized in two parts: coordination of ETO supply chain processes and agile management pertaining to the implementation of advanced technologies and their close relationship with lean principles.

2.1 Coordination of engineer-to-order supply chain processes

ETO components in building projects are very unlike the mass production elements, as they are highly customized to unique order specifications and within specific ranges of installation tolerances (Mello *et al.*, 2015). For example, the glass fiber reinforced concrete columns can be designed with a comprehensive selection of colors and a variety of unique column bases, which are often subject to changes during the construction processes. It is essential to integrate design production with the downstream installation so that any uncertainties and resulting changes to these components can be incorporated and coordinated timely across different functions to meet the client's needs.

Several studies have acknowledged the importance of supply chain integration because the design changes to ETO components are demanded mostly after the production or installation has already started (Matt and Rauch, 2014; Wesz *et al.*, 2018). Design changes can be triggered by various project stakeholders, such as clients, contractors, suppliers and regulatory bodies throughout supply chain processes (Saoud *et al.*, 2017). There are often conflicting requirements and incomplete information, needing more effort to manage and coordinate the trade-offs between stakeholders. The changes can affect ongoing production and installation as the change propagates to components that have already been produced and delivered to the construction site (Han *et al.*, 2014).

A large body of literature regarding the different approaches to improving coordination of ETO supply chain have discussed supply chain transparency, supply chain visibility, supply chain collaboration, agile planning and control, lean workflows and just in-time delivery (Ala-Risku and Kärkkäinen, 2006; Young *et al.*, 2011; Lavikka *et al.*, 2015; Hall *et al.*, 2018). These concepts encourage both contractors and suppliers to have shared knowledge of the current status of the materials being requested and supplied. The sharing of knowledge also facilitates supply chain collaboration to improve stakeholder decision-making.

In practice, construction companies installed various types of online platforms to ensure collaboration of ETO supply chain stakeholders, such as Vela Systems field software Materials Tracker (Autodesk Inc, 2009), INTELSYS.build (INTELSYS.build, 2020), IBM Maximo (IBM Inc, 2020), WebTMA (WebTMA Inc, 2020) and TotalETO (TotalETO Inc, 2017). These platforms partially provide the total solutions to streamline the information flow from the design to production of ETO products and they focus on optimizing cash flow and enterprise resource planning associated with digital product design. Practical studies have shown extensive benefits by implementing these platforms in daily workflows, including supply chain agility and cost-efficiency. Further improvements are expected from such IT-supported design-to-production integration, such as enhancing users' ability to organize and track material flow milestones across different supply chain stages.

2.2 Agility in construction supply chain processes

2.2.1 Co-development of agile and lean management principles. Agile and lean management principles have co-existed for a long time and have been researched together in the context of construction management (Naim and Gosling, 2011; Virmani *et al.*, 2018). Agile is understood as an ability to quickly respond to changes required by customers in an uncertain and changing environment (Owen and Koskela, 2006). The most common agile method is Scrum, consisting of Sprint planning and review meetings for stakeholders to iteratively sets targets and deliver product increment (Streule *et al.*, 2016). Lean is understood as the ability to use the least amount of resources to give customers exactly what they want (Ballard, 2000; Braglia *et al.*, 2018). The most popular lean method is the Last Planner System including the look-ahead planning meetings for the identification of

flow constraints (Heigermoser *et al.*, 2019). Lacher and Varisco (2008) proved that agile is the implementation of lean thinking, where lean is the “what” and agile is the “how” to execute the workflows to reduce wastes.

A very recent comparative study by Poudel *et al.* (2020) has found that “rule keeper” in a Scrum planning process could contribute to the consistency and continuity in the implementation look-ahead planning sessions. They suggested that a weekly work plan could be defined as a Sprint or a usable slice of work packages of building projects. Lu *et al.* (2011) tried to create an event-flow-construction lean-agile model and simulated it for a homebuilder’s production case study. Their results showed significant time and cost reduction because of the synchronized housing inventory levels with fluctuating market demands. Therefore, agile and lean methods can be intertwined to allow project teams to have the flexibility to absorb changes to business workflows. On top of that, some software applications are available for stakeholders to use and achieve agility and lean performance, such as KanBIM (Sacks *et al.*, 2013), Visilean (VisiLean, 2020), Lean4Team (Lean4Team, 2019) and vPlanner (vPlanner Inc., 2019); none of them have yet been able to provide suppliers with proactive planning capabilities to specifically cope with required changes together with contractors for supply chain processes.

2.2.2 Technological advancements for agility. Apart from its link to lean methods, agility in construction has been achieved by using construction automation (Chen *et al.*, 2018) and digital manufacturing (Hall *et al.*, 2019) technologies. These have included a wide range of integrated applications of BIM and wireless transmission technologies. Taking four-dimensional (4D) BIM and RFID technologies as an example, researchers have focused on providing quick and reliable bidirectional communication platforms for networked project participants and have improved the efficiency of tracking and exchanging material information.

