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A systematic approach to enabling digital supply chain coordination in construction projects

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Foreword

The construction industry is racing forwards with their efforts to exploit digitalisation. The future they are pursuing is one that will have construction projects, i) started and completed in record times with minimal disruption to the users of existing infrastructure, ii) completed on budget with virtually no waste of construction materials or negative impact on the environment, and iii) that will result infrastructure of impeccably high quality. This wonderful future will be achieved by automating many of the mundane and failure prone activities on construction sites, enhancing visibility of all supply chain activities, and ensuring that there is fast and failure free information exchanged between partners. Through her thesis, Ms. Chen has made numerous contributions to achieving this future, which can be perhaps best explained together as being a systematic approach to enable digital supply chain coordination in construction projects, which includes the use of lean workflows, digital technologies, and optimization algorithms. Her first two contributions consist of an approach using a lean work flow that links the use of BIM and RFID technologies with look-ahead plans to better manage the production, delivery and use of the construction materials to be used on site, and a supporting IT framework. This approach and its implementation is the first time that detailed look ahead plans, BIM and RFID technologies have been used together in a common data environment to facilitate collaboration in the supply chain. She demonstrates the potential benefit of her approach using the management of the flow of prefabricated columns during the construction of a 22 story high-rise building in Oerlikon, Switzerland.

As all materials on construction sites are not prefabricated, Ms. Chen then proceeds to make her third and fourth contributions, by zooming in on bulk materials. Here she first modifies the approach she developed for prefabricated columns so that it can be used to manage the flow of bulk materials for the construction of concrete walls, and then extends it so that it is clear how excess bulk materials can be estimated and distributed to multiple construction sites taking into consideration fluctuating construction site demands and shipping distances. Her examples clearly show that use of her approach will lead to substantial improvements in the management of material flows for construction projects, which in turn will result in accelerated construction projects, fewer budget overruns, reductions in waste, and help ensure high quality end products.

Additionally, in the process of conducting her research, Ms. Chen helps point the way forward for the future of research in the construction industry by using agent based simulations to demonstrate the potential of her ideas. This type of research will continue to gain grounds in the years to come as the traditionally risk adverse construction industry requires substantial proof of the effectiveness of new technologies and processes before they are implemented. Through her thesis, Ms. Chen has demonstrated that she has the ability to make scientific contributions to the state-of-the-art that comfortably span the worlds of research and practice, and that she has both deep and wide insights into how the construction industry should evolve over time; both which are immeasurably important in moving the construction industry forwards. On behalf of the Institute for Construction and Infrastructure Management at the Swiss Federal Institute of Technology, Zürich, I thank her for her thorough and constant investment to her thesis, her help over the years in teaching, including her support in Infrastructure Management 1: Process, and her personal contributions to team spirit in IBI.

Professor Dr. Bryan T. Adey

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Abstract

Supply chain management plays a fundamental role in running a successful construction project to ensure cost-efficient, accurate, and on-time material delivery to construction sites. Supply chain management has been favored by researchers and construction practitioners over traditional material management practices that focus on a single logistic perspective. It can be used to manage interdependent project phases and improve stakeholder relationships. Although supply chain management helps stakeholders complete construction projects, the problems associated with material flow processes, such as material delays, rework, and incorrect deliveries remain frequent due to a lack of efficient supply chain integration and coordination. As a result, projects often face schedule delays and cost overruns. To keep construction projects on time and on budget, novel methodologies are needed for the management of material flow processes.

Good management of material flow processes requires efficient coordination of material and associated information flows, which leads to reduced misalignment in deliveries. Responses to this need often focus on the use of advanced management principles, technologies, and intelligent algorithms to manage the supply chains. Lean management principles and Industry 4.0 technologies combined with various optimization algorithms have dominated manufacturing supply chains in the past decade and have the potential to enhance stakeholder collaboration and workflow efficiency. The supply chain processes in construction projects are normally dynamic in nature and are subjected to open-air environmental conditions. This adds considerable uncertainties to the management of material flows from the planning phase to the installation phase, in contrast to the manufacturing processes that happen in a closed and consistent work environment. Data silos further limit the capabilities of construction stakeholders to collaborate and inhibit the reliability of their decisions on material supplies and demands. To overcome the challenges and limitations, prevailing principles and methods in manufacturing industry are required to address the needs of construction supply chains. In pursuit of this, the dissertation aims to *develop a systematic approach and the corresponding techniques to improve the coordination of material and information flows in construction projects, considering the integration of lean workflows, digital technologies, and optimization algorithms, with a special focus on stakeholders' collaborative decision-making processes.*

The first part of the dissertation focuses on the comprehensive review of contemporary supply chain management in construction projects. Various methods that facilitate construction supply chain coordination are identified through different review processes. One review is conducted to develop an objective and data-driven assessment of the use of automation and digital technologies to provide a better understanding of their potential benefits and limitations. The other review summarizes useful enablers to facilitate the coordination activities and to link different construction supply chain stages (i.e., design-to-production, production-to-logistics, and production-to-site-assembly). Results from both reviews suggest that a holistic integration of the supply chains and stakeholders' collaborative decision making through digitalization (e.g., integrated BIM-IoT technologies) together with and lean workflows are essential to improve supply chain coordination but are missing from current practices. This part lays the knowledge foundation for the second and third parts of the dissertation.

The second part of the dissertation explores the combination of lean principles and digital technologies; namely, lean workflows with integrated management systems. The lean workflow is designed to link digital information on material demands with look-ahead plans. This is illustrated in the material flow processes for the erection of an office building with prefabricated columns. The performance of the lean workflow is compared with that of a traditional workflow using discrete-event simulations. The lean workflow advances the traditional workflow as it allows project participants to combine detailed look-ahead plans with BIM and RFID technologies to better manage material flow processes. It is particularly useful for the management of engineer-to-order components considering dynamic site progress. To embed the lean workflow in a digital platform, an integrated management system is developed that focuses on the communication of design-change and schedule-change information. The system includes design-change, schedule-change, production, and transport functional modules. Project stakeholders can prevent material flows from the negative impact of late change using the system to digitally support the lean workflow. The system uses a client-server architecture, though it can be easily reconfigured to a cloud-based system architecture. The capability of the system to improve the coordination of changes over an engineer-to-order material flow process simulation of the office building project is demonstrated to be superior than that of the traditional management framework. This work represents the first instance where detailed look-ahead plans, BIM, RFID, and a common data environment are integrated in supply chain collaboration to replace otherwise ad-hoc procedures.

The third part of the dissertation moves the focus to the management of bulk commodity. This part explores the combination of lean principles, digital technologies, and optimization algorithms to improve stakeholders' decision-making processes in the coordination of material flows. This part selects ready-mix concrete as a representative type of bulk commodity to study this dynamic. Given the fluctuating demand for concrete, an approach that uses digitized information within a short-term planning window is presented to improve the ordering of concrete by minimizing waste and cost. The approach consists of two main steps that contractors should take: 1) monitoring the dynamic demand fluctuations using a 4D model that captures the as-built site progress and updated look-ahead schedules, 2) modifying original orders to accommodate the demand fluctuations where quantities of additional orders and outsourced orders are determined by a heuristic evolutionary algorithm. The proposed approach is demonstrated to be useful to provide optimal order quantities of concrete with minimal costs within a five-day planning window. The scope of implementing the approach is expanded from a single project to a group of projects in a contractor's or owner's broader portfolio. To optimize the allocation of materials among multiple projects, a transshipment method is developed to enable the lateral sharing of materials in a supply chain network using the same two-step approach; a streamlined coordination process comprising the extraction of digital information and the decision-making on material allocation. To accommodate the expansion of the approach to varied material demands among projects, a network model is required to simulate the material and information flows from one project to another. Either within or among projects, the implementation of the two-step approach in both cases proves the benefits of balancing the daily material supply and demand according to a continuously updated schedule. As a result, the materials can be managed with minimal waste and costs.

This dissertation contributes to the field of construction management of material flow processes by providing a systematic approach and corresponding techniques to address the challenges in construction supply chain processes. More precisely, it provides a novel method for integrating lean principles, digital technologies, and optimization algorithms for construction supply chain practices. The proposed approach improves supply chain efficiency, transparency, agility, sustainability, and accuracy, paving the way for a better future of construction projects.

Zusammenfassung

Das *Supply Chain Management* spielt eine grundlegende Rolle bei der Durchführung eines erfolgreichen Bauprojekts, um eine kosteneffiziente, genaue und pünktliche Materiallieferung an die Baustellen zu gewährleisten. Supply Chain Management wird von Forschern und Baupraktikern gegenüber traditionellen Materialmanagementpraktiken bevorzugt. Es kann verwendet werden, um voneinander abhängige Projektphasen zu verwalten und die Beziehungen zu den Interessengruppen zu verbessern. Obwohl das Supply Chain Management den Beteiligten bei der Fertigstellung von Bauprojekten hilft, sind die mit Materialfluss verbundenen Probleme wie Materialverzögerungen, Nacharbeiten und Fehllieferungen, aufgrund mangelnder effizienter Integration und Koordination der Lieferkette, nach wie vor häufig. Infolgedessen kommt es bei Projekten regelmässig zu Terminverzögerungen und Kostenüberschreitungen. Um Bauprojekte im Zeit- und Budgetrahmen zu halten sind neue Methoden für das Management von Materialflussprozessen erforderlich.

Ein gutes Management von Materialflussprozessen erfordert eine effiziente Koordination von Materialfluss- und damit verbundenen Informationsflüssen, was zu einer Verringerung von Fehlerquote bei Lieferungen führt. Antworten auf dieses Bedürfnis konzentrieren sich oft auf den Einsatz fortschrittlicher Managementprinzipien, Technologien und intelligenter Algorithmen zur Verwaltung der Supply Chains. Lean Management Prinzipien und Industrie 4.0-Technologien in Verbindung mit verschiedenen Optimierungsalgorithmen haben in den letzten Jahrzehnt die Supply Chains in der Produktionsindustrie dominiert und haben das Potenzial, die Zusammenarbeit der Beteiligten und die Effizienz der Arbeitsabläufe zu verbessern. Die Supply Chain Prozesse bei Bauprojekten sind in der Regel dynamischer Natur und sind unter freiem Himmel Umweltbedingungen ausgesetzt. Dies führt zu erheblichen Unsicherheiten beim Management der Materialflüsse von der Planungsphase bis zur Installationsphase, was sich gegenüber den Produktionsprozessen unterscheidet, die in einer geschlossenen und konsistenten Arbeitsumgebung ablaufen. Datensilos schränken die Möglichkeiten der am Bau Beteiligten weiter ein, Unsicherheiten zu minimieren und zuverlässige Entscheidungen über Materialangebot und -nachfrage zu treffen. Um die Herausforderungen und Einschränkungen zu überwinden, könnten die in der Produktionsindustrie vorherrschenden Prinzipien und Methoden auf die Bedürfnisse der Supply Chains im Baugewerbe angewandt werden. In diesem Sinne zielt die Dissertation darauf ab, einen systematischen Ansatz und die entsprechenden Techniken zu entwickeln, um die Koordination von Material- und Informationsflüssen in Bauprojekten zu verbessern, wobei die Integration von Lean-Workflows, dig-

italen Technologien und Optimierungsalgorithmen unter besonderer Berücksichtigung der kollaborativen Entscheidungsprozesse der Beteiligten berücksichtigt wird.

Der erste Teil der Dissertation konzentriert sich auf eine umfassende Übersicht des heutigen Supply Chain Managements bei Bauprojekten. Es werden verschiedene Methoden identifiziert, welche die Koordination der Supply Chains im Bauwesen erleichtern. Zum einen wird eine objektive und datengestützte Bewertung des Einsatzes von Automatisierung und digitalen Technologien entwickelt, um ein besseres Verständnis ihrer potenziellen Vorteile und Anwendungsgrenzen zu erhalten. Zum anderen werden nützliche Hilfsmittel zusammengefasst, die die Koordinationstätigkeiten erleichtern und die verschiedenen Stufen der Supply Chains im Bauwesen (d.h. vom Entwurf bis zur Produktion, von der Produktion bis zur Logistik und von der Produktion bis zur Montage vor Ort) miteinander verbinden. Die Ergebnisse beider Übersichtsarbeiten deuten darauf hin, dass eine ganzheitliche Integration der Supply Chains und der kollaborativen Entscheidungsfindung der Beteiligten durch Digitalisierung (z.B. integrierte BIM-IoT-Technologien) zusammen mit schlanken Arbeitsabläufen für die Verbesserung der Supply Chain Koordination unerlässlich sind, aber in der derzeitigen Praxis fehlen. Dieser Teil legt die Wissensgrundlage für den zweiten und dritten Teil der Dissertation.

Der zweite Teil der Dissertation untersucht die Kombination von Lean-Prinzipien und digitalen Technologien, nämlich Lean-Workflows mit integrierten Managementsystemen. Der Lean-Workflow soll digitale Informationen über den Materialbedarf mit den Look-Ahead-Plänen verknüpfen. Veranschaulicht wird dies an den Materialflussprozessen für die Errichtung eines Bürogebäudes mit vorgefertigten Säulen. Die Performance des Lean-Workflows wird mit der eines traditionellen Arbeitsablaufs unter Verwendung ereignisdiskreter Simulationen verglichen. Der Lean-Workflow stellt eine Weiterentwicklung des traditionellen Arbeitsablaufs dar, da er es den Projektteilnehmern ermöglicht detaillierte Look-Ahead-Pläne mit BIM- und RFID-Technologien zu kombinieren, um Materialflussprozesse besser zu steuern. Er ist besonders nützlich für die Verwaltung von engineer-to-order Komponenten unter Berücksichtigung des dynamischen Standortfortschritts. Zur Einbettung der Lean-Workflows in eine digitale Plattform wird ein integriertes Managementsystem entwickelt, das sich auf die Kommunikation von Design- und Terminänderungsinformationen konzentriert. Das System umfasst funktionale Module für Designänderungen, Terminplanänderungen, Produktion und Transporte. Projektbeteiligte können mit dem System zur digitalen Unterstützung von Lean-Workflows die Materialflüsse vor den negativen Auswirkungen späterer Änderungen schützen. In dieser Studie verwendet das System eine Client-Server-Architektur, welches leicht zu einer Cloud-basierten Systemarchitektur umkonfiguriert werden kann. Die Fähigkeit des Systems die Koordination von Änderungen über einen engineer-to-order Materialflussprozess zu verbessern, wird mittels Simulation der Konstruktion desselben Bürogebäude-

projekts demonstriert. Diese Arbeit stellt die erste Instanz dar, in der detaillierte Look-Ahead-Pläne, BIM, RFID und eine gemeinsame Datenumgebung in die Supply Chain Koordination integriert werden, um die sonst üblichen Ad-hoc-Verfahren zu ersetzen. Dies geschieht unter Verwendung des Lean-Workflows und des integrierten Managementsystems.

Der dritte Teil dieser Dissertation verlagert den Schwerpunkt auf das Management von Schüttgütern. In diesem Teil wird die Kombination von Lean-Prinzipien, digitalen Technologien und Optimierungsalgorithmen zur Verbesserung der Entscheidungsprozesse der Beteiligten bei der Koordination von Materialflüssen untersucht. Fertigbeton ist ein repräsentativer Typ von Schüttgütern, der zur Untersuchung dieser Dynamik ausgewählt wurde. Angesichts der schwankenden Nachfrage nach Beton wird ein Ansatz zum Verbessern der Betonbestellung vorgestellt, der die Kosten und den produzierten Abfall minimiert und digitalisierte Informationen innerhalb eines kurzfristigen Planungsfensters verwendet. Der Ansatz besteht aus zwei Schritten, die von den Auftragnehmern durchgeführt werden sollten: 1) Überwachung der dynamischen Nachfrageschwankungen mit Hilfe eines 4D-Modells, das den Fortschritt der Baustelle im Ist-Zustand erfasst und aktualisierte Look-Ahead-Pläne berücksichtigt, 2) Modifizierung der ursprünglichen Bestellungen, um die Nachfrageschwankungen auszugleichen, wobei die zusätzliche Bestellungen und der ausgelagerten Bestellungen durch einen heuristischen Evolutionsalgorithmus bestimmt werden. Der vorgeschlagene Ansatz erweist sich als nützlich, um innerhalb eines Planungsfensters von fünf Tagen optimale Bestellmengen von Beton mit minimalen Kosten zu liefern. Der Anwendungsbereich des Ansatzes wird von einem einzelnen Projekt auf eine Gruppe von Projekten aus dem Portfolio des Auftragnehmers oder Eigentümers erweitert. Um die Zuteilung von Materialien auf mehrere Projekte zu optimieren, wird eine Umschlagmethode entwickelt, die das Lateral-Sharing von Materialien in einem Supply Chain Netzwerk unter Verwendung desselben zweistufigen Ansatzes ermöglicht; ein rationalisierter Koordinationsprozess, der die Extraktion digitaler Informationen und die Entscheidungsfindung über die Materialzuteilung umfasst. Um unterschiedlichen Materialnachfragen zwischen den Projekten Rechnung zu tragen, ist ein Netzwerkmodell erforderlich, das die Material- und Informationsflüsse von einem Projekt zum anderen simuliert. Die Anwendung des zweistufigen Ansatzes zeigte den Vorteil eines Ausgleichs zwischen dem täglichen Materialangebot und der Nachfrage basierend auf einem ständig aktualisierten Zeitplan für Materialflüsse innerhalb eines Projekts sowie zwischen Projekten auf. Als Ergebnis können die Materialien mit minimalem Abfall und minimalen Kosten verwaltet werden.

Diese Dissertation leistet einen Beitrag auf dem Gebiet des Baumanagements von Materialflussprozessen, indem sie einen systematischen Ansatz und entsprechende Techniken zur Bewältigung der Herausforderungen in Supply Chain Prozessen im Bauwesen bereitstellt. Präzisiert bietet sie eine neue Methode zur Integration von Lean-Prinzipien, digitalen Technologien und fortschrittlichen Al-

gorithmen in das Supply Chain Management im Bauwesen. Der vorgeschlagene Ansatz verbessert die Effizienz, Transparenz, Anpassungsfähigkeit, Nachhaltigkeit und Genauigkeit der Supply Chains und ebnet damit den Weg für eine bessere Zukunft von Bauprojekten.

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Chapter 1

Introduction

This chapter introduces the challenges in current practices of construction supply chain management, focusing on the coordination of material and information flows. The motivation of this thesis is explained, followed by a brief overview of related advancement on this topic and the identified research objectives. The foundational assumptions and methodology are then outlined. This chapter concludes with the description of the structure of the dissertation.

1.1 Motivation

Construction is one of the largest industries in the world with approximately 10 trillion dollars spent on materials and services every year [27]. However, compared to other industries like manufacturing, construction continues to lag behind due to stagnant productivity and low levels of digitization. Globally, the construction industry labor-productivity growth averaged only 1.0 percent a year over the past two decades, compared with 2.8 percent for the global economy and 3.6 percent for manufacturing in particular [333]. On average, construction laborers spend more than 50 percent of their workday on paper-based administrative tasks and waiting on equipment, materials, and information [258]. The construction materials and services have not been well managed overall, frequently leading to project delays and cost overruns [327, 51]. One primary reason is that construction projects are executed through temporary relationships across stakeholder groups with high levels of fragmentation throughout construction supply chains [31]. Although a group of architects, specialist engineers, suppliers, project managers, contractors, and subcontractors work on the same project, they have disparate and non-standard information exchange and coordination processes. This disjointed dynamic frequently inhibits collaboration and information exchange between project team members and increases the likelihood that a project will not meet its schedule and cost goals. Stakeholders need to develop novel concepts, processes, methods, and technologies to allow collaboration and supply chain integration and enable projects to be completed on time and on budget.

The supply chain is a concept that originated from the manufacturing industry, covering a management process of plan, source, make, deliver, and return [327]. When adapted to a construction context, it is understood as a set of processes of material estimation, procurement, transportation, inspection and storage, and usage, involving a network of firms or stakeholders [238]. The concept of a construction supply chain also challenges the traditional view of material flows, which only look at logistics and warehousing activities in construction projects [201, 12, 26]. In traditional practice, misaligned incentives and decision-making processes can make it difficult for stakeholders to establish a clear, shared understanding of project milestones and deliverables – a problem exacerbated by disconnected processes upstream and downstream of the supply chain. Supply chain management could be used to overcome these limitations and encourage collaboration throughout the construction phase [43, 239]. It focuses on the management of stakeholder relationships and the interdependence of different processes to ensure a smooth material and information flow.

Technological innovations provide many ways to improve the performance of supply chain management. In manufacturing, the concept of Industry 4.0 (Fourth Industrial Revolution) has emerged to refer to the transformation of the manufacturing industry and its production systems through digitalization and exploitation of various technologies. Examples include cyber-physical systems, embedded computer networks, and smart factories connected by the industrial Internet of Things (IoT) building blocks [249, 260]. The technical aspects of these technologies address the collection and exchange of information in real time for identifying, locating, tracking, optimizing, and monitoring of supply chain processes with decentralized control and a high degree of connectivity. They also allow a faster response to customer needs, more flexibility in production systems, and higher quality of products. To explore the same potential in construction supply chains, researchers have investigated various automation and digitalization technologies for construction needs and advocated the concept of Construction 4.0 and the digital twin systems [52, 122, 101, 159]. Examples of using digital technologies for material flow management include the integrated use of building information modelling (BIM)-based systems (e.g. 4D BIM planning platform [37] and cloud-based BIM systems [213]), and wireless transmission technologies (e.g. radio frequency identification [350, 256], barcode or quick response code [191], near-field communication [224], ultra-wideband [240], Bluetooth low-energy [254] and mobile geographical information systems [76]). Much of this research, however, focuses primarily on detailed technical aspects to improve information exchange efficiency and accuracy. The inherently dynamic nature of construction supply chains has not been adequately addressed in this previous work. The construction industry has been slow to see the benefits of the technologies and reluctant for digital transformation. Project stakeholders need to find an efficient approach to incorporate a dynamic workflow and fully integrate technologies over the whole supply chain process.

Lean principles originated from the Toyota Production System [234] are useful management principles to guide efficient workflows. Essentially, lean principles require stakeholders to optimize processes by reducing, eliminating or integrating non-value-added work [275]. The lean principles have been mainly understood to include five action principles: 1) specify the value desired by the customer, 2) identity value stream and wasted parts, 3) ensure a continuous flow, 4) establish a pull signal between steps, and 5) learn and manage steps toward perfection [234, 275]. On that basis, researchers have evaluated the appropriateness of implementing lean principles in construction projects and formulated the lean construction theories. Similarly, the theories spotlight the use of value mapping and encourage stakeholders to look beyond the local and individual efforts. Stakeholders should study the overall outcome to determine where value is added or where waste is included in each process considering the value proposition in construction projects [175]. With a special focus on implementing lean construction theories for site tasks, the pull planning and the look-ahead planning method have been used to detect daily hurdles for installation tasks, which help alleviate workflow uncertainty [17, 91, 268, 189, 218]. The lean principles unlock a novel means of addressing the dynamism of uncertainties in supply chains. Applied to construction supply chains specifically, lean principles could help fragmented stakeholder groups to identify constraints across different phases, align project goals, manage stakeholder communications, and ultimately improve the coordination of material flows.

In addition to technological innovations and lean principles, various algorithmic approach have been studied to support material flows [272, 34]. Instead of using the rule of thumb approach, algorithms could be used to support decisions on how to match the supply and demand considering various risk factors such as supply disruptions and demand fluctuations [6, 273, 245]. Concerning engineer-to-order components, the associated design change and schedule change can add additional risks to the coordination of material flow processes [125, 227, 69]. Such coordination is particularly challenging when certain bulk materials have little tolerance for variability in their delivery time, such as with ready-mix concrete (RMC) [347]. The problems of inaccurate planning on material quantities and delivery times can be alleviated by multi-objective optimization algorithms and heuristic algorithms.

Traditionally, technological innovations, lean principles, and algorithmic approach for supply chain decision making have been researched in isolation, but they may offer synergistic advantages when combined in use. Lean principles help firms guide workflows to reduce wasteful resource use. Technological innovations help automate the lean workflow so that coordination activities can be automated to reduce the time required for communication. Algorithmic approach help stakeholders replace rule of thumb decisions to better manage uncertainty in material supply and demand [5]. Combined, these offer one route of systematically approaching material flow processes, where the corresponding coordination activities can be more agile, accurate, and efficient. However, due to existing knowledge gaps, the approach is absent in literature and far from industry implementation.

1.2 An overview of advances relevant to construction material flow management

1.2.1 Advances in technological innovations

The purpose of the technological innovations related to Industry 4.0 or digital twins is to ensure data connection between virtual models with physical infrastructure. It is important to construct a connection loop between the virtual models and physical buildings for the construction supply chain network where different stakeholders from different expertise domains access data and react to changes promptly [267, 159]. For example, as the architects and construction engineers have overlapping tasks to provide building designs that can meet all the required building codes, they need a way to communicate their ideas quickly to each other through technical drawing processes. Some virtual building design software, such as BIM authoring platforms, provide opportunities for architects and construction engineers to collaborate and exchange information within a common environment.