Numerous case studies have shown that the use of integrated application of BIM and RFID has particular promise, considering the parametric modeling capability of BIM authoring software and the durability of RFID tags in harsh and dirty construction sites. Chin *et al.* (2008) integrated 4D models with RFID in an information system to support logistic management. They validated the system in a real-world high-rise building project and concluded that a true win-win situation is possible between the general contractor and manufacturer. On the basis of this framework, Shin *et al.* (2011) developed a service-oriented integrated information framework for intelligent management purposes. They identified the challenges of frequent changes during design and planning processes and then implemented the framework to encourage project stakeholders to make decisions quickly. They found that the time efficiency was raised by about 32% compared to the traditional supply chain management. A similar study was conducted by Yin *et al.* (2009), which put a specific focus on using a standalone RFID information platform to improve the responsiveness of logistic planners. Bortolini *et al.* (2019) have shown that the integration of BIM and RFID allowed contractors and suppliers to easily access a synchronized database, which contains both the information of construction schedules and parametric design in three-dimensional (3D) models. Their case study results showed that automatic collection of materials quantity take-offs improves the efficiency of logistics planning.

Through those studies, it was proved that the integrated BIM and RFID platforms helped reduce the time needed for addressing requests for information on material orders, minimizing wrong orders, and ultimately helps ensure the right deliveries. The time reduction also reflects great agility from design to construction processes over the entire supply chain. When combined with the required workflows, the BIM and RFID integration could further stimulate the agility in ETO projects.

2.3 Identification of the research gap

A summary of the relevant works is presented in [Table 1](#). Current management practices based on those information communication technologies have not fundamentally resolved the coordination complexities because they have lacked a process-based perspective or framework to guide the coordination activities. Thus, stakeholders remain unclear when and what to do with the information updates over different supply chain stages. This calls on a process-centered agile mechanism, integrating the milestones in look-ahead plans and structured iterative processes in a construction supply chain context. Two research gaps emanating from the literature are therefore summarized:

- Research gap one: What would be the management framework that enables major stakeholders to collaborate over iterative planning processes and shield the material flow processes from negative impact by last-minute changes?
- Research gap two: What would be the informatics to functionally demonstrate the framework?

3. The integrated management framework

To address research gap one, this paper develops an integrated management framework to incorporate structured iterative look-ahead planning processes into a digital workflow. Its theoretical foundation is therefore the interaction between lean and agile methods, which focuses on a flow perspective to prevent mistakes in the downstream phase through early mistake proofing in the upstream phase. The schematic representation of the proposed integrated management framework is illustrated in [Figure 1](#). The framework requires two foundational assumptions: all of the major stakeholders have agreed to share data and work through a collaborative contractual relationship, such as Integrated Form of Agreement and the data accessibility and ownership are well defined for every stakeholder in the project contract. Compared to that, the schematic representation of the traditional management framework is illustrated in [Figure 2](#).

In [Figure 1](#), within the integrated framework, following the concept of “Sprint,” each planning session is organized with a short length and quickly iterates (iteration 1, [...], iteration $n + 1$) until all the material orders and tasks are completed. In contrast, the traditional framework contains multiple long planning sessions that overlap, which causes ambiguity during the transfer of information for required material orders and associated tasks. Besides, stakeholders have to work on standalone databases, including using multiple spreadsheets and relying on fragmented message flows via e-mails and phone calls. For each iteration of the planning session in the integrated framework, there are three unique features as described below.

First, a look-ahead plan is used based on digital information flowing among stakeholders. It is determined based on the consensus of the project participants on when the tasks in the upcoming weeks start and finish in the look-ahead planning period. In the shared database, it contains:

- the work zone(s) in which the work will be conducted;
- the sequencing of the tasks;
- the constraints on the tasks (i.e. the constraints of labor preparation, machine preparation, space preparation, permits and precedential relationship constraints);
- the daily update notifications to be sent when the tasks are pulled and changes to schedules are made; and

Papers	Focus	Main approach	Highlights of potentials	Focused supply chain phase	Perspective
This research	Coordination of required changes through look-ahead planning processes	Development of integrated management framework and design of a prototype system	Collaborative and agile decision-making, preventive control of changes	Design to site installation	Both workflow and technology perspective on material flows
Matt and Rauch (2014), Mello <i>et al.</i> (2015), Saoud <i>et al.</i> (2017), Wesz <i>et al.</i> (2018)	Supplier involvement in contractor's decision making processes	Qualitative analysis and case studies	Collaborative decision-making	Design to site installation	Workflow perspective on material flows
Lu <i>et al.</i> (2011), Sacks <i>et al.</i> (2013), Sreule <i>et al.</i> (2016), Braglia <i>et al.</i> (2018), Heigermoser <i>et al.</i> (2019), Dallasega <i>et al.</i> (2019), Chen <i>et al.</i> (2020a)Poudel <i>et al.</i> (2020)	Lean and agile implementation to remove constraints and ensure workflow continuity	Case studies or prototype demonstration	Iterative and structured planning processes	Site installation	Workflow perspective on installation tasks
Commercial platforms: Visilean Lean4Team vPlanner Chin <i>et al.</i> (2008), Yin <i>et al.</i> (2009), Shin <i>et al.</i> (2011), Bortolini <i>et al.</i> (2019) Commercial platforms: Vela Systems field software materials tracker; INTELSYS, build; IBM Maximo; WebTMA; TotalETO	Automation of the inter-firm's information flows through integration of heterogeneous information (e.g. BIM, RFID)	Development of prototype or commercial software platforms	Pervasive deployment with low-cost tags, material status visibility, indoor location accuracy	Logistics/inventory Building operation and maintenance	Technology perspective on material flows

Table 1.
Summary of the relevant works

- the actions to be taken following the decisions made at the two decision points (e.g. the action items to postpone the transportation of materials).

Second, each planning session requires a common data environment (in a form of a shared database) to support the following steps:

- Step P1 – Architects, engineers, contractors and suppliers work collaboratively to exchange the change-request forms, drawings and documentation of design changes to resolve a design change.
- Step P2 – Contractors need to check the site schedule and update the look-ahead plans considering the design impact on the estimated start dates of look-ahead tasks (e.g. installation tasks in the upcoming N weeks) (i.e. highlighted yellow area in Figure 1).
- Step P3 – Once the look-ahead plans receive updates, the suppliers need to update new order information and production lead times taking into consideration the impact of design changes and schedule changes.
- Step P4 – Once updated look-ahead plans indicate newly estimated task start time and production lead time, the suppliers can estimate the appropriate transport lead time to ensure that the delivery can meet the changed need time.

Figure 2.
Traditional
management
framework

- Steps P2, P3 and P5 – A feedback loop starts and could undergo numerous iterations, before design freezes or material production starts or material transport starts.

Third, each iteration contains two decision points, which are two milestones that suppliers and contractors co-monitor continuously to prevent the possible negative impact of last-minute changes:

- (1) Milestone 1 – The time to freeze design for production.
- (2) Milestone 2 – The time to freeze the transport time of materials.

The determination of the two milestone dates is dependent on site progress, production lead time and transport lead time. The control process is highlighted in the gray box in Figure 1. This also ensures that the ETO elements will not be produced until they are asked.

Compared to Figure 1, iterative planning sessions are not organized using the traditional framework because of the long and overlapping planning horizons. Also, there are no explicit decision points regarding the milestones in the traditional framework. The resolution of the changes is reactive and always late.

4. Prototype for the integrated management framework

To address research gap two, a prototype system for the integrated management framework is described here. It is developed to enable the synchronization of data from BIM authoring software, RFID tags and look-ahead plans. It consists of four functional modules and a system architecture that have been specifically designed to enable the coordination of changes address near term progresses. The details are described in the subsequent subsections.

4.1 Functional modules

Based on the features of the integrated management framework, the prototype system is devised to consist of four functional modules to facilitate contractors and suppliers to exchange information updates for the look-ahead plans. They are as follows:

- the design-change module;
- the schedule-change module;
- the production module; and
- the transport module.

A summary of each is provided in [Table 2](#).

4.1.1 *Design-change module.* To fulfill the required process P1 in [Figure 1](#), the design-change module is developed to include the information exchange on component design drawings, specifications and a couple of change request forms.

The design-change module is only accessible by the contractors. The design information comes from the BIM authoring software, where each of the ETO component are designed parametrically as a unique element. An element identity (ID) is assigned automatically to an ETO component, when it is modeled in BIM, which is also linked to a task ID that represents a specific construction task. The contractors are able to either query material information by its element ID or task ID. The bill of materials (i.e. a list of material requirements) for that design type or that installation task is then automatically generated.

Table 2.
Summary of the
functional modules

Functional module	Functions	Authority to access all the functions		Processes involved in Figure 1
		Contractors	Suppliers	
Design-change module	Information exchange on component design drawings, specifications and change-request forms	Yes	Partially yes (the “design freeze” function is not accessible)	P1
Schedule-change module	Information exchange on task planning information	Yes	No	P2
Production module	Information exchange on material purchasing orders and production details	No	Yes	P3, P4
Transport module	Information exchange on the arrangements of material transport and quality inspection (including re-shipping if needed)	Partially yes (only can access to quality inspection function)	Yes	P5, P6

When any design change is required, change requests will be initiated either by suppliers or by contractors in this module. The design-change module, therefore, includes functions to enable the exchange of change-request forms. In the proposed system, both contractors and suppliers can access the design-change module to register the change-request forms, information of which includes the request_ID, request_department, request_staff, description of request and the element ID of the affected ETO component. If any conflicts in design are resolved and the changes have been approved by the contractors, they will freeze the design for all the ETO components required for the look-ahead N weeks. The design-change module is designed to include a command button for contractors to access exclusively to freeze the design.