In the construction field, BIM has been the starting point for innovating the traditional way of working (e.g., data silos, multiple 2D drawings, and numerous spreadsheets) [130, 87]. It has enabled a level of stakeholder collaboration. BIM is a well-recognized tool for regulating information flows as it is a structured data model of building information and could offer consistent information flows through open standards, such as industry foundation class (IFC) [131, 238]. With the development of cloud technologies, cloud BIM has gradually taken over the offline BIM to enable online synchronization of building information. In some real-world case studies, the general contractor or chief architect is mostly responsible for coordinating their BIM data occasionally by exchange proprietary files, which is also greatly encouraged by other stakeholders. For suppliers, BIM collaboration takes place by merging the BIM reference model with fabrication software, via BIM authoring add-ins. This allows less data redundancy and inaccuracy for the suppliers to interpret material design data that are provided by architects or contractors [129]. A very relevant case in such a scenario is the design-for-manufacturing (DfMA) project, where prefabricated building elements can be designed, produced, and installed using a shared BIM platform. Some researchers have however argued that these standalone BIM platforms only provide static design and construction data, and thus cannot capture the changing status of building elements or processes [313, 76, 276]. Therefore, only using BIM platforms for project collaboration on design information exchange is not sufficient to improve construction supply chain integration.

To increase the capabilities of BIM, wireless transmission technologies (i.e., Internet of Things as a broad term) have been integrated with BIM platforms to create the most common digital twin models. Example wireless transmission technologies include barcode, quick response code, Zigbee technology, radio frequency identification technology, near-field communication technology, Bluetooth low energy technology, and mobile field-based geographical information system. They are unique from each other regarding the range of data transmission coverage and power requirements, but have comparable potential for improving data collection [71]. In most cases, they are integrated with BIM authoring software through a collection of loosely coupled services communicating with each other following the Service Oriented Architecture design style [342, 300]. Besides technological setups, many researchers have also realized the potential of university campuses as a rich test bed for integrated BIM-IoT deployment. For example, researchers from Carnegie Mellon University developed IoT infrastructure software that uses BIM as a spatial and temporal reference point for all IoT devices deployed in the office buildings on campus. This helped the building manager visualize spatial information of building elements in real time [229]. To focus on supply chain requirements, the integrated BIM-IoT platforms help suppliers and contractors visualize building information to have the correct understanding of the supply chain processes. For example, the integrated BIM-RFID management system can provide data transparency so that suppliers and contractors can track both the site schedules and material status (e.g., delivery time and location) in real time [150, 188, 16]. While integrating BIM and wireless transmission technologies help facilitate the connectivity of data and stakeholders, it remains challenging for stakeholders to uncover the hidden problems in the supply chain processes caused by site demand uncertainties. It was found that design and engineering complexities compound these uncertainties and result in a considerable amount of schedule and design changes. For highly engineered ETO building elements, the management of supply chain processes and coordination of material flows is even more difficult. Despite the potential of integrated BIM-IoT technologies, the improvement of supply chain coordination must consider the uncertainties from the dynamic site environment.

In summary, most of the technologies are designed for stakeholders to automate information exchange and create a shared data environment for collaboration. There is, however, a gap in methodologies to support stakeholders to deal with supply chain uncertainties and risks. Stakeholders need both the technologies and associated useful workflows that guarantee quick identification of uncertainties and agility to solve the problems caused by uncertainties [128]. This is particularly true for building elements that are subject to prompt design changes and continuously changing demand time.

1.2.2 Advances in adopting lean construction principles

The purpose of adopting lean principles into the management of construction projects is to improve the construction processes with minimum waste and maximum value by meeting customer demands [175, 268, 67]. In manufacturing, existing studies provide clear evidence in both depth and breadth for lean tools and their performance. Examples include using the lean Six Sigma tool to overcome production challenges in an aerospace manufacturing company [307], using a lean KanBan system to reduce cycle time for an original equipment manufacturing company in the automobile industry [252], and using value stream mapping tool to reduce material waste and develop continuous improvement for a steel mill company [1].

In contrast to the manufacturing industry, construction projects have slowly adopted lean principles since the emergence of leanness. It is very challenging to fully adapt the lean principles into the construction domain because a construction site is more volatile than a manufacturing site that has a closed working environment. Unlike standardized products and repetitive processes in manufacturing, construction products are often customized and construction processes are often characterized by variability [201, 12]. Pulling workflows backward and minimizing waste are useful to address the variability for both lean manufacturing and lean construction because pulling workflows aim to identify constraints and remove all non-value-adding processes and activities [175]. This kind of lean workflow leads to a smoother, more manageable workflow. The potential of lean workflows is large for the construction supply chain.

The applicability of lean principles to construction has attracted numerous research efforts. Various tools have been developed to help stakeholders identify the constraints and uncertainties during installation processes. This is especially true for contractors. For example, the last planner system and look ahead plans encourage the formulation of pulling workflows and are useful for the identification of abnormal situations of a project for the upcoming two to six weeks [265]. They serve as a means to enable pull-based workflow. Another example tool of lean principles is the standardized work, which requires one to execute work through a standardized work package that consists of work sequence, workforce requirements, and clarified work scope for which a worker is responsible. From a material flow perspective, the lean implementation can bring considerable benefits as it has an emphasis on customer value and commitment to continuous improvement that have a significant impact on project performance in a systematic way.

In summary, construction projects should learn to adopt lean principles but lean construction is not a simple copy of lean manufacturing. Although different people may have different views about how to implement lean thinking appropriately in construction, there is a consensus that lean principles have a great potential to improve the reliability and stability of supply chain processes.

Nonetheless, few studies to date are based on broad empirical information to demonstrate a lean workflow. There is a gap in methodologies to support implementable lean workflow in uncertain supply chain processes that also helps stakeholders align decisions and quickly resolve the required changes, such as changes to the material design and installation schedules during construction processes.

1.2.3 Advances in algorithmic approach for supply chain decision making

The purpose of devising and testing different algorithms is to support decisions on material planning and control, including material order quantities and delivery times that are subject to variability caused by supply disruptions and demand fluctuations. A large body of literature focuses on implementing various heuristic models as well as meta-heuristic models to address these issues, thereby optimizing the purchasing, tracking, and dispatch sequencing of bulk commodity such as ready-mix concrete. This area of research tackles the problem of integrating material production (i.e., supply quantities and schedules) and truck dispatching to the site, which can be formulated as a NP-hard optimization problem.

Many related works contain efficient heuristic optimization models or algorithms, such as ensemble learning heuristics algorithms, mixed-integer network flow meta-heuristics, ant/bee colony algorithms, genetic algorithms, simulated annealing algorithms, column generation algorithms, etc. It is, however, worth noting that these heuristic algorithms differ in computational time and quality of achieved solutions for specific problem descriptions. While as indicated by most relevant studies, the basic implementation steps of the algorithms are similar. To be more specific, most relevant studies considered the just-in-time delivery of concrete as a job shop problem where the construction sites send concrete orders as the jobs to be processed. When they formulate the mathematical models for the heuristics, each concrete delivery represents a job operation carried out by one of the trucks that corresponds to a workstation. The ultimate goal is to satisfy the material demand with minimal cost or time.

Among different types of materials, ready-mix concrete has received considerable attention due to its perishability and dynamically changing demands [19, 18]. It is also worth noting that most researchers consider modelling processes for concrete supply chain optimization as non-convex NP-hard problems, and heuristic models are efficient in giving good feasible optimal results [198, 106]. Many case studies show that genetic and evolutionary algorithms are useful to find delivery solutions to match site progress with concrete supplies to achieve minimal procurement and transportation costs. Other than heuristics, some researchers investigated the potential of multi-criteria decision-making algorithms and developed a BIM-integrate TOPSIS-fuzzy framework to optimize the selection of sustainable material to meet changing demands at low costs [95]. Another multi-criteria method was developed based on a cased-based digital building system that improved the planning of materials in the early stages of the supply chain [108]. These different algorithmic approach can resolve cost overrun problems for material planning, coordination, and deliveries, but potential over-ordering and over-storage problems, after contracts are settled, have not been fully addressed.

Even though multiple heuristic algorithms have been used for different case studies, most of them have been based on known demand, and thus the uncertainty in demand has been neglected. There is still a gap in methodologies that supports the best use of information to navigate the material planning and control processes and address supply disruptions and demand fluctuations.

1.2.4 Research gaps

The brief overview of the advancements in construction supply chain practices shows that the lean construction principles, digital technologies, and algorithmic approach are three pillars to strengthen stakeholder collaboration and the coordination of supply chain processes. However, they have not been investigated in an integrated way to facilitate stakeholders' decision making and achieve full integration in construction supply chain processes. Problems remain frequent in practices, including the delay of material deliveries, the inefficient and delayed feedback processes between stakeholders, material wastes due to over-storage and over-production issues, wasted efforts in coordination processes, and considerable manual work. Four research gaps are identified below:

- *Gap 1*: Presently, the extensive implementation of digital and automation technologies for construction supply chain management focuses on replacing paper-based processes with digitization processes only for a single supply chain phase, which has prevented the potential of these technologies from fully realizing. Project stakeholders need an approach that enables them to connect all the different phases from upstream (design phase) to downstream (installation phase) when utilizing digital information to manage material flows.
- *Gap 2*: Lean construction experts are interested in putting lean workflows into practices to help project stakeholders reduce rework and wasted time due to late changes. Currently, there is no research specifically on supporting lean workflows with digital tools for the coordination of required changes, such as changes to the material design and installation schedules during construction processes.
- *Gap 3*: Currently, project stakeholders have favored utilizing the digital information to expedite the material ordering process while sticking to predefined static order plans for a specific project. However, digital information

has not been used in a way that site processes are captured continuously to reflect the material demand fluctuations, leading to considerable material delays and wastes. Presently, there is no approach to enable stakeholders to deal with demand fluctuations and make reliable decisions on material orders.

- *Gap 4*: In practice, it is easy for a general contractor or an owner to manage multiple projects at a strategic level by managing material supply and demand on a monthly or a longer-term basis, but it is difficult to manage on a short-term basis taking into consideration of the site progresses of all the ongoing projects. A lack of a tactical short-term planning approach has limited stakeholders' capabilities to make decisions on balancing material supply and demand of a group of projects.

1.3 Objectives

The dissertation aims to develop a systematic approach and the corresponding techniques to improve the coordination of material and information flows in construction projects, considering the integration of lean workflows, digital technologies, and optimization algorithms, with a special focus on stakeholders' collaborative decision-making processes. The dissertation intends to achieve two review objectives and four research objectives. By completing these objectives, the construction supply chain can improve its efficiency, visibility, agility, sustainability and accuracy.

Review objective 1: develop a comprehensive review of the use of digital and automation technologies and identify their potential to improve the overall performance of construction supply chain processes.

Review objective 2: narrow down the scope in review objective 1 to the "coordination" perspective - develop a comprehensive review of the use of contractual, procedural and technological approach to enable the coordination of construction supply chain processes.

Research objective 1: design a lean workflow to enable the digital integration of all supply chain phases from upstream (design phase) to downstream (installation phase) considering the need to pull installation demands into upstream material design and production activities. This work intends to fill Gap 1.

Research objective 2: devise an integrated management system to support the lean workflow specifically on the coordination of required changes, such as changes to the material design and installation schedules during construction processes. This work intends to fill Gap 2.

Research objective 3: develop a collaborative approach based on digital information that allows the project stakeholders to deal with demand fluctuations and make reliable decisions on material ordering plans to achieve minimal costs. This work intends to fill Gap 3.

Research objective 4: develop a multi-project coordination technique to help project contractors or owners collect digital information on material supply and demand, and optimize material flows among a network of projects to reduce waste, considering the site progresses of all the ongoing projects on a short-term basis. This work intends to fill Gap 4.

1.4 Research framework

1.4.1 Foundational assumptions

At the beginning of this dissertation, several fundamental assumptions are raised as follows.

- Lean principles, digital technologies, and algorithmic approach are three pillars to improve the supply chain coordination in construction projects, which build the theoretical foundation for this thesis, i.e., the lean-digital paradigm.
- The proposed systematic approach is implemented for the two-echelon supply chain structure, involving the tier-one supplier and other major construction project stakeholders (i.e., contractor, designer/engineer). The third-party logistic provider and distributor are not studied in this dissertation.
- The detailed site layout plan and the site traffic plan are arranged appropriately to ensure the smooth flow of material loading and unloading across the site.
- The supply chain processes for ETO elements are subject to complexity in material design and engineering processes. The supply chain processes for fresh ready-mix concrete are subject to a high volatility in demand. The two types of materials require different techniques to deal with their coordination needs.
- BIM and RFID are used for data collection and communication. SQL database is used for data storage and integration. It is assumed that the information provided by the two technologies and the SQL database is correct and usable.
- The updates of digital information are always allowed within the material lead time, meaning that the information updates can be used to make sure the materials are produced and transported only when they are asked for.

1.4.2 Research framework

The research framework refers to the structure that can hold or support the development of the systematic approach in this dissertation. The dissertation proposes a framework that is derived from state-of-the-art concepts related to digital innovations, lean principles, and algorithmic approach to improve decision making processes. To define the boundaries of this dissertation, the project scope and the material types have been considered for each research objective.

At the core of the research framework is a systematic approach proposed in this dissertation, which is defined as the broad direction towards solving a problem [138] with a system view of different ideas to improve the construction supply chain processes. The systematic approach to enabling the digital supply chain for construction projects is designed in a way that lean principles, BIM and RFID technologies, and optimization algorithms are combined to achieve the most benefits, referred herein as a generic lean-digital paradigm. The lean-digital paradigm is illustrated in Figure 1.1. The systematic approach is also designed to overcome current problems in construction supply chain practices, including the delay of material deliveries, the inefficient and delayed feedback processes between stakeholders, material wastes due to over-storage and over-production issues, wasted efforts in coordination processes, and considerable manual work. The research framework and the proposed systematic approach are outlined in Figure 1.2.

A research technique refers to the technology or action that one deploys to accomplish a specific objective [138]. There are four research techniques (T1, T2, T3, T4 in Figure 1.2) to build up the systematic approach that holds a generic lean-digital paradigm. Each research technique is formulated and used to achieve each research objective. As explained in Section 1.3, research objectives 1, 2, and 3 focus on material flow within a single project to ensure the real-time communication between stakeholders (i.e., improved visibility and accuracy), timeliness (i.e., improved efficiency) and stakeholder responsiveness (improved agility), so do T1, T2, and T3. Research objective 4 and T4 extend the scope of using the similar approach from a single project to a group of projects (i.e., a project portfolio) and investigate the material flows between projects to reduce waste (improved sustainability). Considering their applicability to different types of materials, T1 and T2 are implemented for ETO elements while T3 and T4 are implemented for bulk commodity. Based on the four research techniques, the systematic approach provides the complementary benefits of lean principles, digital technologies, and optimization algorithms to improve supply chain efficiency, information visibility, agility, sustainability, and information accuracy.

The following activities are undertaken to formulate research technique T1:

- Identify the major activities concerning the management of material flows during all phases of the construction project, from planning and design to

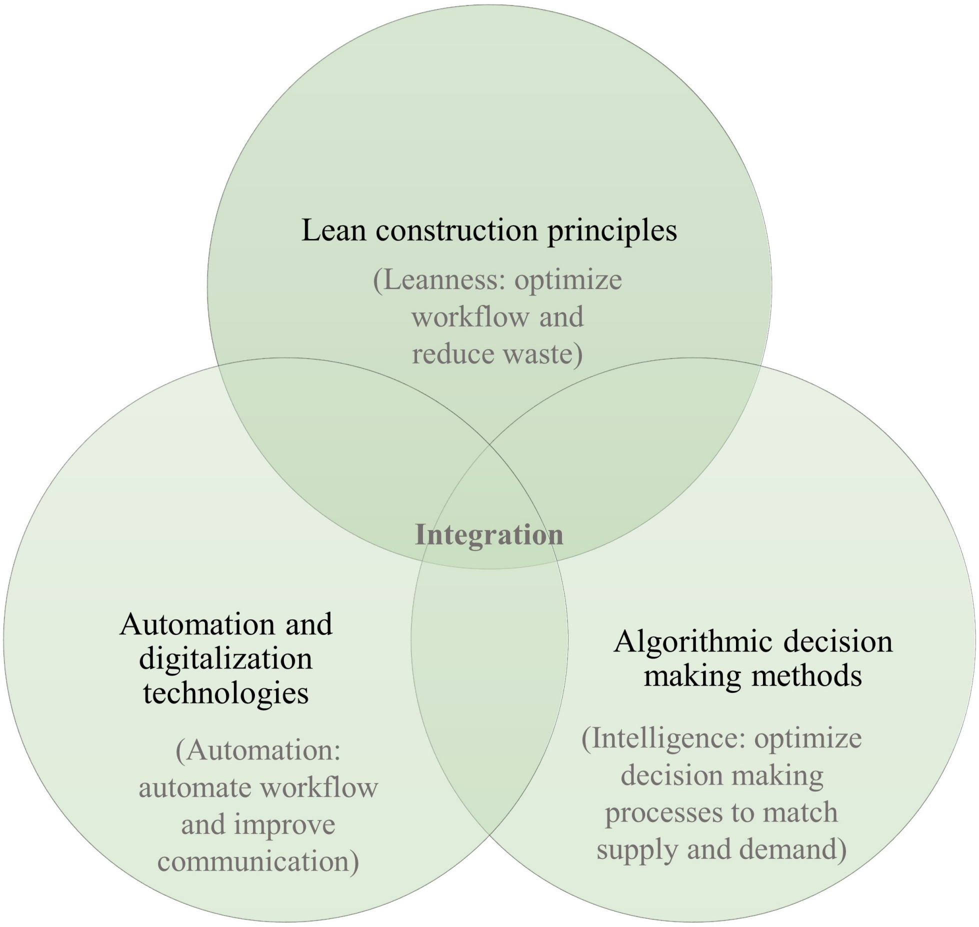

Figure 1.1: The illustration of lean-digital paradigm

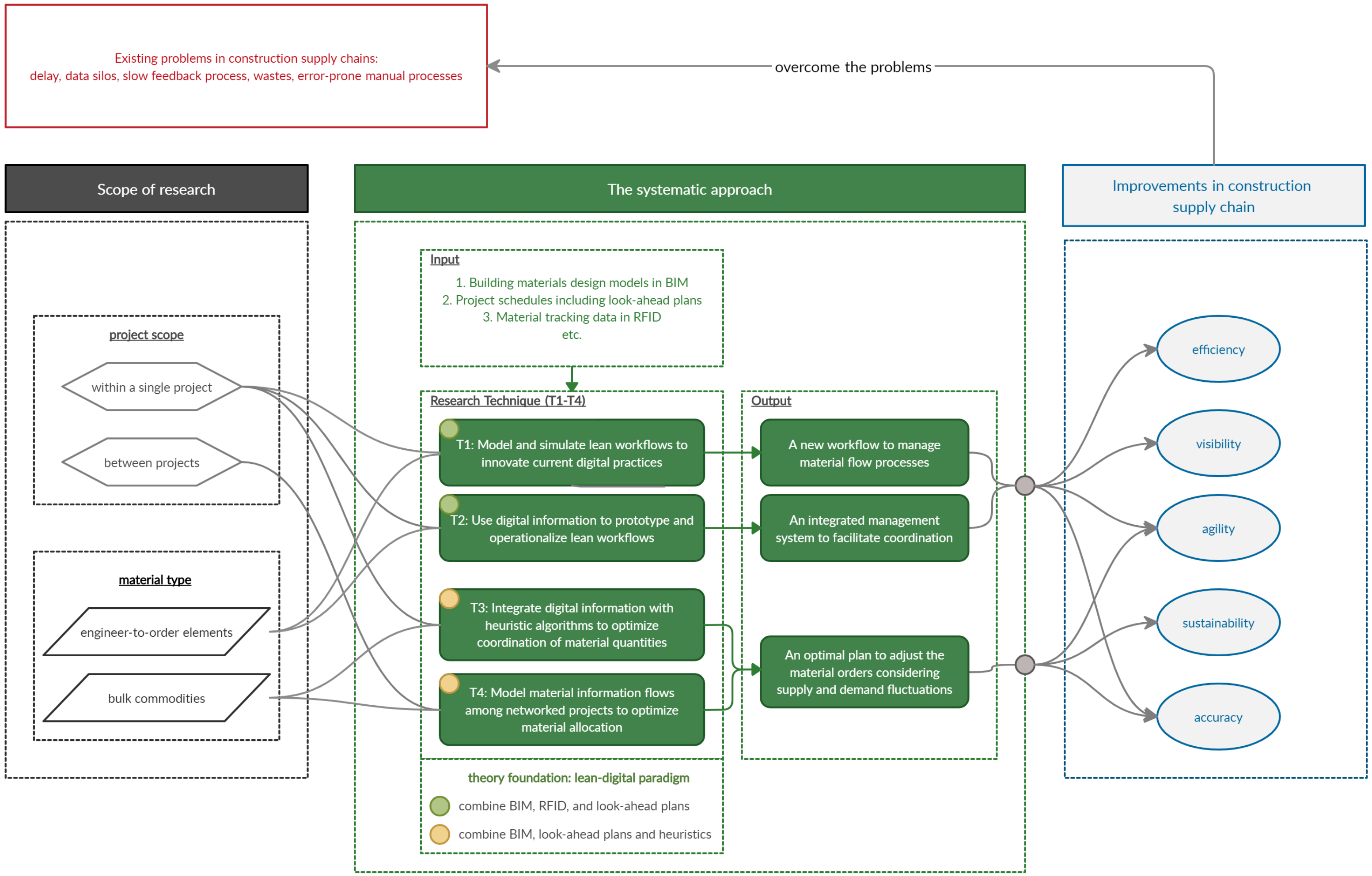

Figure 1.2: The research framework and the proposed systematic approach (i.e., the systematic approach to enabling digital supply chain coordination in construction projects)

the installation phase,

- Use business process notations to model the lean workflow and the traditional workflow to reveal the areas for improvement in material flow processes,
- Integrate look-ahead plans into an integrated BIM-RFID system that collect real-time information for each process step in the lean workflow,
- Conduct process simulations using a stochastic framework of discrete-event simulations to quantify key performance indicators of the lean workflow and the traditional workflow.

The following activities are undertaken to formulate research technique T2:

- Design an integrated management framework in comparison to the traditional management framework concerning the coordination of design changes and schedule changes,
- Identify the technological, functional requirements for the early detection and problem-solving of design changes and schedule changes,
- Develop an integrated system architecture to link multiple information sources (i.e., BIM authoring software, RFID tags, and scheduling files) regarding building elements design and associated installation schedule,
- Automate the notification of time to initiate the manufacturing and transportation of materials,
- Use the Monte Carlo simulation to demonstrate the usefulness of the proposed framework.

The following activities are undertaken to formulate research technique T3:

- Develop a management framework to deal with the different scenarios of material demand fluctuations,
- Create the 4D models to feature the use of X-day look-ahead schedules for the near-term scheduling of construction materials,
- Use a heuristic algorithm, i.e., the covariance matrix adaptation evolutionary algorithm, to provide optimal solutions for reliable re-planning of material orders based on the information from 4D models,
- Test the sensitivity of the parameters modeled in the heuristic algorithm and provide implications on the optimal solutions.

The following activities are undertaken to formulate research technique T4:

- Identify the potential of the transshipment method that is emerging from the manufacturing industry,
- Translate the transshipment method into a network model where the deficit and surplus of the perishable materials are balanced out among projects,
- Use an evolutionary algorithm to optimize the re-allocation of unused materials among different projects with minimal cost.

1.5 Structure of the dissertation

Contributing to the overall aim, the dissertation is structured in three parts. Part I contains two chapters of literature reviews as the point of departure for the following research work. Part II and Part III each contains two chapters of research techniques underpinning the lean-digital paradigm, which correspond to solutions to the four research gaps as identified in Section 1.2.4.

This dissertation is organized into eight chapters and two appendices. Chapter 2 and Chapter 3 were written to lay a fundamental knowledge on the various technologies and methodologies for the development of Chapter 4 through Chapter 7 which aim to improve supply chain coordination in construction projects. Chapter 4 - Chapter 7 represent the main research work in this dissertation, which provide detailed research techniques to address the four research gaps identified in Section 1.2.4. All of them apply the systematic approach to achieve the research aim: improving the coordination of material and information flows in construction projects, considering the integration of lean workflows, digital technologies, and optimization algorithms, with a special focus on stakeholders' collaborative decision-making processes. The chapters that are complementary to each other are grouped into one specific part of this dissertation: Part I (Literature review) is composed of Chapter 2 and Chapter 3; Part II (Improve ETO material flows) is composed of Chapter 4 and Chapter 5; Part III ((Improve bulk material flows) is composed of Chapter 6 and Chapter 7. A graphic overview of the structure of the dissertation is presented in Figure 1.3.