4.1.2 Schedule-change module. To fulfill the required process P2 in Figure 1, the schedule-change module is developed to include the information exchange on task planning for the look-ahead N weeks.

The schedule-change module is accessible by the contractors and suppliers. It provides contractors the ability to query milestone dates and edit task information for the specified look-ahead period. It shows how many installation tasks have been completed and what constraints exist for the upcoming construction tasks. This allows the contractors to identify what upcoming tasks can be committed and will be done in the look-ahead period. The information for each committed task is recorded and updated by contractors, including its task ID, the planned start date, planned finish date and whether the constraints can be removed before the tasks start. More detailed descriptions of the design of task IDs and associated entity relationships of ID attributes are in [Chen et al. \(2020a\)](#). The commitments of upcoming tasks by each site trade are suggested to be made on Friday on a weekly basis. Considering the input of commitments, the planned start dates can be updated during the look-ahead week whether any changes to the originally planned dates are required. As the planned task start dates are the actual material need dates, they are important information for both contractors and suppliers to communicate and coordinate. The task information from this module is seamlessly automatically shared with suppliers to enable proactive decision-making on the two milestones dates for production and transport.

For the contractors to better foresee the changes and estimate the planned task start dates, a material status function is designed for the schedule-change module. The function provides the contractors with the capability to continuously track the status of the required ETO components. A list of conditional statements in programing calculates the status of each ETO component. The status of each ETO component can be queried by contractors using the element ID, order ID and task ID. The query results include different states of each ETO component as it moves through material flow processes: “material ready for transport (holding at factory),” “material in design coordination,” “release for production,” “release for transport” and “installed.” Each ETO component is also color coded for better visualization of material status information, according to the filter rules set in the BIM authoring software. In this way, contractors can quickly identify the material status for the whole building or designated look-ahead weeks in the 3D model.

4.1.3 Production module. To fulfill the required processes P3 and P4 in Figure 1, the production module is developed to include the information exchange on material purchasing orders and production details (e.g. production lead time, dates for releasing production and production status).

The production module is only accessible by the suppliers. Depending on the specific type and order quantity of ETO components, their production lead times can vary. This often causes suppliers considerable challenges to optimize production schedules for multiple projects proceeding concurrently. Additionally, it is assumed that suppliers using the

proposed system will prioritize responding to contractors who signal emergent schedule changes earlier. When schedule changes are communicated to suppliers, they will update the estimated production lead time for a particular order. Accordingly, the latest date to release production is renewed. The suppliers can query and update the information about production status of each production run (e.g. reinforcing, concreting and milling).

An order ID is assigned for a group of ETO components with the same type and the same work zone. A task ID specified in the schedule-change module indicates to which construction zone the ETO components belong. A design change may lead to a change in the type and a schedule change may lead to a change in work zone. If these changes are needed and captured, the order ID will be changed automatically in the production module. Therefore, suppliers can use the order ID to query what types are newly needed and the newly ordered quantities for the look-ahead N weeks.

4.1.4 Transport module. To fulfill the required processes P5 and P6 in [Figure 1](#), the transport module is developed to include the information exchange on the arrangements of material transport.

The transport module is accessible by the suppliers to arrange transport trucks and estimate the latest release date for transport. The suppliers need input vehicle ID, unloading location and estimated transportation lead times. ETO components that have the same need date have the same order ID. Suppliers determine the latest release date for transport for the same order, based on the schedule updates by the contractors. The suppliers also need to document the actual release date for transport in the module. The documentation helps them arrange the next transport.

The transport module is also designed to include a location tracker based on a coupled active RFID-GPS locator. For the RFID-GPS locator, a wireless communication channel is established between tagged materials and GPS, RFID, wireless and mobile networks to ascertain and communicate location of materials. The location data is sent to database servers on a regular basis (e.g. every 10 min) or when the truck moves or upon request by the suppliers or the contractors. Location data can be accessed from anywhere over the internet and displayed in the transport module. The suppliers can query what specific RFID tags are contained for one delivery via an order ID. The data is also communicated to contractors to make adjustments on task planning whether any delay is notified from the transport process. For example, if there is a significant delay because of traffic jams or accidents, the site will be notified early delay warnings.

The transport module also includes a quality inspection function for the ETO components transported on site, only accessible by the contractors. The quality of each ETO component is inspected via its RFID tag. Multiple data entries are completed through one RFID scan, which is more efficient than using bar codes or QR codes. The contractors specify the defect root causes in the module and notify the suppliers. If ETO components pass the inspection, the contractors query the associated task information to prepare the installation. By doing so, little onsite storage is needed for the transported ETO components. Temporary storage is, however, still considered if the work zone is not immediately ready for installation.