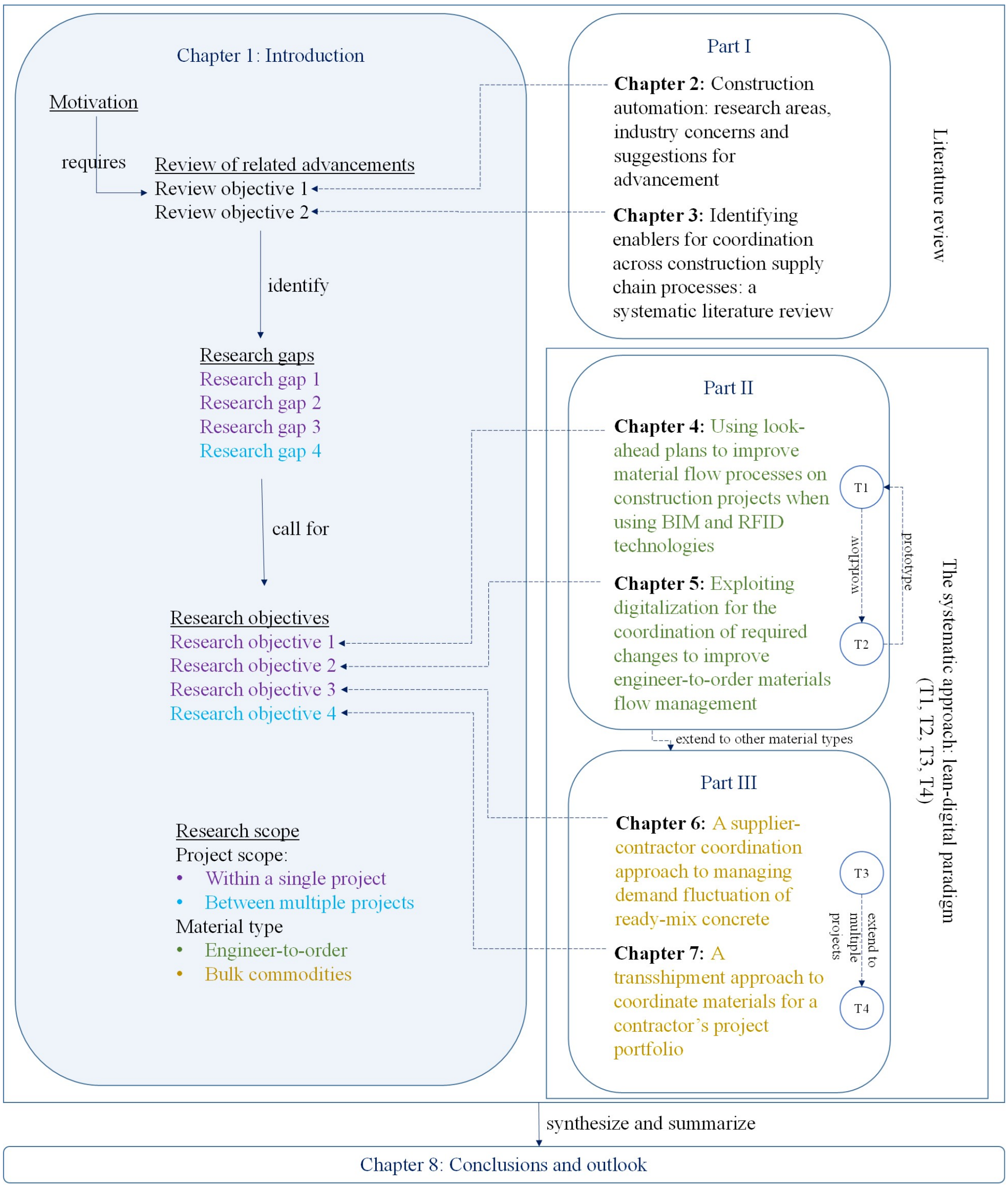

Figure 1.3: The structure of the dissertation

Chapter 1 gives an overview of the current challenges and problems that project stakeholders encounter when dealing with the coordination of material and information flows. This chapter introduces the importance and advantages of using lean principles, automation, and digital technologies and intelligent algorithms to overcome the challenges of supply chain coordination. Four research gaps are explicitly identified in this chapter. Four research objectives are raised following the introduction of two review objectives as the knowledge foundation of this dissertation. This chapter is then concluded with a description of the structure of the dissertation.

Chapter 2 provides a literature review about advanced technologies, which are prevalent in managing construction supply chain processes. In this chapter, the definitions of construction automation are unified to provide a common understanding of automation and digital technologies used in construction projects. The review is conducted by using text-mining methods on publicly available written documents, covering a wide range of relevant data including scientific publications and social media. The review identifies the most promising areas of research through the analysis of scientific publications, and the main areas of concern of industry through the analysis of text on social media, respectively. These research areas and concerns are summarized and suggestions for the industry are made to help advance the uptake of automation and digital technologies in construction projects.

Chapter 3 is a literature review that complements Chapter 2 with a specific perspective on coordination activities across different supply chain phases. To further summarize the essential research areas concerning the improvement of supply chain coordination activities, this chapter provides a systematic literature review that synthesizes relevant publications specifically concerning the approach to enable coordination, such as the lean principles and technological enablers. These publications were coded to link main research findings with specific enabler categories. This chapter also provides a clear picture of what are essential components of coordination, what should be carried out to manage reciprocal communications between stakeholders at design-to-production, production-to-logistics, and production-to-site-assembly phases, and to fulfill the needs for the integration of stakeholders for the quick response and feedback processes.

Chapter 4 is built on the contents of Chapter 2 and Chapter 3 and is written to address Research gap 1 and Research objective 1. This chapter describes a lean workflow that is designed according to the lean theory and is modeled using business process modelling notation. To digitally support the workflow, an integrated BIM-RFID database system is constructed that links information on material demands with look-ahead plans. The lean workflow is then used to manage material flows during the erection of an office building with prefabricated columns. The performance of the lean workflow is compared with that of a traditional workflow, using discrete-event simulations. The input for the simulations was derived from expert opinion in semi-structured interviews. The lean workflow model advances the traditional workflow as it allows project participants to combine detailed near-term look-ahead plans with BIM and RFID technologies to better manage material flow processes. It is particularly useful for the management of ETO components considering the dynamic site progress.

Chapter 5 is the extension of the work in Chapter 4, which further detailed the digitally supported lean workflow when managing design and schedule change requests in the ETO project context. An integrated management framework is functionally demonstrated by a BIM based system protoype. Four functional modules, including design-change, schedule-change, production, and transport modules, are designed to enable the execution of quick coordination of changes. The information is sourced from look-ahead plans, BIM, RFID, which is then integrated into a central database. A client-server architecture is established for the system. The capability of the system to improve coordination of changes over an ETO material flow process is demonstrated by using it to coordinate changes in the same building project as shown in Chapter 4. The research indicates that exploiting digitization agility in the management of engineer-to-order materials flow is possible through improved communication to replace existing ad hoc procedures and the resulting improved coordination of activities.

Chapter 6 proposes a technique to improve the coordination of the bulk commodity other than the ETO type of components, which are demonstrated in Chapter 4 and Chapter 5. Chapter 6 highlights how digital information is used for algorithm based decision-making processes to balance material demand and supply. This is particularly important for the highly perishable coordination of bulk commodity, for example, the ready-mix concrete, as they have little tolerance to time delay and can cause a considerable amount of waste if not installed on time. Given the fluctuating demand of the concrete, Chapter 6 presents an approach that uses digital data to enhance coordination during the dynamic construction processes. The approach is designed to enable the optimization of the ordering of perishable construction materials to minimize waste and cost. The approach consists of two main steps specifically for contractors: 1) monitor the dynamic demand fluctuations based on a 4D model that captures the as-built site progress and updated look-ahead schedules, 2) make decisions to modify original orders to accommodate the demand fluctuations where quantities of extra-orders and outsourcing orders are determined by a heuristic evolutionary algorithm. As a proof of concept, the approach is demonstrated using the same example project involved in Chapter 4 and Chapter 5.

Chapter 7 expands the scope of application of the two-step approach in Chapter 6 from a single project to multiple projects in a contractor's or an owner's project portfolio. To accommodate the expansion of the approach to varied material demands among projects, a network model is required to construct the material and information flows from one project to another. While both Chapter

6 and Chapter 7 have two steps, Chapter 7 focuses on a transshipment approach to enable the lateral sharing of perishable materials and optimize material allocation for a project portfolio in a supply chain network. The two-step approach in Chapter 6 is useful to address the problem of construction interruptions due to material unavailability, in contrast, the approach in Chapter 7 is helpful to address the material over-storage problem. In Chapter 7, the first step is to collect the daily material supply and demand data from a continuously updated schedule and 3D models in different projects. Then an evolutionary optimization algorithm is used for optimizing the transshipment quantities with minimal cost. As proof of concept, the proposed transshipment approach is demonstrated by looking at a portfolio of seven building projects managed by the same contractor.

Chapter 8 provides the synthesis of the research objectives, the main contributions of this dissertation, and main limitations along with future research work areas. This chapter concludes the entire dissertation work with reflections on the importance and the potential of the proposed systemic approach, which help project stakeholders manage material flows to ultimately improve project performance.

Finally, Appendix A, Appendix B and Appendix C offer the supplementary materials needed for the main research work in Chapter 2 through Chapter 7. Appendix A shows the supplementary information relevant to literature review processes. Appendix B includes the detailed process modelling diagrams and process simulation information requirements to support the demonstration of the proposed workflows. Appendix C contains the detailed modelling information from 4D BIM of the case study project, Andreasturm, which is consistently used to demonstrate the usefulness of different methodologies in Chapter 4 through Chapter 6. The BIM data of prefabricated columns installation, insitu concrete slab installation, insitu concrete wall installation are studied for the respective configuration of coordinating material flows: the prefabricated columns are studied in the ETO material flow processes; the insitu concrete slab and wall are studied in the bulk commodity material flow processes. Appendix D shows the terms and acronyms that are used throughout this dissertation.

PART I

Literature review

CHAPTER 2

Construction automation: research areas, industry concerns and suggestions for advancement

This chapter corresponds to the published article:[1]

Chen, Q., García de Soto, B. and Adey, B.T. (2018). Construction automation: Research areas, industry concerns and suggestions for advancement. Automation in Construction, 94, pp.22–38.

Abstract

Construction automation has shown the potential to increase construction productivity after years of technical development and experimenting in its field. Exactly how, and the possible benefits and challenges of construction automation, though is unclear and missing from current research efforts. In order to better understand the comprehensive potential of construction automation for increasing construction productivity and the associated possible ramifications, an objective and data-driven review of the use of automation technologies in construction was done. The review was accomplished by using text mining methods on publically available written documents, covering a wide range of relevant data including scientific publications and social media. The text mining software VOS Viewer and RapidMiner Studio were used to determine the most promising areas of research through the analysis of scientific publications, and the main areas of concern of industry through the analysis of text on social media, respectively. These research areas and concerns are summarized in this paper, and based on them suggestions for industry are made to help advance the uptake of automation

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[1] Please note, this is the author's version of the manuscript published in the Journal of *Automation in Construction*. For the reasons of consistency, the style of this chapter matches that of the dissertation. Changes resulting from the publishing process, namely editing, corrections, final formatting for printed or online publication, and other modifications resulting from quality control procedures may have been subsequently added. When citing this chapter, please refer to the original article found in the reference above.

in construction.

2.1 Introduction

The construction industry is falling behind others in terms of making productivity gains [304, 305]. One of the most promising ways to improve productivity is through the automation of parts of the construction process, which of course, can happen in many different ways, including the increased use of cross-functional teams in construction projects where emphasis is placed on learning and deploying the latest technologies, such as of the use of scrum techniques [297] or the use of robots to replace onsite labors [119, 120, 105]. As many people both in research and in industry are working vigorously in the field of construction automation, a synthesis of their work and suggestions of where future efforts should be focused is of considerable interest to people trying to improve construction productivity.

One of the challenges of providing an overview of construction automation is that different people have different interpretations of what is meant with the words construction automation. For example, most designers consider it as a way to automate the planning and design of projects, but construction contractors consider it as the use of robots for onsite tasks. For example, some specialty construction contracting firms have developed prototypes of single-application robots (e.g., bridge painting robot, concrete blasting robot, rebar placement robot, fireproof coating robot and steel-skeleton welding robot, road maintenance robot) [285, 284]. Given different interpretations, a conventional literature review is difficult to conduct. First, the appropriate articles, or pieces of text, need to be found, and then they can be reviewed.

Finding the appropriate articles can be done using text mining methods for both the analysis of structured text [223, 29] (e.g. journal articles), and the analysis of unstructured text [246, 133], such as social media [142] (e.g., webpages of blogs and online news, podcasts (e.g., Twitter), web communities and blogs (e.g., Reddit Construction Blog), knowledge generating platforms (e.g., The Construction Index website), and web-based news (e.g., Construction News), among others). Text mining methods can be used to scour many different articles to obtain a general overview of the developments related to a specific topic, a scientific domain or a research area including the identification of patterns and relationships between new developments and, the tracking of how areas of strategic importance change over time [140]. Labonnote et al. [178], for example, used citation databases to identify journal publications with information that would be helpful in the investigation of the extent with which additive manufacturing technologies could be successfully applied to large-scale construction projects. Most of the text mining analysis included the use of CiteSpace [47] and the Science of Science tool (Sci2) [14]. Khadjeh Nassirtoussi et al, [167], for example, used text mining on the major news webpages (e.g., webpage of Financial Times) to identify texts that would be helpful in the investigation of customer emotional sentiment preserved in the text to gauge the quality of market reception for a product.

The review presented in this paper was done by using VOS Viewer [325] and RapidMiner Studio [253] to identify the collected texts to investigate the developments in construction automation in research through the analysis of scientific publications, using text mining algorithms on Web of Science indexed journals[2], and text on social media from the websites (the websites shown in the Appendix A Table A.1), respectively. Based on the developments mentioned in these texts, suggestions were made as to how researchers and construction companies should focus their efforts to enable the construction industry to obtain maximum benefit from increasingly automating construction projects. The four steps used for both the analysis of the research publications and the social media were 1) determine exact research context, when starting with a general research context, 2) retrieve text, 3) assess data quality, and 4) model and visualize the patterns. With the analysis complete, the suggestions were made taking into consideration how the construction industry is most likely to benefit from increasing automation and how it might be hindered in developing in this direction.

2.2 Construction automation

Construction automation has many general definitions and different people see it at different levels of generality. For example, very generally a definition of “construction automation” was proposed by Bock [32] as a new set of technologies and processes that will change the whole course and idea of construction in a fundamental way. Jung et al. [158] used a more exact definition, referring to “construction automation” as a machine-centered construction factory technology for applying robotic systems on the construction field. A more limited definition was used by Vähä et al. [328] by describing “construction automation” as the automatic assembly method enabled by computer numerical control and real time sensing technologies. Skibniewski and et al. [288, 286] used the term construction automation to principally mean the execution of construction tasks using robots. Their work showed that the automation of construction tasks requires substantial adjustments to the construction schedule and shifting of project recourses. Since the concept of Industry 4.0 has been introduced as a popular term for digitalization and automation of the manufacturing environment, the definition of construction automation has been extended to include information modelling and digitalization [233]. Some researchers argue that “construction automation” is the integration of computer-aided design and robot-based onsite technologies for simplification of overall activities [166]. A few of them, such as

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[2] The information about indexed journals is provided online `https://polybox.ethz.ch/index.php/s/OtHmP9wYp4uwRNg`

Willmann et al. [337], now use the term “digital fabrication” to as a synonym for “construction automation”, particularly when referring to customized building construction. The definition used in the work presented in this paper in the search for new developments in the field of “construction automation” was the use of technologies younger than 20 years in the design and construction processes with the goal of improving construction productivity.

2.3 Text mining processes

Text mining processes for structured and unstructured text are different. Structured texts, such as journal publications have a clear abstract, introduction and conclusions, and contain lists of keywords, whereas unstructured texts, such as though found on social media do not. Although numerous software packages for text mining exist, and they all use the same analyzing process, some are more useful for analyzing structured texts and others for unstructured texts. In this work, VOS Viewer, was used for the structured text analysis and RapidMiner Studio was used for the analysis of unstructured texts. VOS Viewer is a computer software primarily used for creating, visualizing and exploring bibliometric maps of scientific publications. It is able to convert the publication information into a text corpus for statistical analysis of words. It can be used to analyze the citation relations between publications, collaboration relations between researchers and co-occurrence relations between scientific terms (i.e., words). The text mining process in VOS Viewer for the analysis of co-occurrence relations between scientific terms consists of using a word similarity function to output a graph with clusters of these words. RapidMiner Studio is computer software that allows to transform text into a format useable for operator processing, such as finding the words that appear together in at least a threshold ratio of occurrences [177]. The text mining process in RapidMiner Studio is usually customized using different operators, wherein the most basic operators include “process documents from files”, “convert numerical vectors into binomials”, “FP-growth” and “create association rules” [75].

Both of VOS Viewer and RapidMiner Studio analyze documents or text files with the same text mining algorithms (e.g., similarity functions) in order to construct and visualize the important words. They are equipped with similar text mining functions and steps, such as calculating the occurrence of a word or a word stem as the first step. Although the final outputs of the two software display in different forms, they both show the important words that are relevant to construction automation as well as their relatedness. The analytic results from VOS Viewer and RapidMiner can be compared.

Either for VOS Viewer or in RapidMiner Studio, the text mining processes consists of four steps (see Figure 2.1), with detailed sub processes when using each of the two software to model and visualize patterns. The basic assumptions made in the analyses were: 1) The publications cited from the Web of Science database adequately indicate the developments in research, 2) The most popular and influential websites (i.e., top 50 websites determined by Feedspot [96]) used indicate the developments in practice, and 3) The basic sense of the term "construction automation", has not significantly changed over within the last 20 years (Jan 1997 to May 2017)).

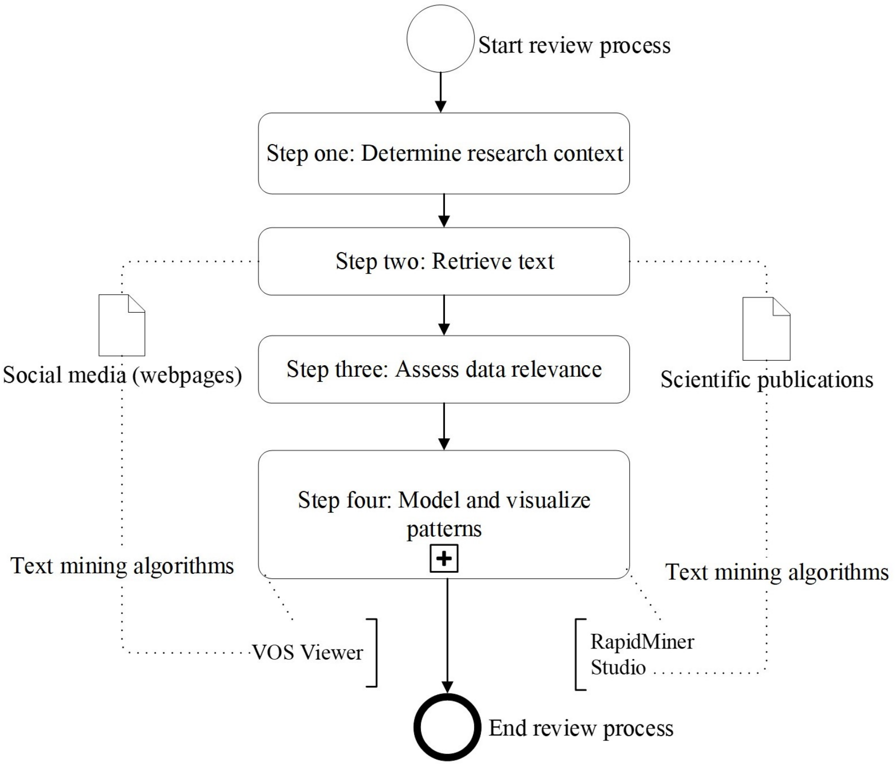


Figure 2.1: Text mining process

2.3.1 Step one: Determine research context

In this step the research context used to search the texts was determined. Determining the research context clearly is the premise to obtain relevant information regarding a researched topic (e.g., construction automation). A clear research context is required to distinguish relevant texts from non-relevant ones. For example, an article on automation technologies 50 years ago (e.g., a crane) are not relevant if the research context is the state-of-the-art in automation today.

The research context was the search for new developments in the field of "construction automation" defined as the use of technologies younger than 20 years in the design and construction processes with the goal of improving construction productivity, in the construction of residential and industrial buildings, and public infrastructure. Construction automation was assumed to be used in both design (e.g., the use of Computer Aided Design), construction (e.g. to control the use of machines onsite) and management (e.g., the use of Building Information Models). As an additional clarification of research context, it was assumed that construction automation is being used to:

- decrease dependency on manual labor, which would decrease the number of problems related to quality, would alleviate the monotony associated with doing repetitive work, and reduce costs by reducing the need for manual labor.
- increase productivity, as algorithmic computing and machines can work faster than manual labor.
- increase safety and quality, as manual labor can be removed from all dangerous situations.
- increase control over the design and construction processes, as machines can be monitored continuously and in very detailed ways without affecting their performance, where as humans cannot.

As it is difficult to distinguish a conventional construction automation technology (e.g., a construction worker operating a crane) from the state-of-the-art construction automation technology (e.g., completely unmanned robot fabricator), no distinction between the two were made. Instead, it was assumed that by limiting the analyses of the structured text analysis to publications in the last 20 years, and only considering current web sites for the unstructured text analysis, that only state-of-the-art construction automation technology would be captured.

2.3.2 Step two: Retrieve text

In this step, the structured texts were retrieved from the scientific publication database of Web of Science and the unstructured texts were retrieved from the 35 relevant publically available construction blogs of the top 50 determined by Feedspot using Web Scraper [331] (see column “Applicable for data retrieval” in Table A.1 in Appendix A). Web Scraper, a web harvesting or web data extraction tool, is used for automatically fetching and extracting texts from websites. Web pages (shown by the web links) are built using text-based mark-up languages (e.g., HTML and XHTML), and frequently contain useful data in text form. Web Scraper is able to parse these web links into text formats. The selection of social media data webpages relies on the web harvesting results.

To identify relevant texts, search rules were used, which are simply the linked Boolean operators (e.g., construction robot AND building construction NOT

Table 2.1: The search rules of publications in Web of Science

How	AND	What	NOT	To exclude
construction robot		building construction		manufacturing
building information model		construction cost		hardware
industrial 4.0		construction schedule		software
digital fabrication		construction performance		
3D printing		construction safety		
cloud computing		construction survey		
(virtual, augmented) reality		lean construction		
drone				

manufacturing as an inclusion-exclusion mixture criteria for searching). The search rules for publications used are given in Table 2.1. They were used to find publications on how construction automation technologies, such as a construction robot, are used in a particular context, such as building construction. The search excludes the topics on unrelated subjects, such as “manufacturing” that was focusing on automation in manufacturing industry, “hardware” and “software” that were associated with specific advancements in computer configurations and computer systems.

The results returned 5’087 publications. Of these publications additional filtering was used to eliminate irrelevant publications, e.g. by removing publications in the field of nuclear science which were concentrating on automating nuclear experiments rather than the automation of building nuclear power plants. The data of 741 remaining publications were stored in text files, with their data structured in titles, keywords, abstracts, journal source, and cited references. The distribution of 741 scientific publications from 1997 to 2017 is shown in Figure 2.2. It can be seen that the number of relevant scientific publications has drastically increased over time. It is also noted that the number of scientific publications in 2017 is not complete as publications were retrieved up to May 2017. Top 10 journals ranked according to percentage of publications retrieved is shown in Table 2.2, indicating the percentage of publications that come from the same source of journal. Most of the extracted scientific publications are from the Journal of Automation in Construction.

Table 2.2: Top 10 journals ranked according to percentage of publications retrieved

Name of journals	Publications retrieved(%)
Automation in construction	28.5
Journal of construction engineering and management-ASCE	10.5
Journal of management in engineering	3.5
Journal of information technology in construction	3.4
Journal of civil engineering and management	3.2
Building and environment	2.6
KSCE journal of civil engineering	2.2
Engineering structures	1.9
Canadian journal of civil engineering	1.6

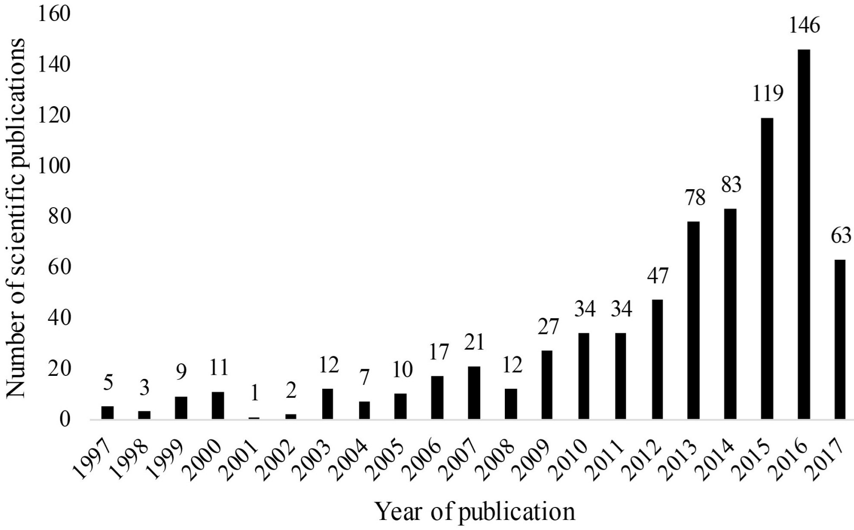


Figure 2.2: Distribution of 741 scientific publications from 1997 to 2017 (up to May)

The search rules for social media publications were not as easy to construct as for scientific publications, since webpages have limited capability of applying Boolean operators when compared to Web of Science. In their place, the search word, “construction automation” was entered on each webpages to further filter all the web links containing “construction automation”. Then these web links, built upon text-based mark-up languages, were parsed by Web Scraper in order to extract all the data of blogs, news, etc. All the data extracted from the 35 websites was stored in text files for further analysis. The text data included information of construction automation case studies as well as opinions and trends on industrial applications.

2.3.3 Step three: Assess text relevance

To ensure that the results of text mining were as good as possible, in addition to conforming to the research context and search rules, the relevance of each text was manually assessed, with respect to the following factors, as suggested by Lee [184]:

- The state of completeness, validity, consistency, timeliness and accuracy that makes data appropriate for a specific use (i.e., data is accessible for processing in VOS Viewer and RapidMiner Studio).
- Degree of excellence exhibited by the data in relation to the portrayal of the actual scenario (i.e., data is not skewed and is able to reflect the actual trends in construction automation).
- The totality of features and characteristics of data that bears on its ability to satisfy a given purpose (i.e., all the retrieved data is robustly related to the research context and the keyword “construction automation”).

If the answer was yes to all of these then the text was considered relevant. If one was considered to be no then the text was considered not relevant and removed from the analyses. In this work, all 741 scientific publications and 35 selected websites were deemed relevant after manually screening the retrieved texts. For scientific publications, the “titles” and “abstracts” attributes were read and checked manually. Without “title” or “abstract” attributes that were split by delimiters, the plain texts retrieved from webpages were mechanically checked line by line. All the retrieved texts were relevant because 1) their completeness, validity, consistency, timeliness and accuracy were guaranteed by the sufficient amount of extracted texts over a long period of time; scientific publications over years from 1997 to 2017 and social media data without specifying any time limit, 2) the degree of excellence exhibited by the data in relation to the portrayal of the actual scenario was ensured through obtaining the articles from top peer reviewed journals and top ranked websites, 3) the totality of features and characteristics of data that bears on its ability to satisfy a given purpose was ensured through the manually checking the details of texts.

2.3.4 Step four: Model and visualize patterns

The structured text analysis was done using VOS Viewer. The main tasks of the text mining process using VOS Viewer are shown in Figure 2.3. The first step was to extract titles and abstracts generated from the scientific publications. The number of occurrences of each word was then calculated and using a threshold of 10 occurrences, as suggested by Van Eck [320], the relevancy of the word was decided, i.e. if a word was seen ten or more times it was considered relevant and otherwise not. Words not directly related to the automation of construction, such as “article”, “paper”, were also removed. The similarity of two selected words was calculated using the similarity function shown in Equation 2.1 which has been used extensively in clustering algorithms [3]. For example, if the total number of occurrences of “automation” is 31, the total number of occurrence of “accuracy” is 40, and the number of co-occurrences of “automation” and “accuracy” is 25. Then the similarity between “automation” and “accuracy” is 25/(31*40)=0.02. Similar words were then clustered together, given a title and classified as main research areas. Their similarity could also be visualized by the distance between two words in the output figure in VOS Viewer. The shorter distance between the two words, the higher degree of similarity (i.e., higher relevance).

$$S_{ij} = \frac{c_{ij}}{w_i w_j} \tag{2.1}$$

Where,

S_{ij} = similarity between word i and word j

c_{ij} = number of co-occurrence of word i and word j

w_i, w_j = total number of occurrence of word i, word j

The unstructured text analysis was done using RapidMiner. The main tasks of the text mining process using RapidMiner Studio are shown in Figure 2.4.

In step 1, the texts were submitted to the software through the use of the “process documents from files” operator, which transforms the text into a word stem list which are represented by numerical vectors. This was done using four sub steps: tokenizing, transforming cases, filtering stop-words, and stemming words. The text to be analyzed can be viewed as a vector representation of tokens. Each entry in that vector is the presence or absence of words, which will further be converted to binary numbers corresponding to a word or word stem of that text. Tokenizing was used to break a stream of text (i.e., paragraphs) up into words and symbols, which are called tokens. These tokens were then converted to one case (either lower case or upper case). Prepositions, articles, and pronouns, were removed from the analysis through the sub step: filtering stop-words. Word stems were then created from the remaining words, e.g. the word stem “manag” is stemmed from the word “manage”.

In step 2, the numerical vectors (i.e., word stem lists) were converted into binomials. Binominals can have only two possible values; True or False. The original numerical vector, after conversion, would have all the entries with “True” or “False”, depending on whether the words were encountered in the text. In other words, the values “True” or “False” indicate whether the words from text mining corpus library were contained in the text. It is also noted that still two parameters have to be specified: the min and max values for determining “True” and “False”. For example, if min value is set as 0.0 and maximum value is set as

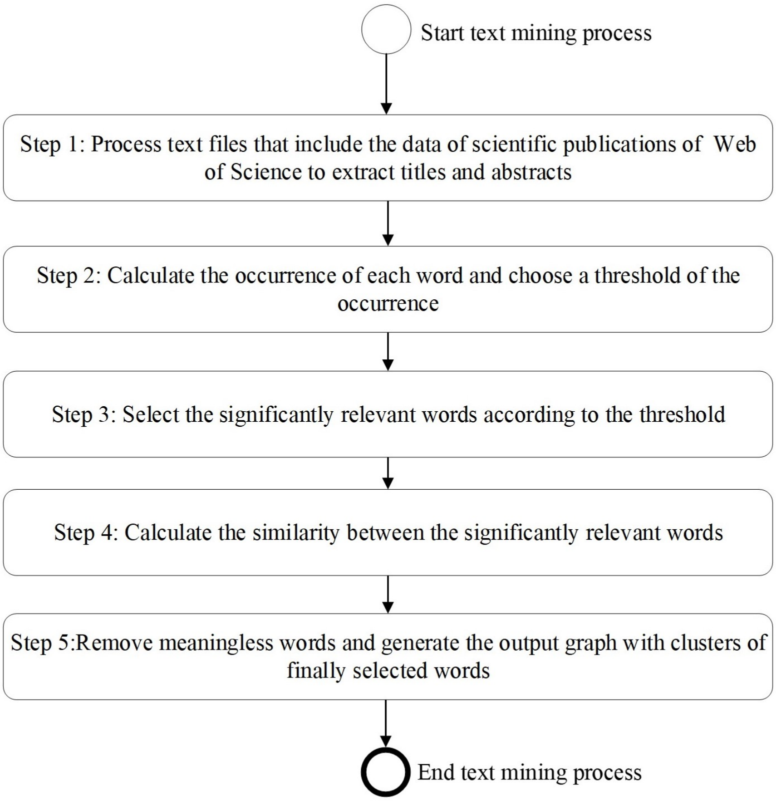


Figure 2.3: Main tasks of the text mining process using VOS Viewer

0.1, the number inside the numerical vector that falls in the range from 0.0 to 0.1 is mapped to “False” and the others are mapped to “True”. Under this condition, the word stem “manag” with an entry value of “1” in the original numerical vector, because of the value being between 0.0 and 0.1, would be mapped to “False”.

In step 3, the operator “FP (frequent patterns)-growth” was used to process the binomials that were generated from step 2. FP-growth is an operator that generates frequent word stems, calculates all the frequent word stem pairs that appear together, and produces a FP-tree data structure. The FP-growth final output, the FP-tree data structure, was specifically produced for “association rules” [197]. The FP-tree data structure is a compressed form of the binomials, consisted of tree paths and nodes that represent the frequency and inter-actions of word stems. The generation of FP-tree was done in an FP-growth algorithm that can output the “support” values of a group of words occurring frequently in a text. Support is an indication of how frequently a given word appears in the text, corresponding to the value of each node in the FP-tree data structure. In order to implement FP-algorithm, the occurrence of each word stem was counted and stored in a header table first, and then an initial FP-tree structure was created

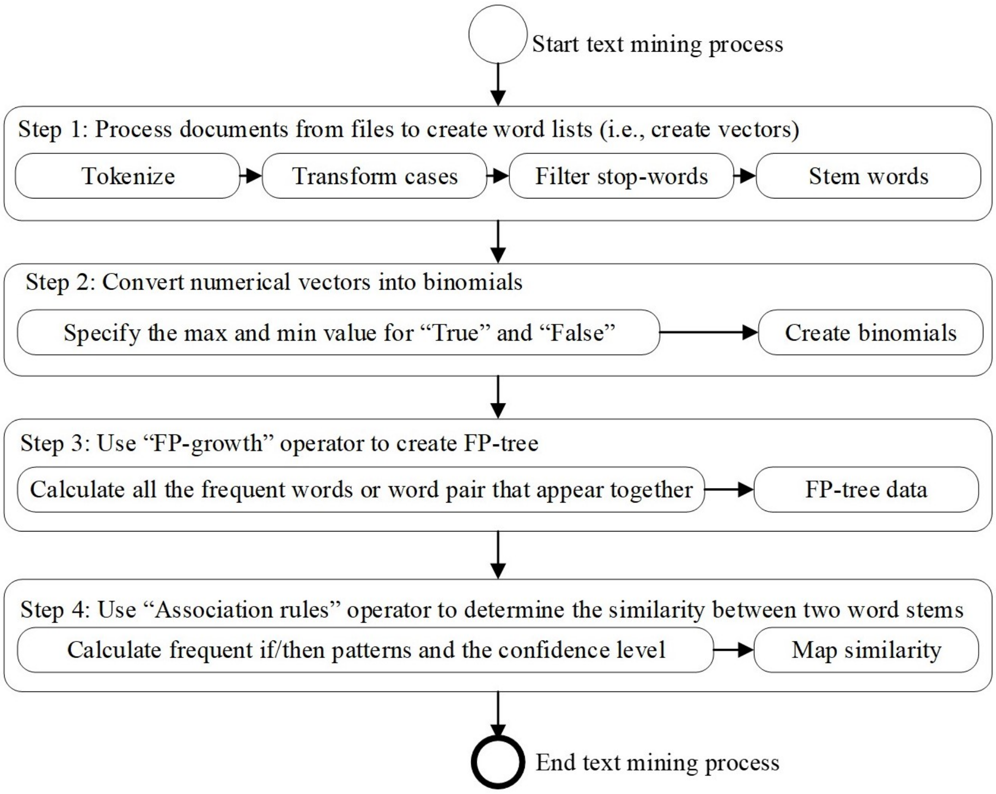
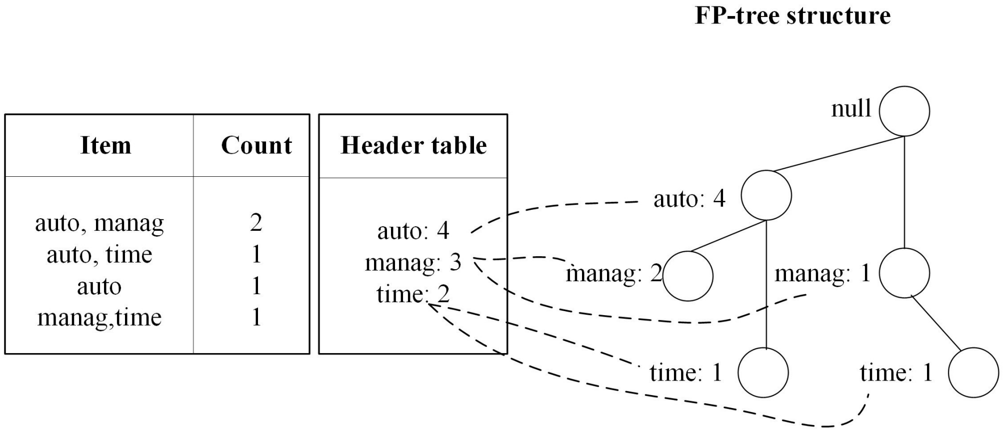


Figure 2.4: Main tasks of the text mining process using RapidMiner Studio

through inserting instances from the header table. Instances were sorted by descending order of their frequency in the dataset, so that the FP-tree structure can be processed iteratively and quickly. A simple example of FP-tree structure is given in Figure 2.5, which starts computing with a root node labeled as a "null node". As an example from Table 2.7, the word stem "manag" was calculated as 95.528 in the FP-tree data structure, which indicated its frequency in the text.

In step 4, the operator "association rules" was used to calculate the FP-tree data and determine the similarity between word stems. The operator works by analyzing data for frequent if/then patterns and the confidence level to identify the most important relationships. The frequent "if-then" patterns for a stream of text (or converted to binomials) were produced using the FP-growth operator, which generate the FP-tree data. An example of an association rule would be "If a customer buys eggs, he is 80% likely to also purchase milk." Then among the FP-tree data, a premise word j (i.e., the antecedent "if" item) and a conclusion word i (i.e., the consequent "then" item), are linked by support, which is the number of co-occurrences of the word i and word j. The confidence level is then calculated, which indicates the number of times the "if" (a premise word) "-then" (a conclusion word) statements have been found to be true. The confidence level



Item	Count
auto, manag	2
auto, time	1
auto	1
manag,time	1

Figure 2.5: A simple example of FP-tree structure

is calculated by dividing the number of co-occurrences of word i and word j by the total number of occurrences of word i (see Equation 2.2). Creating association rules takes these frequent sets of word-pairs and generates their associations. For example, if the total number of occurrence of "auto" is 1000, and the number of co-occurrences of "auto" and "market" is 1000. Then the confidence level that "auto" implies "market" is 1, meaning that if auto appears in a paragraph, there is 100% likelihood that market also appears in that paragraph.

$$ConL_{ij} = \frac{Sup_{ij}}{Sup_i} \tag{2.2}$$

Where,

$ConL_{ij}$ = the confidence level that word i implies word j

Sup_{ij} = the number of co-occurrence of word i and word j

Sup_i = the total number of occurrence of word i

2.4 Results

2.4.1 Main research areas

The structured texts containing information of scientific publications were analyzed in VOS Viewer following the steps in Figure 2.3. Similar words were clustered together (as represented by the different colors), classified as main research areas, and given a specific name. Within a given cluster, words were ranked based on the number of publications in which they were found. This was reflected by the size of the circle for each word. The distance among the circles provides an indication of relatedness, so that the closer the circles the higher the relatedness of the words. The colors were assigned automatically and range from blue to green to red. In Figure 2.6, the green, blue and red circles indicate words associated with clusters 1, 2 and 3, respectively. The degrees of relatedness between words are indicated by the curved lines.

The words associated with each other and their relationships are also shown in Figure 2.6. The number of word occurrences in each cluster are given in Table 2.3.

Table 2.3: Number of word occurrences in each cluster

Green cluster (area 1): Construction Robots and Automation Systems		Blue cluster (area 2): Construction Managerial Objectives		Red cluster (area 3): Building Information Modelling Based Collaborations	
Word	Word occurrence	Word	Word occurrence	Word	Word occurrence
control	55	structure	180	information modelling	86
safety	51	simulation	76	architecture	81
construction site	47	risk	44	survey	62
algorithm	44	schedule	43	role	55
productivity	43	function	40	communication	40
visualization	41	wall	33	collaboration	40
accuracy	40	effectiveness	31	aec	40
location	38	energy	28	organization	37
rule	34	quantity	26	coordination	33
identification	33	uncertainty	25	drawing	31
error	31	damage	25	complexity	28
automation	31	project management	23	construction phase	26
cloud	29	reliability	18	investment	24
prototype	27			client	24
robot	26			web	23
feasibility	26			architect	23
worker	25			design methodology approach	22
3d model	20			BIM adoption	22
ifc	18			sustainability	18
labor	16				

When observing Figure 2.6, it is important to realize here that the words shown are only of importance within the research context and with respect to the associated research area. For example, "structure" in the blue cluster (i.e., Construction Managerial Objectives) is associated with the physical building structure and structural analysis, rather than the company's organizational structure, which is associated with building function, building quantity takeoffs and so on. Within and among the clusters, the distance between two circles offers an indication of the relatedness of them. For example, the distance between "safety" and "construction site" is short, meaning that the two words often appear together and are highly relevant. Interpretation of the results found by the VOS Viewer is given in Table 2.4 through Table 2.6. Specific publications are cited in the interpretation to point the reader to sources of more information. When putting the results (e.g., relevance or words) in context, which is provided in the selected scientific publications, the results become more meaningful. The main benefits of implementation of construction automation can be summarized as: 1) improving the efficiency of work processes, 2) enhancing the communication and

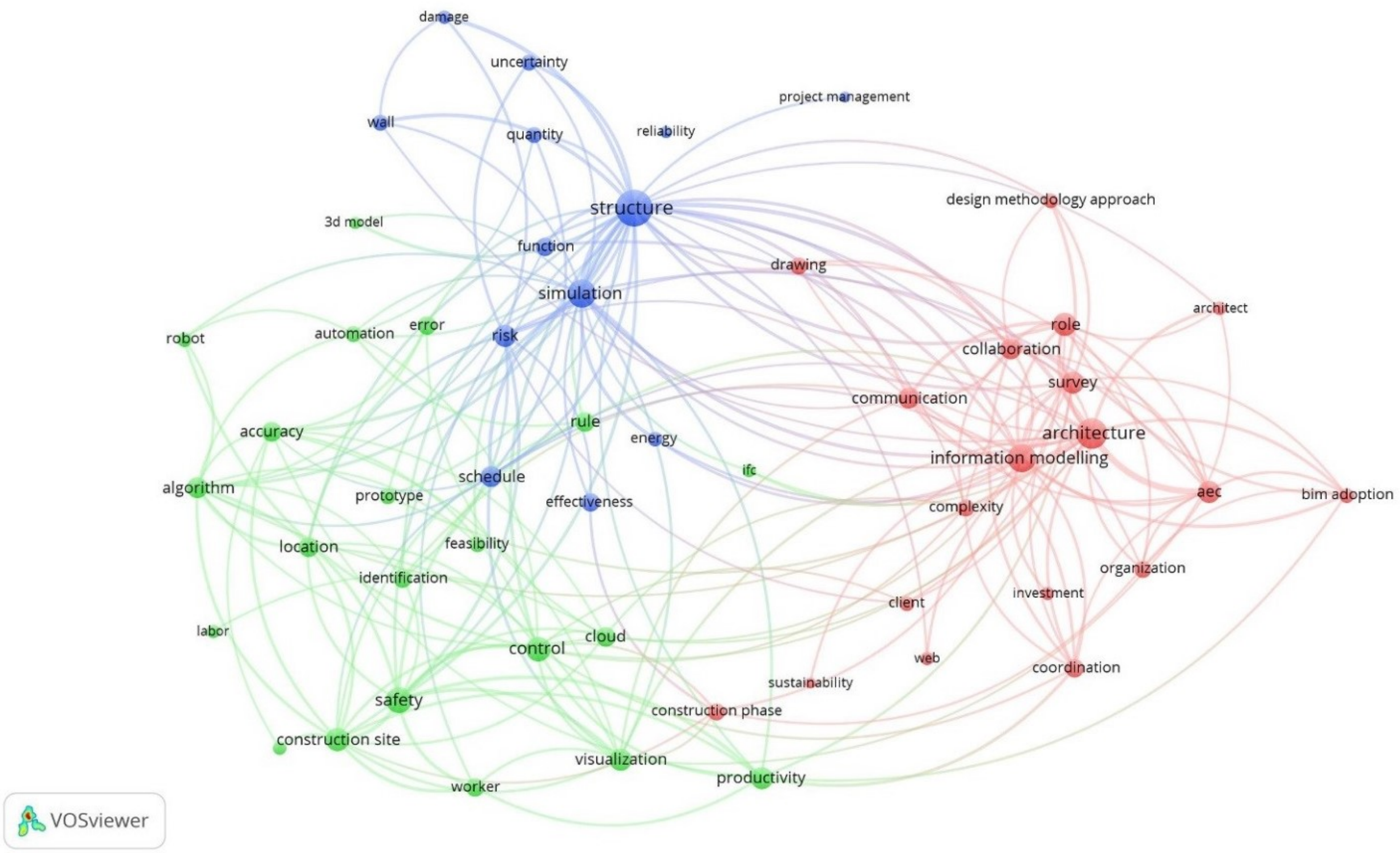


Figure 2.6: The words, and their relationships with each other, used to identify the three main research areas, (1) Construction Robots and Automation Systems – green (the left bottom part), (2) Construction Managerial Objectives – blue (the left up part), and (3) Building Information Modelling Based Collaborations – red (the right part)

collaboration between stakeholders, and 3) a potential to increase market share.

Table 2.4: Interpretation of the VOS Viewer results: Construction robots and automation systems - Green cluster

No.	Result	Interpretation – This reflects the fact that....	Benefits or challenges
1	"Control", "safety", "construction site" and "algorithm" are highly relevant	a number of scientific publications on construction robots and systems focus on optimizing the control of machines [162] and improving safety of operators [329], particularly on construction site [88].	Benefits: improving the efficiency of work processes
2	Robots and other automation technologies, represented by words such as "visualization", "identification", "location accuracy", are grouped with "construction site"	there is an increasing use of technology during the construction phase, e.g., radio frequency identification technology (RFID) [173] has been integrated with material identification and locating processes to enhance the just in time delivery of construction materials [289].	Benefits: improving the efficiency of work processes
		robots have recently been designed for tasks such as painting, and jointing in buildings have higher efficiency with respect to pay load, reach, number of degrees of freedom, etc. [321, 283].	
		robots have been developed to perform autonomous construction tasks onsite, with customized abilities [33] to manipulate construction materials and equipment [287, 290].	
		robots known for "swarm behavior", have recently become attractive for additive construction, since unlike large-scale bricklaying robots, they are smaller so that they can find their own way to specified construction location without human intervention [334].	
3	"3D printing" and "digital fabrication" do not appear as relevant words	even though they are considered as primary components to drive the use of construction robots [66, 343], 3D printing and digital fabrication are not yet dominating the current construction trend or being mature for extensive applications, and therefore cannot be expected to show up in such an analysis.	Challenges: a lack of maturity of use of information
4	There are only a few links between the green and red clusters	there is a lack of research on how to combine computer aided design with onsite robotic and automation systems.	Challenges: a lack of maturity of use of information
5	There are no strong relationships existing between BIM technology and task-oriented robots	there is a lack of research linking automated design and construction integration	Challenges: a lack of maturity of use of information

2.4.2 Main industry concerns

Unlike VOS Viewer, the RapidMiner does not produce the clustering graphs. After implementing the "FP-growth" and the "association rule" operators shown in Figure 2.4, the most frequent word stems and most associated word-stem pairs were compiled into a table format. Each word stem reflects a specific concern or theme from the texts that it belongs to. If a word stem identified with a given concern had a high frequency online with its highly associated word stem, the more important the concern was assumed to be. The most frequent word stems are summarized in Table 2.7 and the top ten most associated word-stem pairs produced from the association rules are shown in Table 2.8. When going over Table 2.7 and Table 2.8, it is important to realize that the meaning of each word stem should be interpreted with respect to the theme of the text to which it belongs. An interpretation of the most frequent word stem and

Table 2.5: Interpretation of the VOS Viewer results: Construction Managerial Objectives - Blue cluster

No.	Result	Interpretation – This reflects the fact that....	Benefits or challenges
1	The most relevant words are "simulation", "risk", "schedule" and "function"	the primary managerial objectives in running construction projects are the focus of simulation [277] and optimization in order to reduce time and risk.	Benefits: improving the efficiency of work processes
2	The blue and red clusters, and the blue and green clusters are closely linked	there is work being focused on improving the management of construction projects by through the use of construction automation technologies and stakeholder collaborations.	Benefits: enhancing the communication and collaboration between stakeholders
3	The word "construction schedule", appears the most frequently in relation to construction automation	out of the many possible management objectives, there is perhaps the most work focused on improving the schedule.	Benefits: improving the efficiency of work processes
4	There are limited links among the words within the blue cluster; but many between the blue and the red and green clusters.	attempts to achieve management objectives are often done through simulations using the techniques associated with other clusters, e.g. automation and building information modelling.	Benefits: enhancing the communication and collaboration between stakeholders with the help of model visualization and sufficient information exchange. Challenges: a lack of maturity of use of information
		a distinct emphasis on improving the schedule and reduce project time using automatic approach, e.g., strong relatedness between BIM and schedule [106].	
		improve scheduling using 4D modelling to avoid modelling errors and construction activity conflicts [353, 308].	
5	The management objectives are linked with the green and blue cluster	recent research has been focused on developing algorithms or prototyping of automation technologies to help achieving management objectives and improve the efficiency of project management.	Benefits: improving the efficiency of work processes with respect to different objectives
6	The words "simulation" and "project management" are strongly associated with BIM-based decision making process and information communication technologies from the red cluster.	BIM provides a collaborative decision-making platforms to facilitate information sharing [55, 235] for model simulation (e.g., 4D simulation for visualization of a building process) and project management (e.g., scheduling control), and that web technologies and artificial intelligence enables access to a vast amount of information from multiple sources easier in construction industry [315]. This can be seen in the work of a number of researchers who have proposed knowledge based decision making models [103, 104] to support time-cost-quality trade-off analysis [171].	Benefits: enhancing the communication and collaboration between stakeholders

most associated word-stem pairs is presented in Table 2.9. The interpretation of the results includes reflection on whether this aspect of construction automation brings benefits or challenges.