If transported ETO components fail to pass the quality inspection, the suppliers are immediately informed through the automatic transfer of quality inspection results such as the defect root causes. A re-shipping function is designed only accessible by the suppliers, which requires the input of re-ship date, responsible supplier and substitute material in case of any emergency use.

4.2 System architecture

The system is a desktop-based application that runs on 64-bit operating system with the Intel (R) Core (TM) i7-8650U CPU at 1.90 GHz. In this research, Autodesk Revit is chosen as the BIM authoring software. In the system, the data of 3D models is transferred and stored by using the Dynamo programming scripts [2] in Autodesk Revit. Dynamo programming scripts are convenient to use to obtain and set parameter values for building elements. A list of parameters of interest is exported from BIM authoring software to an Excel file. Then the Excel file is read and parsed into a shared database using Python programming language that supports both .xls and .xlsx file extensions from a local file system.

To structure the functional modules and handle the functions in the system, an architecture is established and illustrated in Figure 3. The system is developed based on a client-server architecture and is divided into three layers, i.e. the database layer, the logic layer and the presentation layer. The database layer deals with the data from different sources, such as the 3D models in BIM authoring software, the construction scheduling files and RFID tags. The logic layer organizes the four functional modules and uses the data retrieved from the database layer according to the functions. The presentation layer provides the user interface composed of Tk Graphic User Interface (GUI) toolkit. It displays the data and a list of query and update functions to users (i.e. contractors and suppliers).

Each user is connected to the network through a client and a server. The database server is responsible for supporting users to receive queries, interact with the user interface to execute the queries and send the results back to the front end (i.e. user's desktop). The database is linked with BIM authoring software and RFID system.

For the coordination of changes, contractors and suppliers need to store and exchange object information, construction information and material delivery information. Object information is the information pertaining to the ETO component, e.g. a column, a slab, a

Figure 3. System architecture of the prototype for the integrated management framework

wall, to be constructed, e.g. length, weight, color and strength. It is attached directly to an object in a parametric 3D model. Construction information is the information pertaining to construction progress, e.g. the forecasted start and finish time of a task and the requirements for the task to start. Delivery information is the information pertaining to the delivery of the ETO components, e.g. the material order approval date, the material preparation date, the material release date and time, the onsite arrival date and time, the material delivery method and the deviations from initial plans. The information is accessed, collected and updated by suppliers and contractors with role-based access control as specified in [Table 2](#).

To build the database on MySQL server, three steps need be done to integrate the data from different data sources. The first step is to export material schedule from BIM authoring software (e.g. Autodesk Revit) to Microsoft Excel files using the built-in functions (e.g. Dynamo). The second step is to export project schedule data from scheduling software to Microsoft Excel files using the project export wizard function. The third step is to extract data from RFID tags to Microsoft Excel files. The fourth step is to create and import standard data frames in MySQL server that includes these heterogeneous data, such as the change requests, production or transport lead times and milestone dates. The data is interrelated based on logic rules and keys (i.e. primary keys and foreign keys). For example, the material type of a single ETO component is referenced to a task by its unique element ID as the primary key.

Based on the system architecture, the four modules are linked to support the feedback loops and coordination of the milestone dates. A change on the onsite need date specified from look-ahead planning triggers a change on Milestone 1 (date for releasing production) and Milestone 2 (date for releasing transport). As the look-ahead planning process is used to provide a responsive workflow, it is desirable that the maximum frequency of updates of information, considering the “current” construction progress, is now less than once per week.

5. Functional demonstration and evaluation

Studies have shown that the impact of the functional demonstration is considered significant for construction management research ([Liu *et al.*, 2014](#)). Because of the difficulties to access real-world pilot projects, the functional demonstration was conducted by implementing specific modules of the prototype system. To illustrate the usefulness of the integrated management framework, Monte Carlo simulations were conducted that showed the durations of column deliveries in two material flow processes. The details of implementing functional modules and the simulation results are presented in Sections 5.1 and 5.2.

5.1 Functional demonstration

The functional modules were tested by the authors to manage the changes required in the repetitive manufacturing and installation of prefabricated columns on 22 floors of a high-rise office building. Though each floor is identical, they contain highly engineered prefabricated structural elements. The building was modeled using Autodesk Revit software. The design data included the material properties of the columns, i.e. the family and type, the length, the volume and the load-bearing capacity of each column. The prefabricated structural columns were all defined to a LOD300; this was a level sufficient for sharing among contractors and suppliers for making decisions on the required quantities and need time of the materials.

The functional demonstration of the modules was based on one case (i.e. the material flow processes for columns with order ID “06OG_Z1_003” and “06OG_Z2_001”) that was

used consistently through the processes in Figure 1. Suppliers and contractors should login into the system with usernames and passwords to access the modules.