The most frequent word stems found in social media texts are "construct", "market", "product", "manage", "use", "cost", "time" and "company" (Table 2.7). The results confirm that industry cares more about the benefits and challenges that will influence final construction products. It is discernible that the most frequent word stems also appear in the most associated word-stem pairs, for example, the word-stem pair "increas - product, design, industri, manag" includes each word stem as the most frequent.

According to Table 2.8, a confidence level of one indicates that there is high

Table 2.6: Interpretation of the VOS Viewer results: Building Information Modelling Based Collaborations – Red cluster

No.	Result	Interpretation – This reflects the fact that. . . .	Benefits or challenges
1	There is a high occurrence and co-occurrence of the words “information modelling”, “communication”, “coordination”, “collaboration” and “complexity”	there are large advantages to be obtained by using BIM to enable collaborative working environments, which help to reduce miscommunication and errors among construction players [152, 48].	Benefits: enhancing the communication and collaboration between stakeholders
		to help the automation of scheduling and project planning process [132, 319].	
2	The “information modelling” and “complexity” circles are large.	BIM facilitates solving project complexity problems, either with respect to the building design or the collaboration of participants in all project phases [60]. This also coincides with the increasing number of contractors and owners who are experiencing changing roles when involved in BIM-based projects [169], as the traditional hierarchical organizational framework is gradually taken over by a new framework with more effective communication, coordination and collaboration among organizational members, due to the computer-supported benefits of BIM.	Benefits: enhancing the communication and collaboration between stakeholders
3	“ifc” or “Industry Foundation Class” is a connecting word between the green and red clusters	interoperability of information is a significant technological problem of using BIM [164]. A few researchers have developed a full-digital design-to-production process, which enables the use of BIM model directly for steel column detailing and robotic fabrication [179, 157]. Problems appear when responsibility for an information model is transferred from designers to contractors [190].	Challenges: a lack of maturity of use of information
4	There is a weak connection between the green and red clusters	there is a lack of information exchange and integration between BIM enabled design and robot enabled automatic fabrication, and therefore a lack of research focused on improving the design-to-production concept through a tight collaboration and interoperability between upstream design automation and downstream onsite operational automation.	Challenges: a lack of maturity of use of information

probability of the “if” (a premise word) - “then” (a conclusion word) statements found to be true. These ten word-stem pairs, such as “technolog-market, system” and “manag-design, industri”, indicate an active interaction between company development, market and technologies. Unlike academic research field, social opinions tend to address problems encountered in practice. It is noted that the top ten word-stem pairs do not contain any specified technology used, such as a specific type of design software or a specific robot. This reflects the company development instead of particular features of a technology. According to the most associated word-stem pair “increas-product, design, industri, manag”, it is recognized that companies focus on how to increase productivity by innovating product, design processes and management processes. This finding is consistent with the area 1 from the analysis of the scientific publications. In addition, the frequent association between “help-busi, use” and “time-technolog” indicates that the use of construction automation technologies will save time and smooth business operations.

In order to clarify the industry concerns, those frequent word stems and word-stem pairs should be interpreted in the specific context or the extracted texts they belong to. By probing the detailed texts on line, there exists manifold potentials and unsolved problems related to adoption of construction automation technologies. Table 2.9 shows the contextual interpretations of the most frequent word stem and most associated word-stem pairs, which implicate the facts about benefits or challenges of construction automation. The construction industry consists of plenty of small and medium size companies with limited capabilities for investment in automation technologies. Some of them are facing increasing challenges through globally economic competition, in turn resulting in limited investment on advanced technologies. A number of websites point out the difficulty of increasing market share in construction projects using automation technologies. It is also discernible that potential risks exist when companies make investment decisions on how and to what level to implement construction automation technologies. Although “risk” is not showing up as one of the most frequent word stem in the results, it is an important concept reflected from contextual information. By relating “risk” to context in the most of webpages shown in Table 2.9, it is easy to conclude that the construction industry, no matter what size of a company or what level of technological maturity, mainly perceives risk as financial aspects. This also correlates to that high occurrence of “cost” in extracted social media texts. Based on these contextual interpretations from Table 2.9, the challenges are summarized mainly as: 1) a lack of maturity of use of information, 2) a lack of company investment, and 3) a lack of economic competition. The benefits seen from contextual interpretation are: 1) a potential to increase market share, 2) improving the efficiency of working processes with respect to different objectives, 3) enhancing the communication and collaboration between stakeholders. Therefore, the next step for the industry is to concern about how to overcome challenges of using automation in construction, and how to estimate the benefits of using automation in construction.

2.4.3 Summary

As can be seen from the review, researchers are principally focused on pushing the forefronts of science to enable the automation of construction and industry is concerned with overcoming the challenges of implementation and ensuring that implementation is beneficial.

Researchers see that the construction automation system as a whole [282] can be improved by implementing technologies to enable automation. Construction automation enhances collaboration between different stakeholders, shortens the length of time required to complete construction tasks onsite, and hence helps to improve construction efficiency. This can be seen through their focus on the

Table 2.7: Most frequent word stems

Cluster	No.	Word stem	Support (i.e., an indicator of occurrence)
Cluster of the most frequent word stems	1	construct	177.694
	2	product	143.278
	3	market	141.789
	4	manag	95.528
	5	use	94.111
	6	cost	91.889
	7	time	88.361
	8	company	87.972
	9	technolog	82.028
	10	system	76.389
	11	work	75.361
	12	industri	75.222
	13	design	51.306
	14	increas	44.028
	15	busi	38.667
	16	help	36.222
	17	auto	2.806

potential of building information modelling and onsite automation systems as two of the main research areas. Of the many ideas researched it seems the greatest potential for innovation will come from the creation of a continuous process that leverages the benefits from integration of design information and construction information, which would allow more efficient information exchange, through helping to ensure information integrity and comprehensiveness, leading to less iterative work between designer and constructor. The clustering also shows that the most significant division of the construction process is in the “separation” of the design and construction phase. With increased implementation of technologies to enable automation, the number of ambiguities in downstream phases of construction will be minimized and will amount of material wasted due to the availability of more accurate information can be reduced. Additionally researchers see that a significant barrier to the use of building information in integrated construction processes is the lack of standardized data schema and a lack of protocol to delimitate the responsibility for information usage.

The main industry concerns are overcoming challenges of using automation in construction, and correctly estimating the benefits of using automation in construction. The challenges include those for single companies, such as overcoming financial difficulties due to the high implementation costs, and overcoming technological barriers such as providing adequate information security and overcoming information exchange problems, and those for the entire industry, such as ensuring that multiple partners in the construction process can work together seamlessly and encouraging the development and use of appropriate tools. It

Table 2.8: Top ten most associated word-stem pairs produced from the association rules

No.	Premise word	Conclusion word	Confidence level
1	increas	product, design, industri, manag	1
2	manag	design, industri	1
3	technolog, auto	market, system	1
4	construct	technolog, system, cost	1
5	work	product, cost	1
6	help	use, busi	1
7	product, combin	research	1
8	clear, approach	govern	1
9	earli	resource	1
10	earli, complex	transform	1

seems that it will be the push to gain market share or maintain competitiveness that will be the drivers that push industry to automate. Additionally industry appears to be concerned about having no standardized practices for the estimation of costs and benefits of increasingly automating their construction processes, which casts doubt on any of such studies done, and makes it difficult for decision makers to build strong arguments for change. Industry is also concerned with information security. With the increasing dependency on information available to many partners, there will be increased problems, such as cyber-attacks on web based or BIM-based collaborative platforms, blame when information gets changed by people who are perhaps not aware of the downstream consequences, and are not responsible for them.

2.5 Suggestions

In order for the industry to overcome the identified challenges and realize the benefits, suggestions, and related justifications for their implementation, are provided for advancing the use of construction automation. Table 2.10.

2.6 Conclusions

Construction automation has the potential to increase construction productivity. Exactly how, and the possible benefits and challenges of construction automation, are not clear for everyone. In order to increase this understanding and to help focus industry efforts, and research efforts to help industry, a data driven review through text mining on scientific literature and social media with respect to the use of automation technologies in construction was accomplished. In research, it was found that scientific research work was mainly focused on developments that can be grouped as 1) Construction Robots and Automation Systems, 2) Construction Managerial Objectives, and 3) Building Information Modelling Based Collaborations. In industry, an active interaction was found between company investment on technologies, market share and the final construction product. It was also found that there is a lack of integration of various automation technologies, resulting in problems regarding information interoperability, information security and contractual responsibility. Major benefits and challenges were discovered by contextual interpretation of text. In general, the automation of construction provides improvements in 1) the efficiency of work processes with respect to different objectives, 2) the communication and collaboration between stakeholders, and 3) a potential to increase market scale. The challenges with which the industry is faced are: 1) a lack of maturity of use of information, 2) a lack of company investment, and 3) a lack of economic competition. In order to realize the benefits from making use of construction automation and to overcome the challenges to do so, the suggestions proposed are 1) Reengineer business structures and processes, 2) Increase the scale of adoption, 3) Assess project performance, 4) Develop building information protocols, 5) Develop appropriate legal contracts, and 6) Integrate building information through standard data schema. By acting on these suggestions, the construction industry will help to accelerate the automation of their processes and the gains in terms of productivity, which can be translated in to winning market share, increasing profits or both.

It should be highlighted that the focus of this research is to provide an overall picture of construction automation; however, some perspectives that were not obvious from the text mining results (but from details in the literature) are still worth mentioning. For example, besides the need of scale of adoption and standardization, complexity and uniqueness is an important issue to be addressed during the implementation. Mass customization, rather than mass production, is non-negligible considering the uniqueness of each construction project. It is foreseeable, although not well-known so far, that BIM's parametric capacity on modelling complex shapes and the diversity of robot-driven operations will join in force to contribute to construction automation particularly on mass customization of projects. It is difficult to observe these hidden issues from the text mining results, but they are tightly associated with the main trends identified as a premise to understand construction automation. While construction automation is taking place widely nowadays, it is imperative from the start to build the common knowledge to clarify the major benefits and potentials with the help of data-driven review methods, thereby to establish a comprehensive understanding of construction automation.

Table 2.9: Interpretation of the most frequent word stem and most associated word-stem pairs

No.	Word stem or word-stem pair	Contextual information from original social media in examples	Interpretation – This reflects the fact that. . .	Benefits or challenges
1	construct - technolog, system, cost	"When it comes to the precise means of incorporating the Internet of Things into construction, ...and smart technologies can enhance the operation of built assets and infrastructure... necessarily involve dramatic cost growth..." [292]	companies put emphasis on overcoming challenges of limited capabilities for investment in automation technologies.	Challenges: a lack of company investment
2	technolog - market, system	"Every construction company owner faces pressure to control costs and operate at lower profit margins..., determine the types of technologies that will bring the biggest benefit to your organization's bottom line..., stay ahead of their competitors for projects both now and in the future..." [63]	companies are facing increasing challenges through economic competition when incorporating advanced technologies.	Challenges: a lack of economic competition
3	increas - product, design, industri, manag	"The Global Construction Robots Market 2016-2020 report, ..., but the market will exhibit a promising growth rate over the next four years... that an increase in the construction of mega structures and high-quality infrastructure will necessitate the use of construction robots..." [78]	more companies are applying various automation technologies in construction projects which will lead to an increasing market share.	Benefits: a potential to increase market share
4	earli, complex - transform	"Since it is well known that early digital adopters will gain an immense competitive advantage..., complex information is immediately shared,... single source of truth to continue to handover to client and beyond...,transformational re-organization to enhance efficiencies..." [79]	most of construction projects are vulnerable to information attacks as well as failure of information sharing across stakeholders due to the technical difficulties in the early transformation phase.	Challenges: a lack of economic competition
5	construct - technolog, system, cost	"Bentley Systems demonstrated that the construction projects in the virtual reality technology required on building sites involves a capital cost which must be clearly assessed to reduce risks of implementing construction automation technologies." [293]	companies still take the risk of balancing cost-benefit when implementing construction technologies in practice.	Challenges: a lack of maturity of use of information
6	manag - design, industi	"The virtualization of construction is becoming increasingly common..., should make construction managers' jobs easier..., VDC bridges the gap between design data and construction execution..., benefits on supply chain integration and industry leading margins" [81]	companies are able to benefit from better project management process with the help of integrating information from design and construction.	Benefits: improving the efficiency of working processes with respect to different objectives
7	earli - resource	"The in-house parametric design software provides comprehensive details at a very early stages..., BIM models are resource intensive..., trade-off between resource required and changeability..." [316]	companies can gain benefits through parametric design models with less change orders and more communication on sharing recourses.	Benefits: enhancing the communication and collaboration between stakeholders
8	product, combin - research	"Smaller construction enterprises providing integrated design and manufacturing capabilities are turning to related technological products. It is these technologies that will enable new construction startups to build powerful digital enterprise platforms that combine with an ecosystem of business enabling technologies to challenge their traditional construction counterparts..., a serious investment is needed across construction's academic and training institutions to enable a world class hub for modern construction education and research." [294]	companies are encouraged to invest in collaboration with construction academic and training institutions on construction automation technologies in order to develop business competitiveness.	Challenges: a lack of economic competition
9	time - technolog	"Fischer Homes shows that drone survey work offers time and money savings..., considering the worth of drone technology..., track a site's progress with a degree of accuracy previously unknown in the industry..." [80]	companies are able to enjoy time saving when leveraging the functionalities of various automation technologies.	Benefits: improving the efficiency of work processes with respect to different objectives
10	help - busi, use	"It would also help offset the impact of a declining share of the working-age population in many countries. . . , the automation of activities can enable businesses to improve performance by reducing errors and improving quality and speed, and in some cases. . . " [215]	companies will increase profitability and productivity by implementing automation to enable an optimized business process.	Benefits: improving the efficiency of work processes with respect to different objectives

Table 2.10: Suggestions and justifications for advancing the use of construction automation

No.	Suggestions	Justifications
1	Reengineer business structures and processes	In order to accelerate the use of construction automation to benefit from enhancements in the communication and collaboration between stakeholders and improvements in work efficiency, all participants in the construction process should reengineer their business structures and processes. If structures and processes are adapted ahead of time, stakeholders will be well positioned to implement new technologies and benefit from new partnerships. Close collaborations with researchers can help to ensure that industry is well aware of the emerging technologies.
2	Increase the scale of adoption	The benefits of automating construction greatly increase the more stakeholders are involved, i.e., the economies of scale of emerging technologies depends on the total number of users choosing the same technology. If more stakeholders are involved, it will make the costs of changing structures and processes worthwhile.
3	Assess project performance	There has been plenty of evidence that many financial risks are created in the early stage of new technology adoption, particularly when stakeholders do not support a reliable cost-benefit analysis on construction automation projects. Stakeholders should regularly assess project performance to evaluate the benefits being gained from automating parts of the construction process. This, of course, includes clearly defining the benefits for each of the stakeholders. For example, a client gains from the use of building information modelling when complex designs are to be done as it is easier, and therefore less costly to incorporate changes. It is only with this assessment that it will become clear that the early costs of automation implementation is worthwhile.
4	Develop building information protocols	The development of standardized building information protocols would be beneficial to enabling fluid information exchange between stakeholders. For example, problems often appear when responsibility for an information model is transferred from designers to contractors. As construction projects move from the preliminary design phase to delivery, stakeholders should form a set of policies and procedures for information manipulation to protect data and delimitate responsibilities, specifically determining the scope and details of information, the use of information and organization of information.
5	Develop appropriate legal contracts	The development of appropriate legal contracts would be beneficial to enabling secure information exchange between stakeholders. The most important step for setting up an adapted legal contract is the assignment of new roles to each participant (e.g., BIM system integrator or BIM information manager [220]), corresponding to an innovative contract model and a common data platform. Collaborative decision-making and control, dispute resolution, multi-party contract with clear labilities should be addressed through the application of a common building information protocol and a legal contract. Appropriate legal contracts would enable all stakeholders to contribute to the best of their abilities to the creation, modification and review of building information.
6	Integrate building information through standard data schema	The most significant division of construction process is in the separation of the design and construction phase. To ensure the upstream design information is seamlessly delivered to the downstream construction expertise, a standards data schema is needed among different parties. A standard data schema is an information exchange format to organize and carry data of building geometry and material properties. There are several prevalent data schema in use, such as IFC, gbXML, COBie. However, none of them is easily synchronized on multiple model platforms. A standard data schema should be developed to allow object-level coordination across heterogeneous building information models. It will also allow construction automation project stakeholders to gain benefits from efficient information sharing and collaborative working processes.

CHAPTER 3

Identifying enablers for coordination across construction supply chain processes: a systematic literature review

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This chapter corresponds to the published article:[1]

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Abstract

Managing stakeholders' reciprocal interdependencies is always a challenging issue. Stakeholders need to find out different ways to communicate information and coordinate material flows during the supply chain processes. Many recent studies have advanced construction supply chain coordination from multiple perspectives. However, the field still lacks a comprehensive analysis to summarize existing research, to explicitly identify all the possible enablers for coordination, and to investigate how the enablers can be carried out at the supply chain interfaces. To fill the gap, this study aims to conduct a systematic review in order to examine the relevant literature. A systematic literature review process was conducted to identify and synthesize relevant publications (published in the past 20 years) concerning the coordination of construction supply chain functions. These publications were coded to link main research findings with

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[1] Please note, this is the author's version of the manuscript published in the Journal of *Engineering, Construction and Architectural Management*. For the reasons of consistency, the style of this chapter matches that of the dissertation. Changes resulting from the publishing process, namely editing, corrections, final formatting for printed or online publication, and other modifications resulting from quality control procedures may have been subsequently added. When citing this chapter, please refer to the original article found in the reference above.

specific enabler categories. In addition, how these enablers can be used at the interfaces across supply chain processes were reviewed with an in-depth analysis of reciprocal communications between stakeholders at design-to-production, production-to-logistics, and production-to-site-assembly phases. The coordination enablers were classified into three categories: 1) contractual enablers (including sub-topics on relational contracts and incentive models), 2) procedural enablers (including sub-topics on multi-agent knowledge sharing systems and the last planner system), and 3) technological enablers (including sub-topics on linked databases for design coordination, design for manufacturing software platforms and automated monitoring technologies). It was found that interfacing different functions requires a certain level of integration of stakeholders for quick response and feedback processes. The integration of novel contractual forms with digital technologies, such as smart contracts, however, was not adequately addressed in the state-of-the-art. The scope of the systematic review is limited to the static analysis of selected publications. Longitudinal studies should be further included to sharpen the inductions of enablers considering organizational changes and process dynamics in construction projects. Different enablers for coordination were summarized in a concise manner, which provides researchers and project stakeholders with a reinforced understanding of various ways to manage reciprocal interdependencies at different supply chain interfaces. This study constitutes an important input for research on the construction supply chain by illuminating the thematic topic of coordination from inductively developed review processes, which included a holistic framing of the emerging coordination enablers and their use across supply chain functions. Consequently, it closes some identified knowledge gaps and offers additional insights to improve the supply chain performance of construction projects.

3.1 Introduction

Technological novelties and new management principles have altered the way the project stakeholders communicate and interact within a construction supply chain network, mainly towards collaboration and integration. In industry practice, however, many construction project supply chain initiatives have been limited in scope to the perspective of a single project stakeholder and project phase. For example, transportation, logistics services, and warehousing have been mostly regarded from only the contractor's point of view and only during the construction phase of the project [201]. For advances to occur, contractors, designers, suppliers and other project stakeholders have learned that they must collaborate. Together, this enables them to form a holistic view of construction supply chain processes and the complex interdependencies between the stakeholders in order to ensure successful project execution. Fortunately, many studies have led the way in showing that the supply chain processes in construction projects are evolving from a single logistics perspective into an interrelated multi-functional perspective, which highlights the interfaces across design, procurement, production, logistics and site installation [216]. Efforts in this direction link on-site construction needs with upstream supply chain functions, leading to the adoption of offsite and digital manufacturing technologies [122]. For example, companies like Katerra [165] and Boklok [35] have created digital-information-based, vertically-integrated project teams to improve the coordination of architects, contractors and manufacturers. With better coordination, project stakeholders can reduce conflicts during communications to accelerate project timelines and improve overall supply chain predictability. Exploring these developments and discovering how different construction supply chain processes can be efficiently coordinated or managed to reduce cost and waste has been a growing area of research.

A lack of coordination among project stakeholders across different functions and organizations is one key reason why construction schedules and costs are unpredictable [161]. For example, design coordination is a lengthy and iterative process. During this phase, stakeholders often have little information about the available suppliers who will be later selected to provide the material components as designed. When unavailable materials are selected by the design team, suppliers must inform the design team, who must adjust the design accordingly. In most commercial projects, materials and equipment are only generally specified by the designers. Contractors are required to make “submittals” of specific choices for items such as cooling and air conditioning equipment, type of flooring, and windows. When late changes occur to the design, or the submittals process is delayed, supplier materials delays can then occur. The designer-supplier link is an example of where supply chain coordination breaks down. It is caused by inadequate coordination of information and interdependent workflows that occur between designers and suppliers. Both parties are unable to receive timely feedback on design decisions, production status, and reliable material delivery timelines. As a result, the supply chain processes become less responsive and less predictable. This example demonstrates the need for coordination enablers at the interface between project stakeholders, which can ensure information visibility, communication responsiveness and clarity.

Researchers have addressed the challenges in supply chain coordination from various perspectives. Through theoretical lenses, some researchers have developed theories or principles about how coordination should be done in complex organizations. These include the organizational learning theory [186] with a focus on joint decision making and collaboration among stakeholders toward a mutual goal, and the transaction cost theory with a focus on shared rewards and risks. Additionally, a number of systematic reviews have been conducted for the management of construction supply chain processes based on those main principles. For example, Dallasega et al. (2018) [68] review a group of Industry 4.0 technologies to improve construction supply chain performance via information visibility and real time communication among stakeholders. Alsafouri and Ayer (2018) [15] show how different information communication technologies implementations can improve the information flows for the coordination of virtual models and construction project sites. Tang et al. (2019) summarize [300] the potential benefits and challenges of integrating virtual building information modelling (BIM) with communication technologies. Le et al. (2018) [182] present a comprehensive review of collaborative planning and design with advanced techniques for joint decision-making processes, including lean procurement with BIM and third-party logistics. In addition, Balasubramanian and Shukla (2017) [23], Badi and Murtagh (2019) [22] emphasize supply chain integration technologies to reduce carbon footprints to allow construction sustainability. Despite their different foci, the above reviews emphasize the importance of connecting stakeholders to embrace information exchange, knowledge transfer and more collaborative contractual relationships.

However, less effort has been directed to identifying and structuring all the enablers to achieve this needed supply chain coordination. The investigation of enablers has received researchers' attention, e.g., the study of enablers of collaboration in complex organizations [230, 94], however, few studies have explicitly focused on enablers of coordination in construction supply chain. The reviews above identify specific actions that project stakeholders can take to optimize and automate a specific supply chain function or process. They stop short of describing the possible enablers and how those enablers enable project stakeholders to manage the complex interdependencies and communications across different functions. Supply chains are characterized by "*reciprocal interdependence*" that requires "*a high level of mutual adjustment*" between stakeholders [99]. The complex interdependencies between stakeholders can result in adversarial relationships and pose great challenges to effectively managing the supply chain processes in construction projects [180, 108]. Therefore, there is need to formulate a comprehensive understanding of the different enablers that allow efficient coordination to manage the reciprocal interdependencies across different supply chain interfaces.

To address the research gap, this paper conducts a systematic literature review of relevant scientific publications from construction supply chain management. The resulting synthesis provides a holistic framing of the emerging coordination enablers. For each enabler, the paper highlights the potential to manage the reciprocal interdependencies of stakeholders across different supply chain phases. To do so, Section 3.2 provides a basic review of the state of supply chain coordination in construction projects. Section 3.3 introduces the systematic literature review methodology including the selection and evaluation criteria for publications. Section 3.4 presents the results of the review. This includes a detailed analysis, categorization, and synthesis of the identified coordination enablers. Section 3.5 discusses the contributions from the review and outlook. Section 3.6 presents the conclusions. The findings can be used by construction supply chain stakeholders and researchers to understand the coordination enablers available across different functions to improve efficiency of the construction supply chain.

3.2 Understanding coordination in construction projects

3.2.1 Definition of supply chain coordination

There is no single commonly-accepted definition of construction supply chain coordination in construction research. Therefore, for the purpose of this research, a definition and boundary are defined from existing literature and the authors' prior knowledge about supply chain management.