5.1.1 Design-change module. An example of using the design-change module is shown in Figure 4, where there is a design change request regarding the column with an element ID “1774324.” The prefabricated concrete columns were modeled in Autodesk Revit software. Each of the columns had a unique element ID, which was a built-in project parameter in Revit. When the columns were modeled with reinforcement and connection details, the detailed design information could be tracked continuously and adapted with the consideration of the onsite dimensional tolerances. The design change requests were initiated either by the contractors who received the information from the structural engineers. The affected element had a field-request ID, of which the change request information was collected by the change request function. The change requests were linked to a group of other interrelated ETO components subject to potential design revisions. Changes requests were finally approved and addressed by the contractors to freeze the design. It was essential to make sure the design parameters from the 3D models were handed over to the suppliers with no errors.

5.1.2 Schedule-change module. The example of using the schedule-change module is shown in Figure 5. As there was a design change on the loading-bearing capacity of specific columns, contractors checked whether the design change led to a change in the planned start and finish dates of installation tasks in the look-ahead schedules. The task ID, “AT_OR_STR_PCO_INS_06OG_Z1,” refers to the installation of prefabricated columns in work zone Z1 on the sixth floor under structural construction discipline in the example project. According to the status in the 3D model, some ETO components for “AT_OR_STR_PCO_INS_06OG_Z1” were in production phase. In addition to the material status, contractors made estimations on the preparation work, i.e. labor preparation, machine preparation, precedential constraints, space preparation and permit preparation. Because none of the preparation work was 100% ready, the task was considered not mature enough to start and thus cannot be committed to by the trades. Based on the estimation, the contractors proposed a new planned start date and finish date for the task. The new information was then registered in the schedule-change module.

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Figure 4. Example of using design-change module (the information regarding the change request function is circled in the red box and the design freeze button is circled in the blue box)

Figure 5.
Example of using the schedule-change module (for the color-coded material status in the 3D model on the right side: pink color denominates the status “in design coordination,” yellow color denominates the status “in production,” red color denominates the status “release for production,” green color denominates the status “release for transportation” and blue color denominates the status “installed”)

5.1.3 Production module. The example of using the production module is shown in Figure 6. The order IDs of the columns for the look-ahead tasks were generated. The order ID was designed as a combination of the work zone and the material type. For example, “06OG_Z1_003” refers to column type 003 on the sixth floor. Before production, the suppliers input the manufacturing lead time needed to produce 06OG_Z1_003. Based on that, the suppliers were immediately aware of the Milestone 1 “release for production,” which is “2018–04-19” shown in the example. During the production phase, the suppliers updated the current production run on a daily basis. When production was completed, a unique RFID tag was attached to each column on its surface. The suppliers recorded the actual production lead time and actual date to release production in the production module. The actual lead time was collected and considered for the prediction of the lead time for the next production batch that was similar in type and quantities as 06OG_Z1_003. The type of the prefabricated columns was written to RFID tags, which was shared through the database server to notify the contractors on site that the required prefabricated columns were ready for upcoming installation tasks.

5.1.4 Transport module. The example of using the transport module is shown in Figure 7. Upon the completion of production of prefabricated columns with the order ID 06OG_Z1_003, the suppliers considered when to transport the columns to site. Before querying the date, the suppliers updated the transportation lead time linked with the order ID 06OG_Z1_003. Then they queried the latest date to release transport (i.e. Milestone 2) based on the latest schedule change (i.e. updated start date of look-ahead tasks) and actual production time, which is “2018–04-24” shown in the example. According to the newly estimated date to release transport, the suppliers arranged the delivery services for order ID 06OG_Z1_003. For the arrangement of delivery service, the suppliers required a shipping vehicle ID, unloading location and routes. As the proposed system was not tested with real-

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Figure 6.
Example of using the production module

Figure 7.
Example of using the transport module

world projects, the data shown in Figure 7 was artificially created and only for demonstration purposes.

After the prefabricated columns are delivered on site, the suppliers updated the actual transport lead time in the module. Besides, construction site personnel used an RFID reader to scan the tags to receive information about delivered columns. A column had a unique RFID tag linked with its look-ahead task information, therefore, it was easy for the site personnel to identify where the column should be installed (i.e. the work zone). A scan triggered an update of information about inspection staff name, inspection date, inspection method and inspection results, including the defect root causes if there were any. In the example, a column with an RFID tag “7e-4a2a-a9cf-7c157b1915d1” did not pass quality inspection because of the damages during the production processes. The defect information

was recorded in the MySQL database for the suppliers to access later to prepare the re-shipping of the column “7e-4a2a-a9cf-7c157b1915d1.”

5.2 Evaluation

Monte Carlo simulations were conducted to evaluate and compare the durations of column deliveries in two material flow processes, which are supported by the two frameworks. The simulations were not conducted for validation purposes, because of the lack of pilot projects available to test in real-world situations. However, the simulations were useful to theoretically represent the real-world process scenarios, the proposed management context and the traditional management context. Conducting such simulations was a simple and effective way to approximately show different performances in the durations of the two material flow processes. The duration could also be interpreted as a performance indicator to measure the agility of the two processes, from a holistic perspective.