The supply chain is originally a concept from the manufacturing industry and remains an emerging concept in the construction industry. For many manufacturing and distribution organizations, a supply chain process normally consists of multiple functions, such as purchasing and procurement, production, logistics and inventory. In a general scope, the supply chain process is also viewed as a management process of plan, source, make, deliver and return, which originated from Supply Chain Council's Supply Chain Operations Reference (SCOR) model [144]. This addresses the main business activities needed to satisfy a customer's order, and should be properly adapted to the construction industry context. In comparison to manufacturing supply chains, construction supply chains are characterized as temporary and highly-fragmented organizations [42]. This makes management of construction supply chains very complex. It is difficult to make trade-offs between customer requirements and complex engineering solutions for production and installation of construction elements [216].

In construction, researchers have defined supply chain as the network of stakeholders that are involved through upstream and downstream linkages in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer [327]. A similar framing defines supply chain as a series of interconnected activities that involve the coordination, planning and controlling of products and services between suppliers and customers [216].

A construction supply chain, considering those definitions, is typically viewed as a network of hundreds of different firms supplying materials, components and construction services [201, 239]. Construction supply chains are organized so that this network can complete a construction project that provides value for a client. To learn and adapt from the SCOR model, a construction supply chain process consists of multiple functions across its project lifecycle, namely design, procurement, production (i.e., manufacturing of ordered materials), logistics and inventory, site assembly, and building operation and maintenance [51]. For the purposes of this research, the functions considered are planning and design, purchasing and procurement, production, logistics, inventory, and site assembly. The scope of this research focuses on linkages to the supply and installation of on-site construction activities. Other functions include operation and maintenance, end-of-life phases, and closed-loop supply chain processes (e.g. circular economy).

While these functions are also important to consider within the supply chain process [22], they remain outside of the boundary of this research.

Construction coordination is understood to be the act of dynamic communication, information exchange, and collaborative workflows among project participants towards a mutual goal [180]. Successful construction coordination enables the network of participants to supply the right material and complete the building project on time and within budget. In particular, the issues that need be coordinated by stakeholders, also identified by many studies [239, 122, 51], include:

- conflict and discrepancy resolution and emergent problems,
- procurement and orders of materials and equipment,
- quality control and compliance,
- schedule updates, field reports, and site change orders,
- contract clarifications and articles,
- design and engineering drawings, and specifications.

To sum up, we define construction supply chain coordination (CSCC) as the act of managing the communication and information exchange between a network of project stakeholders who work together to ensure timely responses to the changing demand and supply signals across supply chain functions. Efficient construction supply chain coordination has been found to enable cost savings, schedule compression, material lead time reduction and high quality construction projects [216, 182, 300].

3.2.2 Existing challenges for supply chain coordination in construction projects

It has been widely accepted that plenty of coordination problems exist in construction projects across different supply chain functions. Project stakeholders can be geographically separated yet must make interdependent decisions. This creates a big challenge for project stakeholders to collaborate and coordinate the project.

Traditional enablers for CSCC include oral communication – e.g., meetings, site visits, telephone and face-to-face talks – and written communication, e.g. email correspondences, written plans, paper-based schedules and contract documents [201]. Often, coordination of project plans is simply through Gantt charts and 2D plans. In the above cases, the coordination of information can be time consuming and error prone. Furthermore, traditional enablers can suffer from incompatible and old information systems, lack of automation for technical assistance, and lack of digitalization to support information sharing [239, 108, 339]. As a result, work can be poorly defined. Delays in communications are inevitably frequent.

Addition problems have been observed, including a lack of mutual targets, prevailing self-interest, reluctance and opportunism [216, 121]. The construction industry has been reluctant to embrace the collaborative planning and working relationships [174]. Feedback to suppliers is limited and late payments are common. Proactive communications are often missing between designers, suppliers and contractors. Consequently, considerable uncertainties are fostered in the processes from design to construction. These uncertainties can lead to unfavorable results such as delayed material deliveries, wrong material quantities, and thus overall project delays.

To overcome these challenges, an explicit and comprehensive understanding of all the possible coordination enablers is needed to allow efficient communication and collaboration across different supply chain functions.

3.2.3 Understanding enablers for coordination

An enabler is defined as a way to give people competence and power to achieve a purpose, which is often interchangeably and consistently used with the term "mechanism" by many researchers, e.g., [230], [44], and [94]. For this research, therefore, a coordination enabler is understood as the way to give project stakeholders the competence to efficiently communicate and successfully manage their reciprocal interdependences during supply chain processes. Various literatures have discussed different ways to achieve efficient coordination for a specific supply chain function, e.g., information communication technologies for coordination of site activities [216, 68], and demonstrated their potentials to solve those problems and challenges as mentioned in Section 3.2. Unfortunately, a systematic overview of all possible enablers is still missing from the existing body of knowledge. Furthermore, how these enablers could exert their potentials to mitigate those challenges across supply chain functions has not been addressed. Therefore, a systematic literature review is in need to answer the two questions.

3.3 Literature review processes

There are a number of advanced literature review methods applied for the reviewing research, such as systematic literature review methods [262] and text mining based review methods [52]. As theoretically defined by Wolfswinkel et al. (2013) [338], a systematic literature review is conducted through the usage of a comprehensive search that scans the relevant body of literature with clearly stated and comprehensible search choices and selection criteria. This research uses the systematic literature review since it is more appropriate for assessing the details of scientific publications through comprehensive search and scan of easily accessible publication databases.

Scientific publications relevant to CSCC are retrieved from Web of Science databases. The search criteria is defined, on Web of Science website, as keywords (TOPIC (construction) AND TOPIC: (supply chain) AND TOPIC: (coordination or collaboration or integration or communication or synchronization)) plus publication year ranging from year 1999 to year 2019 (up to the date of data collection - 2019 June).

The initial search returned 692 journal articles. This number was reduced by filtering to specific fields. The selected fields were management or engineering civil or engineering industrial or construction building technology or engineering manufacturing (as defined in Web of Science categories). Fields such as navy engineering and agriculture engineering were excluded. After filtering, 234 articles were left. Next, the first author read and analyzed the abstract, introduction, and conclusion sections of each of the 234 papers. A manual selection process stage examined the relevancy of the articles. When the research objective was not relevant or did not align with CSCC, the journal article was excluded. This included studies with a purely technical focus (i.e., software engineering) that did not describe how the software enabled CSCC. In the end, 69 journal articles were selected for in-depth review. All of the 69 publications are indexed by SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC. The selection process for the relevant publications is summarized in Figure A.1. Figure A.2 in the Appendix A illustrates the distribution of the 69 publications by year, and Figure A.3 in the Appendix A shows the distribution of the 69 publications by journal sources.

The selected 69 publications[2] were then coded to link main research findings with specific enabler categories. This process is informed by Wolfswinkel et al.'s iterative coding procedure. The described coding scheme was specifically set up for changes, modifications and enlargements to reduce personal bias as much as possible during the coding process [318]. Throughout the analysis stage, various thematic codes were inductively derived. The articles were coded in an iterative process to identify emerging enablers. Consequently, the various reviewing cycles led to the emergence, and subsequent refinement, of various conceptual groupings and summarizations. Each of the publications was exclusively assigned to a category of the enablers based on its most significant research focus or key concepts. Each publication was linked to only one enabler in this review.

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[2] Detailed article information is provided online `https://polybox.ethz.ch/index.php/s/kK4042dnHZJ8xSQ`

3.4 Results

3.4.1 Identification of CSCC enablers

From the review and coding process, seven specific enablers emerged (see Table 3.1). These enablers can be further categorized into three perspectives: contractual, procedural and technological. Contractual enablers are grouped together to highlight their common potentials to affect the structure of the relationship of stakeholders, including relational contracts and incentive models. Procedural enablers are grouped together to highlight their common potential to drive procedures and stakeholder interactions related to problem solving and knowledge sharing, including the multi-agent knowledge sharing system and the last planner system. Technological enablers are grouped together to highlight their common potential to digitalize and automate traditional workflows, including linked databases for design coordination, design for manufacturing (DfMA) software platforms, and automated monitoring technologies. The key concepts in Table 3.1 were selected as emerging keywords from the publications that are highly associated with a specific enabler.

Many of the selected literature pointed out the necessity of the role of a central coordinator to manage reciprocal relationships among key stakeholders. Researchers have argued that the role of coordination has expanded its scope to include not only designers and contractors, but also suppliers or manufacturers. According to [99], the general contractor, together with the chief supplier, is responsible for coordinating the work of all specialty subcontractors. They act as the hub and the conflict mediator to pass changing engineering decisions to subcontractors. With the extensive adoption of BIM platforms in projects, some researchers have suggested new roles, such as interface manager, BIM engineer or BIM facilitator or “information broker” [357, 341, 45, 238]. This was demonstrated to be helpful to advise the partnerships and the selection of appropriate suppliers. The following in-depth discussion on coordination enablers aims to discover how the reciprocal interdependencies among stakeholders can be managed to improve supply chain performance.

3.4.2 Contractual enablers

Relational contracts

Relational contracts are collaborative agreements [354]. Relational contracts enable coordination by incentivizing clients, designers, main contractors and subcontractors to work together as a unified team, rather than as a disparate collection of separate organizations [26, 299, 207]. Relational contracts are necessary because multi-layer chain subcontracting systems leads to the poor coordination of information flows due to the long communication chains among stakeholders

Table 3.1: The seven specific enablers emerging from selected literature

Category	CSCC Enabler	Total number of relevant publications	Key concepts	Article No. from [2]
Contractual Enablers	Relational contracts	23	Partnership	1, 3, 4, 6, 12, 13, 20, 25, 26, 33, 35, 37, 38, 40, 42, 46, 49, 54, 55, 57, 61, 62, 67
			Trust-building	1, 3, 25, 26, 54, 55, 57
			Willingness to collaborate	1, 3, 40, 42, 46, 49, 54, 55, 57, 61, 62, 67
			Co-location	1, 37, 54, 55, 67
			Joint decision making	1, 3, 25, 33, 46, 49, 61, 62, 67
			Mutual objectives	1, 3, 4, 6, 12, 13, 20, 25, 26, 33, 35, 37, 38, 40, 42, 46, 49, 54, 55, 57, 61, 62, 67
			Risk sharing	12, 20, 25, 35, 40, 49, 54, 61
	Incentive models	5	Cost sharing and allocation	16, 23, 32, 50, 63
			Benchmarking key performance indicators	23, 32
Procedural Enablers	Multi-agent knowledge sharing system	11	Distributed e-work systems	5, 14, 15, 27, 28
			Team learning	17, 43, 64
			Social network analysis	8, 21, 60, 64
	Last planner system	6	Just in time delivery	2, 11, 44, 47, 58, 65
			Make-ready work	2, 11, 44, 58, 65
			Collaborative planning	11, 44, 65
Technological Enablers	Linked databases for design coordination	10	Data integration	9, 10, 18, 19, 34, 53, 59, 66
			Communication Protocols	19, 48
			BIM	9, 34, 48, 52, 53, 59, 66
	Design for Manufacturing and Assembly (DfMA) software platforms	8	Product modularization	22, 30, 36, 39, 41, 51, 56
			Early supplier involvement	22, 36, 39, 50, 51, 56
			Shared product catalogues	36, 39, 41
			Prefabrication platforms	22, 30, 41, 51
			Parametric design	30, 36, 41, 50
	Automated progress monitoring technologies	6	Real time tracking	7, 24, 29, 31, 68, 69
			Information visibility	24, 29, 69
			Information communication technology integration	24, 29, 31, 68, 69

[299, 199]. Gosselin et al. (2018) [115] finds that too much owner contract control – common in traditional contracting practices but not relational contracts – leads to a perceived lack of trust and hinders contractor cooperation [127]. To overcome the problem, some researchers encouraged that conflicts or disputes could be settled by re-negotiations and mediations rather than penalties or litigations [12]. In practice, however, the implementation of relational contracts have been mainly focused on clients and main contractors rather than extending down the supply chain to subcontractors and suppliers [201]. This arguably prohibits the complete integration of processes throughout the construction supply chain [12, 269, 281].

Several factors have been identified to motivate the proper implementation of relational contracts, such as commitment, trust, communication, seamless integration and common goals, and win-win philosophy [221]. In particularly, the spirit of trust was highlighted by Manu et al. (2015) [212] as a critical component to ensure fairness and mutual cooperation from project design to construction, yet within the scope of agreed roles, expertise and responsibilities. In addition, transparent financials (particularly desired by the subcontractors) [212], shared risk and reward [121], and joint decision-making [236, 180, 216] were recognized as necessary components for the management of resource dependence to ensure the efficient coordination of material and information flows.

Many studies illustrated a specific use case of relational contracts, the Integrated Form of Agreement (IFOA) pioneered by Sutter Health [121]. IFOA encourages the early involvement of stakeholders to reinforce the collaboration for the complete supply chain integration. Professional construction trades should also be involved earlier during planning and design phases, which facilitates the sharing and coordination of collective knowledge for manufacturing and assembly.

Incentive models

Incentive models are models to quantitatively determine the mutual benefits [77, 92]. Incentive models enables coordination by enhancing long-term relationships and minimizing cost (e.g., cost of change orders) for transactions and communications. Fulford et al (2014) [100] found that the stakeholders are willing to perform self-control with incentives. If an owner provides a medium for communication and strongly trusts the stakeholders with an incentive, they can find optimized solutions for maximizing their value while minimizing opportunism for their own benefit. In this direction, researchers such as Xue et al. (2011) [346], Zhai et al. (2016) [352], and Lu et al. (2018) [203], have explored mathematical optimization models (e.g., heuristics, dynamic stochastic modelling, integer programming) to help quantitatively adjust stakeholders' decisions on supply costs.

On the other hand, underestimated project risks can lead to financial losses. There has been a growing trend in applying mathematical models to develop risk sharing parameters to optimize allocation of risks. For example, Dharma Kwon et al. (2010) [77] developed a cooperative game theory to make decisions on how much risk to transfer to different stakeholders. With carefully chosen parameters, time-based and cost-sharing incentives can achieve optimal coordination of stakeholders. With a clear definition of responsibilities and roles, suppliers will consent to share the risk and rewards and align the interests of each member with the interests of the project. Therefore, incentive models with the consideration of risks would allow efficient mutual adjustment among stakeholders rather than optimization of their own local benefit.

3.4.3 Procedural enablers

Multi-agent knowledge sharing system

A Multi-agent knowledge sharing system is a network-based system for the distribution and sharing of knowledge [64]. Multi agent knowledge sharing systems enable coordination by maintaining the consistency of decision making through diffusion of experiences, which is considered as a critical element of daily work procedures. The development of multi-agent knowledge sharing systems attracts researchers' attention to stimulate the coordination of information. Some studies have revealed that the trust among members is the consequence of effective coordination and is the antecedent of knowledge sharing [355, 4], thus constraining the potential for multi-agent knowledge sharing systems.

Knowledge sharing primarily improves the relationship and coordination at the individual level, and the organization members are the units of analysis [345, 70]. Zou et al. (2006) [357] found that knowledge sharing helped establish relationships and eliminate learning barrier to allow information flow freely. In other words, it helped supply chain stakeholders to gain an explicit understanding of design, manufacturing and construction processes in response to changing design needs and material requirements. Therefore, the advantages were discovered mostly at the design to construction interface. For example, Lönngren et al. (2010) [204] found that a structured representation of knowledge enables collaboration and communication to cope with construction problems and design changes.

Team learning, a form of knowledge sharing, deals with how to tackle the coherency of problems and diffusion of knowledge across supply chain members [4]. For example, Das et al. (2015) [70] developed an ontology-based knowledge representation scheme to enable the close collaboration between construction contractors and regulative bodies. Xie et al. (2010) [341] suggested that architects should be encouraged to harness the team learning potentials particularly with regard to tacit knowledge. Using the information technology platforms in optimizing the choice of building materials further facilitates the information sharing and knowledge synergism among the engineers and construction contractors.

Another stream of research under this topic is the use of social network analysis together with agent-based negotiation models. Degree centrality is the principal subject studied that refers to the number of connections a member has with others when stakeholders communicate and share knowledge [291]. For example, Adami and Verschoore (2018) [4] discovered that the higher number of connections, the greater the scope of influence of a coordinator over the other stakeholders. As practical implementations, Ajam et al. (2010) [11], Costa and Tavares (2012) [64] proposed an agent model that can motivate all the stakeholders to align material delivery decisions and actions that lead to mutual benefits. As a result, unnecessary material inventory can be eliminated and required materials can be delivered according to the actual demands on site.

Last planner system

A last planner system is defined as a planning system where the start of one activity is triggered by the completion of another [218]. It enables coordination by balancing the objectives of all supply chain stakeholders to collaboratively establish reliable decisions. It has emerged from lean construction practices in the literature. Since site change-orders usually cause material demand fluctuations, the coordination of material supplies to align with the dynamic demands was frequently discussed in the literature. It is useful to secure when an activity should start and whether an activity should be accelerated without delaying the overall supply chain process.

One prerequisite to successfully implement last planner system is that all participants in the chain are willing and able to respond to each other's needs, not just on their own [59, 151]. Isatto et al. (2015) [151] suggested the use of language-action perspective (LAP) to help stakeholders to understand commitments when implementing the last planner system. An example of a last planner system consequence was just-in-time (JIT) ordering processes [71]. The processes were featured by the collaborative scheduling among various stakeholders. With quickly updated and shared scheduling information, the actual material need dates are coordinated. The case studies [91, 67] have demonstrated the potentials and advantages of quick updates. And they showed that last planner system helps create a collaborative environment where stakeholders can communicate their respective work with one another, signaling the demand and supply quickly. As a result, it was considered as a useful tool to execute work in an order that suits the best use of time and resources.

3.4.4 Technological enablers

Linked databases for design coordination

The linked databases have been defined in literatures as federated data models by BIM based platforms or frameworks, with a focus on design coordination [238, 84]. The linked databased enable coordination by integrating design, engineering, and construction data especially in downstream applications such as rule or code checking or guiding production of prefabricated building elements [10]. Most of the case studies relevant to linked databases are off-site or industrialized projects [113, 9]. A variety of software applications have been developed for those purposes. For example, Autodesk Navisworks and Solibri were used in many case studies in the literature [90]. They allow designers and engineers to spatially coordinate the geometry and to detect clashes so that architects and engineers can update the changes as required.

Two approaches were discussed in the literature for the establishment of the linked databases. The first approach is a proprietary approach (i.e., closed BIM approach) that supports multiple heterogeneous file format readers that map to its own managed data structure [8, 210]. The second approach is the use of database servers, otherwise known as model servers (i.e., open BIM approach) [232]. For example, as cloud system becomes mature, cloud BIM gradually attracts people's attention and creates new opportunities for supply chain stakeholders to easily access design models for the coordination of information. Early involvement of engineering design and constructability decisions through the use of Cloud and BIM based systems supports appropriate deliveries, design coordination, and collaboration with improved communication [56]. There is no single way in which data can be managed in a BIM workflow, and as a result, there are a number of different file formats that can be used.

Apart from their potential, literature has pointed out that challenging issues remain in the development of linked databases with respect to data interoperability and coding information correctly at a semantic level. Additionally, face-to-face communications (e.g., meetings and co-location work teams) are still favored, over virtual data integration and exchange, to help stakeholders digest information updates for better decision-making.

Design for Manufacturing and Assembly (DfMA) software platforms

Design for Manufacturing and Assembly (DfMA) software platforms have been defined as the ones that optimize design for ease of manufacturing and assembly of construction components where design should focus on using off-site yet customized manufactured components and planning for efficient logistics and assembly of these components on-site [83, 114, 247]. They enable coordination by ensuring the confidence in prefabrication and then eliminate possible building tolerance problems and balance the precision of installation to prepare for the complex site conditions. In some cases, steel frame suppliers and construction installers work closely to develop joint solutions related to span issues, tolerance levels, material requirements and installation issues [217]. Some researchers suggested that the supplier involvement in design is vital to ensure coordination of tolerance control information and should be emphasized in DfMA [189].

On the other hand, BIM software was considered as an important element of DfMA software platforms, as it provides a library of standard parametric components for architects, engineers and suppliers to efficiently coordinate design information with greater certainty, particularly benefiting from an early project stage [113]. BIM allows designers to pass the model precision to the installer. Additionally, manufacturers can provide BIM models with their own specifications included in the metadata [247]. Therefore, it is suitable for prefabrication or building modularization. From the literature, examples of prefabrication components in mainstream BIM authoring software were mainly precast structural members, modular mechanical and electrical components. BIM software was suggested by most researchers, as functions exist in CAD and CAD/CAM to involve suppliers to plan and to control the detail of manufacturing processes.

Besides that BIM based DfMA platforms allow mainly standardized modular parts, 3D printing platform is emerging to allow customization of building elements with complex geometry. In some cases, small parts of 3D printed elements are produced in small volume, while it is not yet considered widely for mass production for construction assembly [176]. It remains challenging to establish a building information model for construction and for manufacturing regarding any arbitrary geometry. Therefore, the coordination of manufacturability and capability for accurate assembly in a later stage remains constrained.

Automated progress monitoring technologies

Automated progress monitoring technologies are information communication technologies for constantly tracking work progress, constraints and productivity. They enable coordination by signaling changes in schedules and site demand. Periodic measurements of the completion of on-site activities provide valuable information, which can be used to prepare and meet specific project goals agreed by stakeholders. The reliability of information exchange for progress tracking depends heavily on the accuracy and timeliness of data capturing, which requires proper use of data acquisition technologies [150]. As BIM software has been extensively adopted, a novel system was developed that combines 3D object recognition technology with schedule information into a combined 4D object-based progress tracking system, the information from which can be further transmitted to a cloud sharing system to improve collaboration [76]. Information communication technologies were also popular in use to collect data for construction progress monitoring and tracking of materials. Some researchers have explored such use of auto-ID, sensors (e.g., Radio Frequency Identification, etc.), and mobile devices to enable real-time information exchange and communication between human, system and devices [301, 350, 86]. With the help of sensors, progress deviations were tracked through superimposition of 4D as-planned models over as-built models [350]. Communication responsiveness was improved when these monitoring models are used to track material status and location, estimate the task start time, and provide warning signals.

3.4.5 Coordination across supply chain functions

This section explores how the enablers facilitate coordination across different functions. Figure 3.1 shows an overview of the identified enablers used at interfaces across different functions. The interfaces reveal the needs for quick response

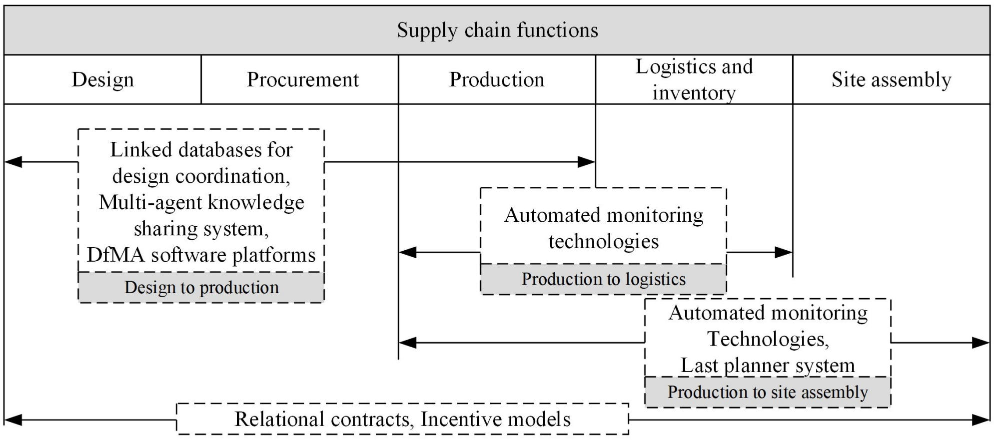

Figure 3.1: The involved enablers for the coordination across supply chain functions/processes

and feedback processes to address reciprocal interdependences between stakeholders. Interfacing different functions requires a certain level of integration. The digital integration of interfaces between design, production, logistic and site assembly was considered as a thrust topic in the literatures, which was discussed in line with the development of new contractual models. The relational contracts and incentive models were not specifically mentioned for any supply chain interface in relevant literatures. They can be considered, however, useful for the whole supply chain process. This section will only discuss the design-to-production interface, production-to-logistics interface, and production-to-site-assembly interface.

Design to production

The purpose of interfacing design and procurement functions is to ensure the coordination of design information flowing correctly to the suppliers. From the literature, the coordination of design information primarily included the configuration of elements, material and components that give a building product its attributes of function, appearance, durability and safety. Conflicts between design information and available supply information are common [216, 84]. Resulting wrong design decisions and design details further lead to the production of wrong materials and site re-work.

A secure, modular, and flexible system that can aggregate scattered design information and share that information across design, procurement and production software applications is highly desirable. Cheng et al. (2010) [56] developed an information system, the supply chain Collaborator, to facilitate the flexible coordination of construction supply chains by leveraging web services, web portal, and open source technologies. A similar study was conducted by Costa et al. (2012) [64], who proposed a web prototype to provide a solution for the coordination through multi-attribute negotiation mechanism and an agent based framework. By the analogy of distributed computing, automated bidding [291], e-Commerce [45], e-Business [64], e-Work [10], and e-Ordering/e-Tendering [11] were investigated to address parallelism, the principle of conflict resolution, new measures of viability and scalability, and the teamwork integration evaluator to reduce coordination cost and improve design-procurement-production coordination.

To link design to production, a number of DfMA software platforms and associated linked databases were developed to facilitate the integration of design data and procurement data. Said et al. (2015) [269] focused on the “ease” of incorporation of off-site manufacturing and collaboration early on in the design and construction process using BIM software. Modelling buildings in BIM software and integrated Virtual Reality software, can allow different project partners including clients to view and confirm or disapprove exact details and finishes virtually in the very early design stage [72]. This aspect of virtual visualization and decision-making facilitates off-site manufacturing, where repetition of components and processes are common. Coordination between the housing market and manufacturing is a crucial capability when engaging in digital design platforms [84]. Though beneficial, the use of BIM software to support design information coordination still has limited design options and flexibility for custom-designed components. Besides, there remains the challenge about the insufficient interface and standard data exchange formats between BIM and production planning and fabrication tools.

Production to logistics

From a supplier’s perspective, it is essential to establish a robust interface between production, logistic and inventory to enable on-demand and just in time delivery of construction materials. Large stockpiles on the construction site and delay of delivery are significant problems due to the inefficiency to coordinate information between the three stages. Some studies highlight how important it is to develop collaborative models for transport management if optimized transport solutions are to be achieved [86]. Additionally, standardization of logistic processes should be promoted to improve operational effectiveness and efficiency as well as cooperation and coordination [83, 217]. A novel integrated automated logistic bidding model based on decentralized systems was proposed to comply with customer suggestions and manufacture the product according to design specifications to improve the coordination of logistics information [291]. An example using digital production-logistics planning was the integrated 4D and GIS system, which helps solve two common tasks at this interface, including the determination of number of material deliveries, and allocation of consolidation centers [150, 76].

Central to the establishment of coordination enablers is the concept of pull-planning used to guide production processes and logistics processes. Some studies recommend applying lean and agile manufacturing principles to manage the offsite supply chain, which specifically focus on lead time compression and reducing product cost [92, 86]. From other research findings, responsive site logistics processes and platforms [150, 76], in the context of construction projects, were applied by a number of researchers to ensure just-in-time delivery. For example, Tanskanen et al. (2008) [301] advocate a vendor-managed-inventory approach, including "small-item store" owned by a supplier to provide materials and equipment as needed by sites in real-time. Lean principles broadly aim to provide more control over value specification and demand while designing the process to eliminate waste inventory and optimize efficiency of logistics.

Production to site assembly

The integration of production and site assembly drives the development of industrialized construction projects and off-site manufacturing. Relevant case studies show that the integration of engineering and production and the production capability are the most critical factors influencing coordination in an engineer to order project supply chain [216]. The typical conflicts between the three stages exist due to the mismatch between supplier's willingness to provide large quantities of materials in stable volumes and construction contractor's willingness to receive just in time supply in small batches due to the changing demand on site [69]. The reciprocal interdependencies in construction require more frequent and direct interaction among the involved stakeholders to enable mutual adjustments among the firms whose activities and resource use need to be coordinated, e.g., linking the production and subsequent delivery and installation of plasterboards [26]. Studies have suggested that subcontractors can improve productivity, if transparency of information is allowed for planning, scheduling and coordination [199]. It was demonstrated that updating and synchronizing the 3D model with data coming from different supply chain stakeholders and software applications can help people effectively visualize updates according to construction processes and site changes, which also serves as an information system that loosely links different ERP systems [56]. Although automatic progress tracking technologies have been investigated to enable the just-in-time delivery, there remain challenges to seamlessly link production and site needs, because supplier lead times are, for the most part, much greater than the possible accurate foresight regarding construction work completion. The production time and the construction assembly time is not well aligned, creating difficulties for the supplier and construction contractor to coordinate a reliable time to get the required materials onsite on time and on demand.

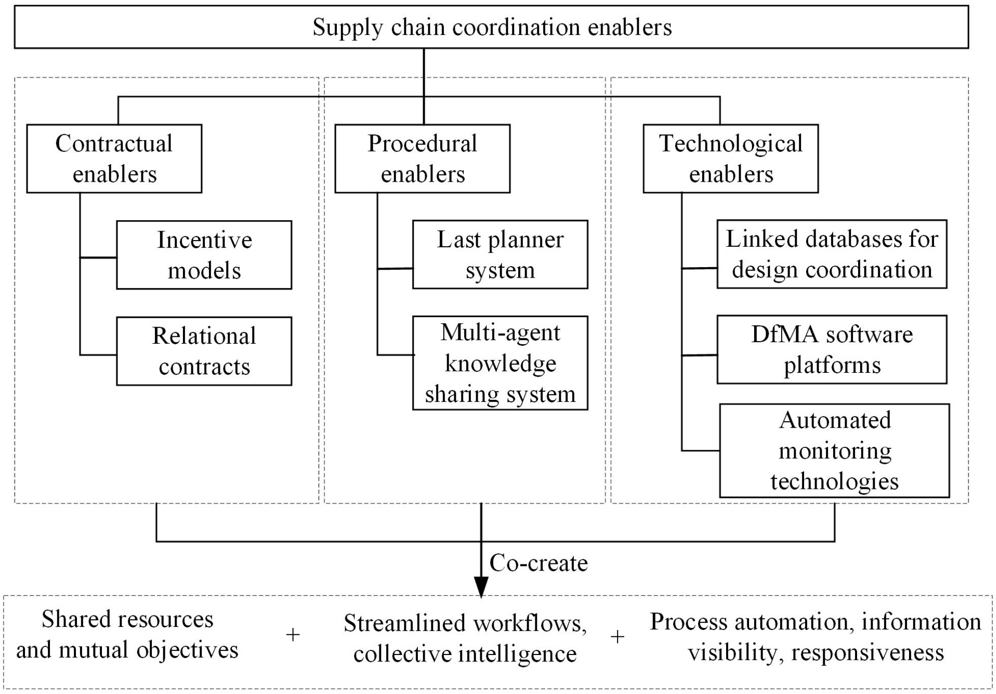

Figure 3.2: A synthesis of review results of coordination enablers

3.4.6 Synthesis of results and the identification of research gaps

The review results are synthesized as an overview of enablers in Figure 3.2. Each category of enablers has specific main features. Contractual enablers support the integration of the workflows based on trust-binding partnerships. Procedural enablers help streamline workflows and develop collective intelligence by encouraging stakeholders to share information. Technological enablers support the process automation of material components tracking and digitalization of component design. It was found that information technologies help make the site-specific details trackable in real time including building design drawings, factory fabricated material parts, material shipping status, and site management processes.

Each category should be considered as a complementary component to each other. Without new contractual forms, automation and digitalization may not be exploited fully for coordination. For example, clients still can distance themselves from suppliers, subcontractors and endless meetings.

Research gaps include:

1. Although research has been conducted to create novel contractual models, the possibility to co-create digital contractual processes has not been

fully considered. Integration through multi-party contracts and mathematical incentive models can be further explored with a digital initiative. For example, it is promising to use block chain technology to establish smart contracts for construction projects. Blockchain technology and smart contracts can improve building trust, when all the supply chain stakeholders can potentially benefit from secured data and financial transactions [145].

2. The implementation of the last planner system was not fully integrated with digital platforms. Although the last planner system was ideal to integrate constraints to allow better manufacturability and constructability, there was a lacking of platforms with intelligent algorithms and secure data environment to encourage the suppliers to be fully involved and dedicated to its implementation. There is also a missing link to align the use of integrated platforms under relational contracts. This will inevitably result in disputes and legal issues regarding specific agreements. Therefore, potential misunderstanding still leads to the distrust and a blame culture among stakeholders.

3. Most of the literature is limited to addressing coordination with sub optimizations of specific supply chain functions. There is a lack of holistic views to integrate all supply chain functions. The full vertical integration strategies suggested by Hall et al. (2019) [122] are helpful to create a shared awareness and transparency for coordination activities by integrating upstream design, manufacturing and downstream installation activities. With full integration, the information such as detailed task instructions and design drawings, can approach the end of the supply chain with less information loss and higher precision. It is, though challenging to realize in practice, an important direction where most companies could shift to enable collaboration.

3.5 Discussion

This review focuses on a niche aspect of the much broader construction supply chain management area of research. The state-of-the-art research has given specific attention to purely coordination. One possible explanation might be that there is no unified definition of coordination, let alone the various enablers to complicate the emergence of a common scientific basis for construction supply chain coordination. Therefore, the authors establish a comprehensive perspective based on a systematic review.

The literature review results cover a wide range of coordination enablers from different perspectives. A significant highlight is the mutual adjustments and reciprocal interdependences addressed by contractual, procedural and technological enablers. The identified enablers are meant to capture the widest range of approach to coordination across construction supply chain functions. The review results are, therefore, comprehensive. As the main features of each category indicate that the potentials of the enablers complement each other, they should be used together to ensure efficient coordination in construction projects. Considering specific project context, the enablers should be prioritized in use. Large companies might emphasize technological enablers because they have sufficient investment for implementation. Various combinations may be explored in future work. In addition, apart from the contractual, procedural and technological perspective, the topic of coordination should be examined with a wider angle of view. For example, different organizational structures (e.g., hierarchical or flat structures) could affect the reporting processes and efficiency of communication during construction projects, and therefore, an organizational perspective to summarize coordination enablers is worth investigating.

The enablers need to be studied in further detail. For example, though most publications studied indicate the necessity of using digital models and linked databases, a few researchers argue that contractors and trades prefer face-to-face communication rather than digital tools [199]. They suggest that technological enablers can help, but are not absolutely required for coordination. Suppliers fear that their innovations are shared with potential competitors and used against them. Market pressure was not examined systematically in the selected literature, which could be an important factor to affect the effectiveness of coordination of suppliers and contractors. Meanwhile, these issues further motivate the authors to study industry practices as they are commonly observed in construction supply chain processes and highly in relevance to managing complex interdependencies of project stakeholders. For example, companies such as Boklok in Sweden and Katerra in the United States use vertical integration to take much greater control of industrialized supply chains to implement design-for-manufacturing software platforms. Therefore, besides scientific publications, case studies of any types and scopes of construction project should be analyzed in details, which may help project stakeholders select the most appropriate actions to enable efficient coordination in order to make projects successful. The authors consider future studies in this regard will help refine the current results.

Finally, longitudinal studies can provide valuable insights to sharpen causal models of components, interrelationships and dynamics related to the field of construction supply chain. For example, longitudinal qualitative studies can advance the perception of coordination enablers by recognizing the changing dynamics of organization structure. Furthermore, longitudinal research could offer further insights into the development stages where certain coordination needs at supply chain interfaces may not be explainable or recognizable through other research designs.

3.6 Conclusions

This paper presents the extent of literature on different enablers for efficient coordination in construction projects. Based on the systematic literature review of 69 carefully selected scientific publications, coordination enablers have been classified into three categories: 1) contractual enablers (including sub-topics on relational contracts, 2) procedural enablers (including sub-topics on incentive models, multi-agent knowledge sharing system, and last planner system), and 3) technological enablers (including sub-topics on linked databases for design coordination, design for manufacturing software platforms and automated monitoring technologies). Based on an in-depth analysis, the review indicates that the enablers should complement each other to allow both process automation and contractual integration to address stakeholders' reciprocal interdependencies. For example, smart contracts can be a form of the combination to be investigated in future research.

Research on coordination appears to be even more ambiguous and disintegrated than that carried out on supply chain management, more broadly. Therefore, this paper contributes to the existing body of knowledge by illuminating the thematic topic of coordination from inductively developed review processes, which included identification of all possible enablers and their exploration across different supply chain functions. Consequently, this research constitutes an important input for the research on coordination, with a wide intended application. While this study is not the first literature review with regards to construction supply chain, it offers additional insights explicitly on coordination of supply chain processes for construction, given the recent surge in publications on this topic. The results of this study underline the different perspectives, which can close some of the identified knowledge gaps in construction supply chain research.

PART II

Improve ETO material flows

CHAPTER 4

Using look-ahead plans to improve material flow processes on construction projects when using BIM and RFID technologies

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This chapter corresponds to the published article:[1]

Chen, Q., Adey, B.T., Haas, C. and Hall, D.M. (2020), Using look-ahead plans to improve material flow processes on construction projects when using BIM and RFID technologies, Construction Innovation, Vol. 20 No. 3, pp. 471-508.

Abstract

BIM and RFID technologies have been extensively explored to improve supply chain visibility and coordination of material flow processes, particularly in the pursuit of Industry 4.0. It remains challenging, however, to effectively use these technologies to enable the precise and reliable coordination of material flow processes. This paper proposes a new workflow designed to include the use of detailed look-ahead plans when using BIM and RFID technologies, which can accurately track and match both the dynamic site needs and supply status of materials. The new workflow is designed according to lean theory and is modeled using business process modelling notation. In order to digitally support the workflow, an integrated BIM-RFID database system is constructed that links information on material demands with look-ahead plans. The new workflow is

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[1] Please note, this is the author's version of the manuscript published in the Journal of *Construction Innovation.* For the reasons of consistency, the style of this chapter matches that of the dissertation. Changes resulting from the publishing process, namely editing, corrections, final formatting for printed or online publication, and other modifications resulting from quality control procedures may have been subsequently added. When citing this chapter, please refer to the original article found in the reference above.

then used to manage material flows in the erection of an office building with prefabricated columns. The performance of the new workflow is compared with that of a traditional workflow, using discrete event simulations. The input for the simulations was derived from expert opinion in semi-structured interviews. The new workflow enables contractors to better observe on-site status and differences between the actual and planned material requirements, as well as to alert suppliers if necessary. The simulation results indicate that the new workflow has the potential to reduce the duration of the material flow processes by 16.1% compared with the traditional workflow. The new workflow is illustrated using a real-world-like situation with input data based on expert opinion. Although the workflow shows potential, it should be tested on a real world site. The new workflow allows project participants to combine detailed near-term look-ahead plans with BIM and RFID technologies to better manage material flow processes. It is particularly useful for the management of engineer-to-order components considering the dynamic site progress. The research improves on existing research focused on using BIM and RFID technologies to improve material flow processes by showing how the workflow can be adapted to use detailed look-ahead plans. It reinforces data-driven construction material management practices through improved visibility and reliability in planning and control of material flow processes.

4.1 Introduction

The costs incurred from material flow processes[2] constitute 50% to 60% of the total cost of many construction projects, and problems associated with material flow processes cause approximately 80% of the project delays [61, 43]. Major problems include material delays, incorrect deliveries and rework, which lead to project delays and cost overruns. Although multiple reasons may explain these problems, one dominant reason is poor management [327]. The management of material flow processes includes all planning and controlling activities that ensure materials to arrive on site with the correct quantity and quality at the appropriate time. As construction projects are fragmented in nature and various participants are involved in planning and control activities, good management of material flow processes is challenging. Numerous studies and surveys have shown that the improved material flow management [295, 205] would result in the improvement of keeping construction projects on time and on budget.

Good management of material flow processes requires good coordination of material and associated information flows, and ensures that the planning for

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[2] 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.

actual material demand is reliable and there are few errors in deliveries. Traditionally, simple information technology tools (e.g., Microsoft Excel and Project) and Enterprise Resource Planning (ERP) systems (e.g., SAP or Oracle) are used to enable coordination, but their use is often unsystematic, sporadic, and requires considerable amounts of time to share information. Use of these simple tools also often results in insufficient and inaccurate information exchange between project participants, and contributes to a lack of systematic feedback of construction progress [313, 216].

A response to the need for improved material flow management has focused attention on the use of Industry 4.0 to manage the supply chain [71, 121]. Focusing on the supply chain is a concept that originates from just-in-time production and logistics in manufacturing. In the context of material flow management, focusing on the supply chain means focusing on the collaboration between project participants to coordinate the material and associated information flows [239]. The use of Industry 4.0, referred to as the “Fourth Industrial Revolution”, is an initiative from Germany to use various information technologies and data analytics to achieve real-time supply chain coordination and optimization [139, 249]. In the context of material flow management, the use of Industry 4.0 means using information technologies and data analytics to help project participants to coordinate the material and information flows both in a timely manner and proactively by enhanced information sharing, information visibility and material traceability [350]. Examples of the use of information technologies for material flow management include the integrated use of BIM based systems (e.g., 4D BIM planning platform [37], cloud based BIM systems [213]) and wireless transmission technologies (e.g., radio frequency identification [256], barcode or quick response code [191], near field communication [224], ultra-wideband [240], Bluetooth low energy [254], and geographical information systems [76]).

Much of this research, however, has focused either on detailed technical aspects of their use, or on the optimization of coordination activities governed by a single participant in only part of a material flow process, e.g., production, logistics or warehousing [57, 37]. It has shown, among other things, that the interactions between suppliers and contractors across the estimation, production, transportation and installation phases of construction projects have room for improvement [84], especially where information with respect to the dynamically changing construction progress cannot be fed into suppliers’ schedules on a daily basis. This means that the reliability and agility of decision making among suppliers and contractors with respect to material flows can be improved. The research indicates that there is still potential to improve material flow management with optimal use of information technologies.

Parallel to the work on improving material management, researchers are attempting to alleviate workflow unpredictability, which would also lead to improvement in material flows. One of the most common focuses is on the use of lean construction principles [17], of which a main feature is the incorporation of look-ahead planning. Look-ahead planning establishes when and how each installation task should proceed without violating any constraints, such as the availability of materials and labor [2]. Naturally, look-ahead planning requires a joint effort of project participants to identify and remove the constraints on a regular and short term basis (e.g., every 2, 4 or 6 weeks depending on the specific needs and scope of the planning for installation work packages). Look-ahead plans, which are integral to look-ahead planning, show which installation tasks will start and finish, and which materials are required when in which work zone. The use of look-ahead plans in the daily workflow of the construction project, makes it relatively easy for contractors to detect daily hurdles for installation tasks, and allows them to make near-term commitments with a relatively high level of confidence [89]. This helps ensure that tasks are completed on time.

Recent work in which new workflows have been developed that use both look-ahead plans and new information technologies have resulted in numerous software applications or prototype systems, e.g. KanBIM [265], Visilean [324], Lean4Team [183] and vPlanner [326]. Some of the benefits of these systems are improved information visibility and improved reliability in planning and control of the installation tasks. The work that has been done to date, however, has only been focused on the planning and control of installation tasks, i.e. without considering the needs to facilitate the planning and control of material and associated information flows. None of these new workflows built using information technologies show how look-ahead plans should be integrated, even though it seems that this could lead to further improvement of material flow management.

In this paper, a workflow, i.e., BIM-RFID-LAP work flow, is proposed that enables the improvement of the material management of construction projects when using BIM and RFID technologies, and thus the success of construction projects. It is designed to systematically use regularly updated detailed look-ahead plans. The potential improvements enabled through the use of the new workflow are shown by comparing the construction of a 22 story high rise office building with engineered-to-order (ETO) elements with the new workflow and a traditional workflow. The use of ETO elements requires coordination of the production of a high variety of material products with some degree of design and engineering complexity as well as the issue of site installation tolerance requirements.

The construction of the high-rise was simulated using a discrete event simulator and realistic input values. Improvement is measured as reductions in the average time spent on change request feedback loops, average floor construction times and average waiting times between the construction of floors. Improvement is achieved primarily through increased accuracy of information, increased efficiency of information exchange, increased visibility of stakeholder decision-making, and improved timeliness of the deliveries.

The remainder of the paper is structured as follows. Section 4.2 provides the context for this work with respect to developments pertaining to Industry 4.0 and the use of look-ahead plans, as well as an explanation of the research gap. Section 4.3 explains the BIM-RFID-LAP work flow and its required components. Section 4.4 shows an example of the process for a 22 floor high-rise office building. The potential improvements of the new workflow over traditional work flow are shown in Section 4.5. Section 4.6 and Section 4.7 contain a discussion of the strengths and weaknesses of the new workflow, and the conclusions of the work, as well as proposals for future work.

4.2 Context and research gap

4.2.1 Industry 4.0

Industry 4.0 has the goal to transform manufacturing industry and its production systems through digitalization and exploitation of various technologies, such as cyber-physical systems, embedded computer networks or smart factories connected by the industrial Internet of Things (IoT) building blocks [260]. The technical aspects of these technologies mainly address the collection and exchange of information in real-time for identifying, locating, tracking, optimizing and monitoring of supply chain processes with decentralized control and a high degree of connectivity. They also allow a faster response to customer needs, more flexibility in production systems, and higher quality of products. With such potentials, these technologies have driven productivity gains of 5% to 8% in some manufacturing companies [73]. As construction supply chain processes are learning from the manufacturing industry, it becomes an important concept for the digital transformation of the construction industry.

To realize industry 4.0 in construction supply chain processes, researchers have developed various technologies to allow construction automation [52] and digital manufacturing [122]. Particularly regarding the management of material flow processes, researchers have investigated different types of information communication technologies for construction sites to facilitate the digital transformation. These have included a wide range of integrated applications of BIM and wireless transmission technologies, such as aforementioned RFID, barcode, quick response code, near field communication, ultra-wideband, Bluetooth low energy, and geographical information system. In general, researchers have aimed to provide a digital data sharing environment for construction projects and have improved the efficiency of tracking and exchange of material information.

With respect to the utilization of RFID in the construction industry, Jaselskis et al. (2003) [154] presented evidence that RFID could facilitate improved concrete processing and handling, as well as materials control. On this basis, alternative approaches have been investigated in this domain. Compared to RFID, however, some alternative approaches have less potential in terms of reading ranges required by construction sites. Park et al. (2017) [241] argue that the Bluetooth low energy system is often unreliable in terms of detecting workers or other resources between the construction zones, as their case studies only showed reliable signal communication when beacons were spaced not more than five meters apart. The use of barcode or quick response code requires line of sight to read the tags, which typically can be easily occluded by obstructed barcodes, e.g., dirt covering the code [200]. In contrast, RFID technology does not require line-of-sight to the scanner and is able to track materials with a read-range around 25 meters. Because of this feature, Yin et al. (2009) [349] investigated RFID based processes in a production plant of precast walls and beams and found that the duration of locating materials was reduced from 25.23 to 0.57 minutes compared with traditional manual methods. From a cost perspective, using RFID technology is also relatively inexpensive and durable in harsh and dirty construction environments [137, 350]. Bhattacharyya et al. (2010) [30] reported that RFID tags have already been mass produced at a cost of \$0.07–0.15, which have the potential for pervasive deployment. Furthermore, Segura Velandia et al. (2016) [274] suggested that economies of scale of RFID tag production may bring the volume cost down, which may encourage adoption of RFID technology. These potential advantages have brought considerable benefits for the project participants to coordinate material and associated information flows for construction projects with low-cost and reliable implementation of RFID technology.

Additionally, numerous case studies have shown that the use of information technologies have advantages and that the integrated application of BIM and RFID has particular promise. Bortolini et al. (2019) [37] have shown that the integration of BIM and RFID allows project participants to easily develop and access 4D models[3], which contain both the information of construction schedules and parametric design in 3D models. They have also shown that it improves the efficiency of dynamic material requirement planning through automatic collection of quantity take-offs and bills of materials. One of their empirical study indicates that the implementation of this 4D modelling system helped reduce man-hours spent in site logistics by 38%. Niu et al. (2016) [231] have developed RFID tagged 3D objects as smart construction objects, which provided decision makers with ubiquitous and instantaneously accessible data (i.e., material location and availability in particular) from remote sites. This increases the level of awareness of material availability and the degree to which project participants have knowledge of material information.

To put a focus on the accuracy of material location tracking, Wang et al. (2017) [330] have developed a BIM-RFID knowledge framework to ensure the location coordinates of the prefabricated concrete elements were read and com-

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[3] 4D model is the 3D model to which adds a time dimension, enabling teams to analyze the sequence of events on a time-line and visualize the time it takes to complete tasks within the construction process.

pared with the expected location in BIM. They also evaluated the potential of the framework by using discrete event simulations to reveal a 71.34% reduction of total lead time of prefabricated concrete elements. This significant reduction was mostly due to the decreased demand of extended searches for missing elements with an accurate tracking approach. A previous similar study by Grau et al. (2009) [117] also showed that integrated RFID and global positioning system (GPS) automation approaches could result in 87.5% time savings when locating materials in construction buffer areas. Most of these studies focused on the benefits for a specific activity or process, which were material tracking and locating in particular.

In addition, some researchers have shown that integrated BIM and RFID technologies have been investigated with the cloud system to increase the convenience of information exchange. For example, Li et al. (2017) [187] developed a BIM cloud system based on the received RFID timestamps and the material geolocation. It was found that 15.23% of lead time was reduced given the increased efficiency of tracking the delivery status of individual prefabricated elements and sharing the information quickly among associated project participants. A similar case study was done by Xu et al. (2018) [342], which shows that using the cloud based BIM and RFID system can facilitate real-time information sharing to reduce project time. It was found that the time for locating prefabricated elements, waiting time for delivery, and order-picking time have been reduced by over 20%. At the same time, the on-time delivery rate has been improved by 7.3%. Through these research, it has been widely recognized that BIM and RFID improves the traceability of materials, thereby improving the coordination of material and associated information flows.