The Monte Carlo simulations with 1,000 runs were conducted in this study using RiskyProject7 ([RiskyProject7 \(Schedule Risk Analysis standalone and as Microsoft Project Add-in\)](#), 2019), a plugin application in Microsoft Project. The parameter used in the Monte Carlo simulations is mainly the duration of each step in the modeled framework. The data collected for the durations was based on expert opinions from two construction professionals with over five years of work experience in prefabricated building projects. The process data is presented in [Table 3](#), which were rough estimations derived from their experience on respective daily workflows (P1–P6) concerning the two example material orders (06OG_Z1_003 and 06OG_Z2_001). Two iterations (iteration $n = 2$) of the workflows were therefore simulated. The experts estimated shorter durations for P1–P3 in the integrated management framework because of the use of the shared database. The triangular distribution TRIA (0.8, 1.0 and 1.2) was used for the steps that would need around one day time (i.e. one working day of 8 h) to complete. The triangular distribution TRIA (4.0, 5.0 and 6.0) was used for the production (P4) and installation (P7) of required prefabricated columns, each of which would not exceed one week.

[Figure 8](#) shows the comparison of the probabilistic distribution of duration of completing the specific material flow processes using the integrated management framework and the traditional management framework. The simulation results show that using the proposed framework saves 18% [i.e. $(23.3 - 19.0)/23.3 = 0.18$] in process duration to complete the material flow processes for prefabricated columns with order ID “06OG_Z1_003” and “06OG_Z2_001.” Although it is obvious that the duration for each step is less in the integrated management framework, one important fact to account for the time reduction is the short length of each iteration to plan on the two material orders. The structured and short feedback processes are not available in the traditional management framework.

6. Discussion

6.1 Agility of engineer-to-order supply chain coordination

The prototype for the integrated management framework equips stakeholders with the ability to respond fast to last-minute changes, because of the developed linkage between design, schedule, production and transportation. Besides, communication between stakeholders is supported by a common data environment. The parameters of column properties, specifications, need time for site installation, production lead time and transport lead time can be easily created, edited and updated through the four functional modules and convenient user interfaces. The changes on the material need time or design parameters can be shared instantly among the designer/engineer, supplier and contractor. Changes can be

Coordination of two material orders using the proposed integrated management framework	Coordination of two material orders using the traditional management framework		
A common data environment	Information silos		
Dynamic updates in the look-ahead plans	Rough and static information		
Preventive control of milestones in case of changes	Reactive resolution of changes on an as-needed basis		
Steps	Steps	Estimated duration (day)	Estimated duration (day)
P1: Resolve design changes in design-change module	P1: Resolve design changes using multiple 2D drawings	TRIA(0,8,1,0,1,2)	TRIA(2,5,3,0,4,0)
P2: Check site schedule and update look-ahead plans in schedule-change module (in parallel with P1)	P2: Check site schedule on a need basis using multiple spreadsheets (P1 as the prerequisite)	TRIA(0,8,1,0,1,2)	TRIA(1,5,2,0,3,0)
P3: Update need orders and production lead time in production module	P3: Update need orders and production lead time	TRIA(0,8,1,0,1,2)	TRIA(1,5,2,0,4,0)
Milestone 1: Freeze design and prepare production	No decision points available	0	–
P4: Produce the materials	P4: Produce the materials	TRIA(4,0,5,0,6,0)	TRIA(4,0,5,0,6,0)
P5: Arrange transport and update transportation lead time in transport module	P5: Arrange transport and update transportation lead time	TRIA(0,8,1,0,1,2)	TRIA(0,8,1,0,1,2)
Milestone 2: Freeze transport	No decision points available	0	–
P6: Transport the materials	P6: Transport the materials	TRIA(0,8,1,0,1,2)	TRIA(0,8,1,0,1,2)
P7: Install the materials onsite	P7: Install the materials onsite	TRIA(4,0,5,0,6,0)	TRIA(4,0,5,0,6,0)

Notes: * Although the descriptions of steps are the same, the configurations of the steps are different. Please refer the configurations of the steps in [Figures 1](#) and [2](#). TRIA (a, c, b) means a triangular distribution with lower limit value a, upper limit value b and mode value c

Table 3.
Process data collected for the two management frameworks

addressed quickly without delaying the site schedule. Using the system, the major stakeholders can be responsive and proactive to changes.

6.2 Efficiency of engineer-to-order supply chain coordination

Although only a fictive example was used, it is shown that use of the prototype for the integrated management framework is likely to result in a substantial reduction in the time required to deal with required changes when delivering ETO materials onsite (by 18% in the example based on the Monte Carlo simulations). The 18% time reduction is also relatively consistent with the test results found from other relevant research, e.g. [Li et al. \(2017\)](#) found that 15.23% of lead time was reduced by integrated BIM and RFID technology given the increased efficiency of tracking the delivery status of individual prefabricated elements. Impact on total project schedule duration and predictability should thus be substantial.

6.3 Scalability of the prototype system

The example tested was relatively simple as it only considered design changes on columns and schedule changes in a small scope, only for a specific order of prefabricated columns. From supply chain perspective, however, the example demonstration revealed the potentials of the framework to help the project stakeholders manage change requests and deliveries of prefabricated elements. Elements such as interior partition elements, ductwork, plumbing, mechanical systems and exterior cladding pre-assemblies would lend themselves to the benefits of the system, because they typically require late dimensional changes to fit the constructed structure and connection points of the building. Besides, the level of details in design and schedule change should affect the capabilities allowed by using the functional modules. As suggested by [Leite et al. \(2011\)](#), the intended use of a 3D model substantially affects the richness of the information embedded in it. Considering that coordination can occur at different hierarchical levels, different levels of details in coordinated information should be investigated using the system in response to changes.

The system was designed and developed using the client-server architecture to ensure a shared data environment for users. It can be easily maintained and configured to

Figure 8. Comparison of probabilistic distribution of duration of completing the specific material flow processes between using the integrated management framework and the traditional management framework

accommodate specific projects, including ones of larger sizes. Because of the limited access to real-world projects, however, it is challenging to test the scalability and compatibility of the system with different projects. Additionally, the system architecture can be reconfigured to a cloud service architecture, which improves collaborative working culture to integrate major stakeholders. For example, the proposed system could be built on Microsoft Azure, so that it would be easily scalable and synchronization among different project stakeholders could be managed most effectively.

6.4 Suggestions for the development of the prototype system

Considering the practical implications on the real-world cases, the following suggestions could be deduced for the further developments of the prototype system:

- More intelligence is required in the system to enhance the reliability of decision-making processes (Ji *et al.*, 2019). In the production and transport module, the determination to update production lead time and transportation lead time remained dependent on personal experience. To address this issue, history data could be used in predictive algorithms, such as the sequential pattern-mining algorithm suitable for time prediction, to be incorporated in the logic layer in the system.
- Although a common data environment was incorporated to streamline the information between the suppliers and the contractors, it is still challenging to fully overcome the data interoperability problems. Therefore, a universally used standard data format is required to support to form the common data environment.
- Considering the practicality of implementing the system in real projects, the design of the system should add a focus on cyber security and data protection. This is particularly important if the proposed system is going to be extended to include financial functions, such as receipts of payments from the project stakeholders.
- Highly relevant to the data protection issue is the legal problem during the use and maintenance of the data. In the proposed framework, the roles and responsibilities of the stakeholders were simplified; however, they are very complex in real-world scenarios. There are emerging contractual frameworks, such as the integrated project delivery construction agreements (Hall *et al.*, 2018), to help define a clear legal boundary for the collaboration of different stakeholders. Besides, with the emergence of blockchain technology in the construction industry, these issues could be effectively avoided because the ownership and power to edit data remain with the original creator of the file (Hunhevicz and Hall, 2020).

7. Conclusion and future work

This paper presented a framework for an integrated management system to use information from BIM and RFID to support iterative look-ahead planning processes to help major stakeholders shield material flows from negative impact by last-minute changes of design or schedule. To functionally demonstrate the framework, four functional modules were devised:

- (1) design-change module;
- (2) schedule-change module;
- (3) production module; and
- (4) transport module.

They were linked via a central database system built for a common data environment. The client-server system architecture was established to structure the functional modules of the logic layer, the integrated data layer and the user interface of the presentation layer. Unlike traditional IT-based supply chain management practices, this research is characterized by a process-centered management framework and provides explicit decision points over iterative planning processes for major stakeholders to manage material information. The iterations through digital data sharing allow stakeholders to quickly respond to last-minute changes on site, which fundamentally achieves workflow agility in the construction supply chain context.

The functional modules of the system were demonstrated using the construction of part of a fictive, but realistic high-rise building. The Monte Carlo simulation results show that the time spent for completing specific material flow processes can be significantly reduced (in the example by 18%) by using the integrated management framework to facilitate the coordination of design changes and schedule changes, compared to the traditional management framework. Although this is sufficient for the demonstration, it is not sufficient to show the extent of the possible improvement for entire construction projects. Future work should focus on investigating the possible improvements for other types of components and materials, other types and sizes of construction projects and eventually in real-world construction projects. In addition, various contractual types and additional supply chain roles (e.g. third-party logistic providers) will be investigated together with the real-world implementation. Agent-based modeling and discrete event simulations could be studied to reveal the process dynamics and the interactions between the major stakeholders during collaboration.

Notes

1. Material flow processes, in this research, can be defined as a path through which a construction project progresses as it is processed from raw material to finished construction product (e.g. a building), including a set of processes of the estimation, procurement, transportation, inspection and storage and material usage, involved by a network of organizations or stakeholders.
2. Dynamo (open-source graphical programming for design), available at: <https://dynamobim.org/>

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