4.2.2 Look-ahead plans

In addition to pursuing Industry 4.0, researchers have also focused efforts on investigating the use of look-ahead plans to cope with a lack of reliability during construction planning and control. An early study by Ballard and Howell (1998) [24] show that over 50% of construction projects of many types have large discrepancies between their initially planned completion dates and their actual completion dates. To improve on this, the use of look-ahead plans are considered a viable possibility, that could result in improved resource utilization, increased work plan reliability, increasingly stable workflows, increased construction productivity, and reduced difference between planned and actual project completion dates. The use of look-ahead plans is an essential part of the last planner system as one aspect of lean construction principles [62, 124, 69, 134].

From a workflow perspective, Ballard (2000) [25] and Hall et al. [121] showed that using look-ahead plans help squeeze out buffers and inefficiencies from site installation processes and increase ownership of process planning by subcontractors, which consequently increases the conversation and dialogue about cross-discipline coordination problems in construction projects. It is, however, very challenging for various participants, especially the project planners and site engineers, to create executable look-ahead plans with detailed work assignments for site work. To address that, Dong et al. (2013) [82] proposed an automated look-ahead scheduling tool that can model the critical constraints in look-ahead work assignments and then establish the correct connection between a task assignment and its relevant constraints. Their studies were based on the space-constrained and resource-constrained scheduling methodologies developed by Thabet and Beliveau (1997) [306]. On the same basis, Lindhard and Wandahl (2014) [192] conducted a survey on the reliability of planning and concluded that planning should be done in real time taking into consideration all resource availabilities and potential constraints. Compared to look-ahead plans, traditional planning methods, such as Work Breakdown Structure, Critical Path Method, and Earned Value Analysis, are less responsive to emerging constraints, and undoubtedly, they often fail to help deliver projects on time and within budget. Therefore, look-ahead plans serve as an important means of planning to help bring emerging constraints and related coordination problems to the surface more quickly in order to ensure successful construction workflows.

Through case studies, some researchers investigated how weekly meetings can be used to develop look-ahead plans, identify constraints, prepare information and resources, communicate work progress, and implement design changes. For example, Dallasega et al. (2019) [69] showed that this enabled the installation times in some ETO projects to be reduced by approximately 2.7% through early identification of site misfit problems. Heigermoser et al. (2019) [134] found that look-ahead planning could bridge the gap between long-term project planning and short-term execution planning. Their study also indicates that an enormous potential of planning improvement was due to weekly adjustment of the planned duration of the tasks in the look-ahead plans, which further resulted in the variance tending towards zero during the following weeks of construction. To highlight the complexity in the coordination of multi-disciplinary subcontractors and interfacing problems, Priven and Sacks (2016) [250] have investigated eight projects to analyze the planning best-practice index and lean-workflow index. It became standard practice for the site superintendent and the various crew leaders to have lunch together after the weekly work planning meetings, which were held at 11:00 a.m. Their research revealed that a collaboration culture and "shared meals" are important factors to improve the reliability in the look-ahead planning processes. Look-ahead plans have thus been established as useful means and need collaboration by the various project participants; digitalizing the use of look-ahead plans will bring more potential to its use.

A number of software applications have been developed that explicitly facilitate the use of look-ahead plans, such as KanBIM, Visilean, Lean4Team and vPlanner, as mentioned earlier. The notion is to bring digital information directly to the workforce planning at the construction site. Meanwhile, they were also designed to support the negotiation of planning and registration of commitments as required by different project participants. These applications provide clear visualization of work progress and immediate negotiation of changes. There have been, however, only a few academic publications that explicitly show how and to what degree the different software applications improve site workflows through the look-ahead planning processes. Take the field test using KanBIM [265] as an example. It resulted in increases in the percentage of planned work completed on time from 33% to 62%, primarily due to the instant information on work status. Additionally, only a limited amount of research from a perspective of material flows, Dallasega et al. (2019) [69] as an example, has suggested look-ahead plans to connect suppliers' material logistic plans or shipping plans, which enhanced the granularity of information on shipping status of required materials and resulted in improved continuity and less duration of installation tasks on site. Of all the research focused on using look-ahead plans to improve the workflows of installation tasks, however, none of it has yet focused explicitly on how they can be used to improve the material flows. In other words, there is a lack of research on how look-ahead plans can be used to schedule for material flow processes.

4.2.3 Research gaps

In summary, most of the research on using information technologies and lean construction principles to improve material flow management in construction projects (Table 4.1), has used either a technology or lean workflow oriented approach with an aim to improve the information transparency and collaboration between project participants. This research, despite all of its success, has left a number of research gaps, including the fact that it is unclear as to:

- how technology and lean workflow oriented approaches can be integrated to improve the management of material flows during all phases of the construction project.

- the possible improvements of a work flow that uses look-ahead plans and BIM and RFID technologies.

- how look-ahead plans can be integrated into a digital system to improve material flow management in addition to the planning and control of site installation tasks.

Table 4.1: A summary of relevant works

Papers	**Research focus**	**Main approach**	**Highlights of potentials**	**Focused supply chain phase**	**Perspective**
This research	Integrated 4D technology with look-head planning implementation	Prototype demonstration and process simulations	Information transparency and planning reliability	A holistic view of supply chain phases	Workflow perspective on material flows
Jaselskis et al. (2003) Grau et al. (2009) Yin et al. (2009) Bhattacharyya et al. (2010) Razavi abd Haas (2011) Young et al. (2011) Hinkka et al. (2013) Lin et al. (2014) Moon and Kwon (2014) Cheng and Chang (2018)	RFID or other tracking technology implementation	Prototype demonstration	Pervasive deployment with low-cost tags, material status visibility	Logistics/ inventory	Technology perspective on material flows
Park et al. (2016) Park et al. (2017) Rashid et al. (2019)	RFID or other tracking technology implementation	Prototype demonstration	Indoor location accuracy	Building operation and maintenance	Technology perspective on material flows
Matthews et al. (2015) Trebbe et al. (2015) Niu et al. (2016) Li et al. (2017) Wang et al. (2017) Xu et al. (2018) Bortolini et al. (2019) Deng et al. (2019) Schwabe et al. (2019)	Integrated 4D technology implementation	Prototype demonstration	Information transparency, collaborative decision-making	Logistics/ site installation	Technology perspective on material flows
Ballard (2000) Al-Sudairi (2007) Dong et al.(2013) Lindhard and Wandahl (2014) Hamzeh et al. (2015) Priven and Sacks (2016) Dallasega et al. (2018) El-Sabek et al. (2018) Abou-Ibrahim et al. (2019) Dallasega et al. (2019)	Traditional look-head planning processes implementation	Process analysis, simulation methods	Planning reliability; agile scheduling	Site installation	Workflow perspective on tasks
Sacks et al. (2011) Sacks et al. (2013) Ma et al. (2018) Heigermoser et al. (2019) Tayeh et al. (2019)	Digital look-ahead planning process implementation	Prototype demonstration	Digitalization and visualization, agile scheduling	Site installation	Workflow perspective on tasks

4.3 BIM-RFID-LAP workflow and required components

4.3.1 BIM-RFID-LAP workflow

The use of a new workflow for construction projects that uses BIM and RFID technologies as well as regularly updated detailed look ahead plans, herein referred to as the BIM-RFID-LAP workflow, is proposed to address the stated research gaps. The example shown[4] is specifically adapted for the construction of multiple identical floors in a high-rise building. An example is presented, as each specific workflow is dependent on the specific construction project for which it is developed. The construction of identical floors means that the same basic tasks (e.g., assembly of columns, constructing slabs, constructing core shear walls) are required for each. The materials required for the same construction tasks are ETO components. The workflow characterizes the entire process of delivering ETO components to site to be installed. Each ETO component is managed as a unique element. One instance of the workflow starts with decision to proceed with construction of floor X and ends with the completion of floor X.

The workflow consists of five phases where each contains specific coded subprocesses: estimation (MRP01-MRP16), procurement (PRO01-PRO33), transportation (TRA01-TRA08), inspection and storage (INS01-INS07), and material usage (USE01–USE03) for final assembly work. The workflow at a high level of abstraction is shown in Figure 4.1. The supplier of ETO components provides in-house delivery service to ship the materials to site, and there is no third party involvement. The workflow at a more detailed level of abstraction level and the associated information flows are provided in supplementary materials available online[5]. The symbols used are presented in Lucidchart[6]. Each task requires specific project participants and resources (i.e., time). The participants include the owner and project manager, architects and engineers, procurement manager, material supplier and construction contractors. The interactions between the participants are shown in Figure 4.1.

There are two points in the workflow where the decision is made whether or not to pull work according to look-ahead plans. The first point is immediately after the supplier's production system is optimized and production is prepared. The ongoing site schedule is updated with the supplier so that the upcoming material need dates can be fixed. Here the decision is made to either proceed with construction based on the existing production drawings or to delay construction. If no changes are required to the production drawings, or changes are required

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[4] In this work, the workflows are modelled using BPMN (Business Process modelling Notation) within the Signavio BPM Academic Initiative platform.

[5] Supplementary files. Available for downloading at: `https://polybox.ethz.ch/index.php/s/gjnVb1t6bHrR7rp`

[6] BPMN Diagram Symbols & Notation, Lucidchart. Available at: `https://www.lucidchart.com/pages/bpmn-symbols-explained?a=0`

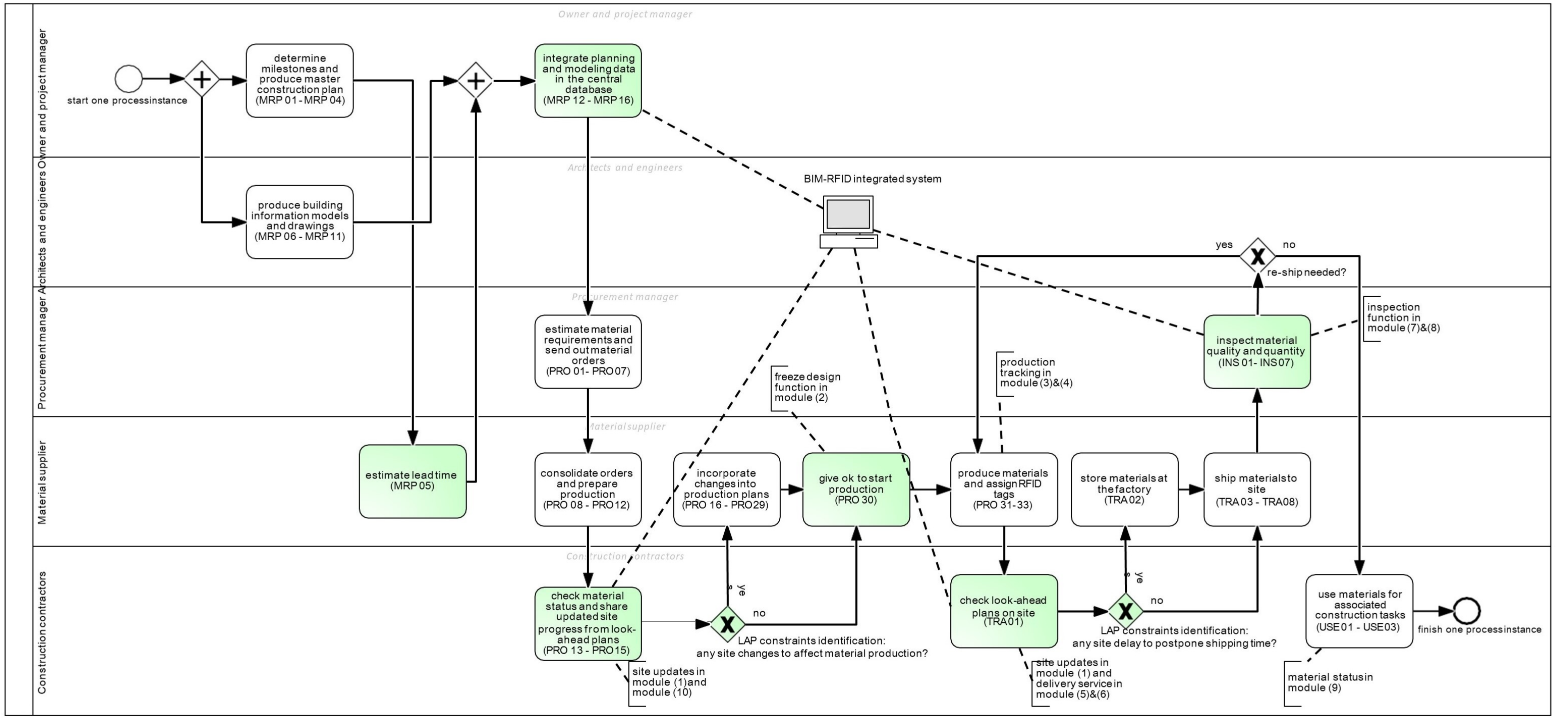

Figure 4.1: The BIM-RFID-LAP workflow at a high level of abstraction

that can be made in a way that they will not affect the upcoming tasks' start dates, the decision is made to proceed with the construction as originally planned. Otherwise, those tasks have to be delayed as do the material need dates. The second point is immediately after the materials are produced and the RFID tags are assigned. Again, the onsite schedule is updated with the supplier to fix the date to release material for transportation. Here, the decision is made to either proceed with shipping the materials to the construction site based on the progress on the construction site, or to store the materials at the factory until construction has progressed to a sufficient stage.

Normally when using look ahead plans, the decision to proceed with construction tasks are made on a weekly basis. At these meetings decisions are made with respect to 1) the start of material production which depend on both the material related task start date and estimated material manufacturing lead time, 2) storing produced materials at the factory rather than shipping them to the construction site, which depends on the estimated material manufacturing and shipping lead times, as well as the expected weather and labor strikes. Changes in weather and labor strikes are incorporated into the workflow as risk factors when estimating the lead times and making the look-ahead plans.

The sub-processes before the first decision point are a one-time high level planning processes which are made based on the long term master plan. The sub-processes after the first decision point are iterative, and how often they occur depends on the evolution of the short term look-ahead plan during the construction project. The cyclic controlling activities (PRO13 – PRO30 in Figure 4.1) comprise a feedback loop that gives the construction contractor the ability to send progress updates to the supplier to help ensure just in time delivery of the materials. The feedback loop starts, and could undergo numerous iterations, before material production starts. These early iterations reduce the uncertainties related to changes that might be requested by the construction contractors. An example of such uncertainties is the discrepancies that sometimes occur between the dimensions of the prefabricated columns and the exact dimensions of these columns required on site.

The workflow is enabled by the ability of participants to store and exchange object information[7], construction information[8] and material delivery information[9]. BIM is used for storing and exchanging the building object material properties information, which facilitates the planning and design change portions of

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[7] Object information is the information pertaining to the object, e.g., a column, a slab, a wall, to be constructed, e.g., length, weight, color, strength. It is attached directly to an object in a parametric 3D model.

[8] Construction information is the information pertaining to construction progress, e.g. the forecasted start and finish time of a task, the requirements for the task to start.

[9] Delivery information is the information pertaining to the delivery of materials, 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, the deviations from initial plans.

the workflow. RFID is used to generate material delivery information. This information is recorded in RFID tags, which can be automatically read and extracted by RFID readers. For a single prefabricated element, a RFID tag is attached directly on material surfaces. When site trades use RFID readers to scan the RFID tags, information collected from the tags is stored in a database to be analyzed later. It facilitates the control of the material flow.

A software system developed in this research, and herein referred to as the BIM-RFID system is used to simulate the exchange of information during the sub-processes. It contains functional modules, which constitutes the application layer, a graphic user interface (GUI), which constitutes the presentation layer, and a central database, which constitutes the data layer. The functional modules are: 1) task planning module, 2) ETO component estimation module, 3) material ordering module, 4) production module, 5) location tracking module, 6) delivery service module, 7) quality inspection module, 8) re-shipping module, 9) material status module, and 10) change request module. The linkage between these modules and the sub-processes are shown in Figure 4.1.

The sub-processes that are assisted by the use of the BIM-RFID system are colored green. Two LAP constraints are highlighted; “any site changes to affect material production?” and “any site delay to postpone material shipping time?”. The material information and task planning information becomes easier and more transparent when participants use the BIM-RFID system in four ways. First, once the supplier enters the material lead time on the user interface of production module it is shared with the contractor for site task planning. Second, the system automatically matches the material property information with construction needs (e.g., material need date) as soon as they are entered. Third, there is real time updating of design and schedule changes via the task planning module and change request module. Forth, information updates are shared with all participants, enabling real time changes in material production and shipping lead times.

In order for the BIM-RFID-LAP workflow to be used, the following components are required, 1) a short term look-ahead plan, 2) an automated information extraction process, 3) a coding system to link building object, construction and delivery information, 4) a process to generate material requirements, and 5) a process to notify project participants of decisions and construction progress. These are explained in the following sections.

4.3.2 Short term look-ahead plan

A short term look-ahead plan is used to know with a high level of certainty when the tasks in the upcoming weeks are to start and finish in the look-ahead planning period, which is determined based on the consensus of the project participants. It contains, 1) the work zones in which the work will be conducted, 2) the sequencing of the tasks, 3) the constraints on the tasks (i.e., the constraints of labor preparation, machine preparation, space preparation, permits and precedential relationship constraints), 4) the daily update notifications to be sent when the tasks are pulled and changes to schedules are made, and 5) 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).

4.3.3 Material information exchange

A material information exchange process, which is used to ensure that the information of material delivery status and specifications are seamlessly communicated among BIM authoring software, project scheduling software, RFID reader and the central database (Figure 4.2). Using a central database to communicate the heterogeneous information helps achieve semantic interoperability for the information exchange process. The central database is updated on a daily basis to provide participants with consistent data for material planning and control. For example, the site trades exchange the task time with suppliers via the database, which helps the suppliers reduce considerable paperwork, phone calls to decide the appropriate material production date.

Step 1 is to export building object material, construction task scheduling and RFID tag scanning information into the multiple Microsoft Excel files. This requires the use of a standardize data format. The building object material information, which is contained in the BIM software (e.g., Autodesk Revit) is exported using BimorphNodes coding packages from Revit API Dynamo[10], saved as lists and converted into Excel files. The established Dynamo scripts for BIM data export and import are illustrated in Figure C.4 and Figure C.5 in the Appendix C, respectively. The task scheduling information is created in Microsoft Project files, using Project Export Wizard to map different fields into proper Excel templates. The built-in program in the RFID reader is used to convert the material location information into Excel files once the RFID tags are assigned to the ETO components and scanned for delivery information.

Step 2 is to extract the information from the multiple Excel files and store the information in the Sqlite database. The database functions as a federated database that integrates the information from different sources. This is done using a python script, which includes the Sqlite connection and cursor functions of parsing the Excel data into database variables.

Step 3 is to parse the Sqlite data and save it in the database for planning and control of on-demand material information. The Python tkinter library is used in Python script to create the GUI and connect the data automatically to Sqlite data. The GUI allows different participants to handle data directly via the central database, which expedites information sharing.

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[10] Dynamo is a visual programming editor that allows people to manipulate data and explore design option.

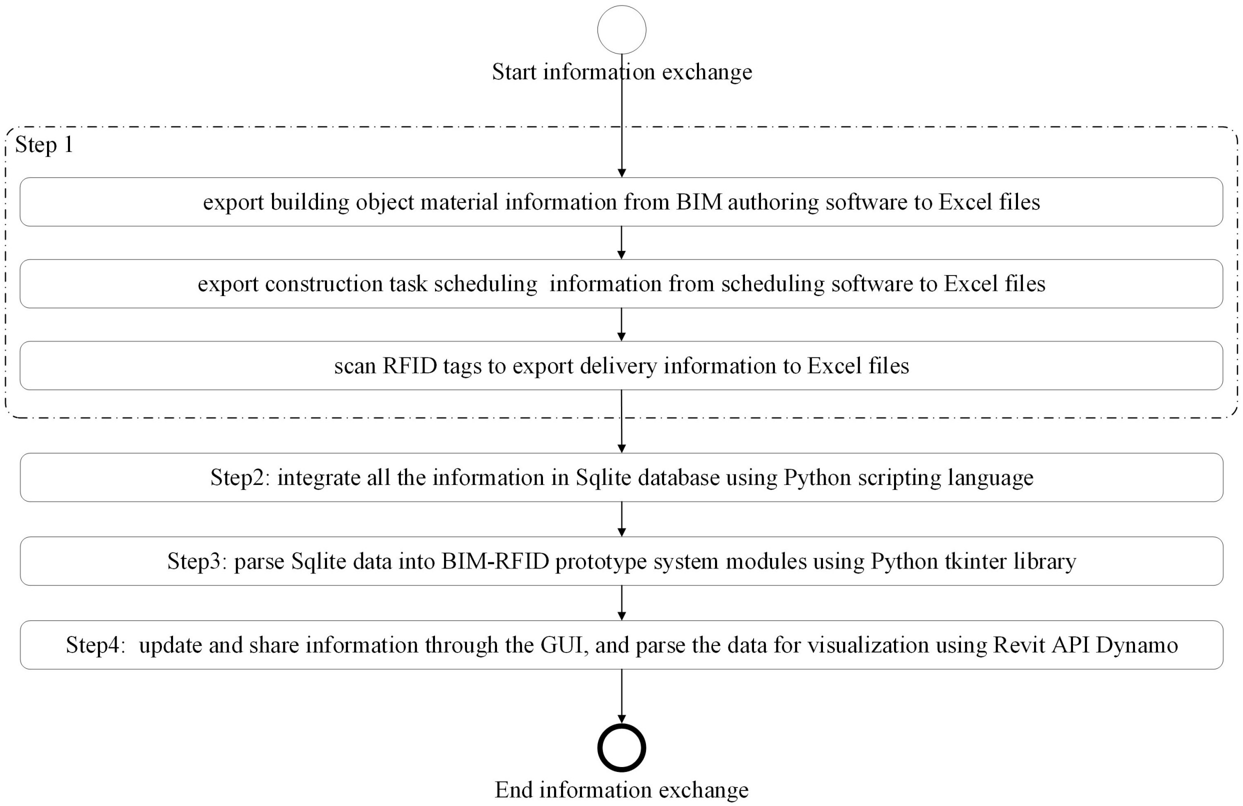


Figure 4.2: The material information exchange process (i.e., data flow)

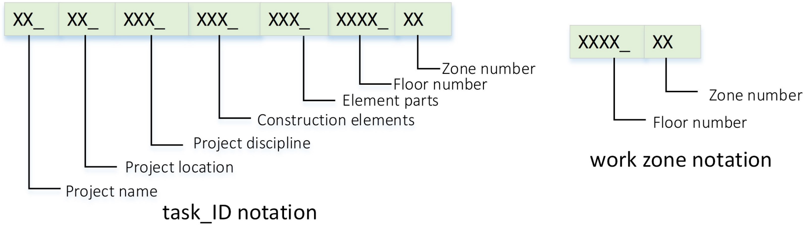
Step 4 is to update and share information through the GUI when design or scheduling changes are requested. Specifically, the information exchange between the BIM software and Sqlite database is done using customized libraries (e.g., Data.ImportExcel, Element.SetParameterByName, etc.) from Revit API Dynamo. The exchanged information from Sqlite database to BIM software allows the visualization of the material delivery status in 3D models.

4.3.4 Coding system linking building object, construction and delivery information

A coding system is required to link the building object, construction and delivery information in the Sqlite database. It consists of an element ID, a task ID, an order ID and a RFID tag ID. Examples are given in Table 4.2. The task IDs are set during the development of the project structure plan. The task IDs are assigned to specific work zones and the materials are delivered to each work zone for associated assembly tasks. An example of task ID is shown in Figure 4.3. The element ID, order ID and RFID tag ID are generated during the material flow processes. An example entity relationship diagram for all the information is given in Figure 4.4.

Table 4.2: The usage of IDs and examples of IDs

IDs	Purpose	Example
Element	to link materials to orders	2177642
Task	to link material delivery times to schedules	AT_OR_STR_PCO_INS_06OG_Z2
Order	to track the material orders	06OG_Z2_010
RFID tag ID	to track the locations and status of materials	3e7cc3de-d761-46b3-881f-3f27428b7e22



task_ID notation

work zone notation

Figure 4.3: An example of task ID

4.3.5 Material requirement generation

A process is required to generate the material requirements associated with the tasks included in the short term look-ahead plan. It ensures that materials are prepared and transported to site on time, taking into consideration manufacturing and transportation lead times. The process has to be flexible enough to enable relatively short term changes in the delivery of materials, but allow a moment of time when the design is considered fixed so that the raw materials can be released and the manufacturing process can start. An example moment of time for this to happen is on day X, where X = (the date the material is to be used – expected transportation lead time – expected manufacturing lead time). In the BIM-RFID-LAP workflow, the material requirements are generated through material orders modules which calls python group functions to collect the data

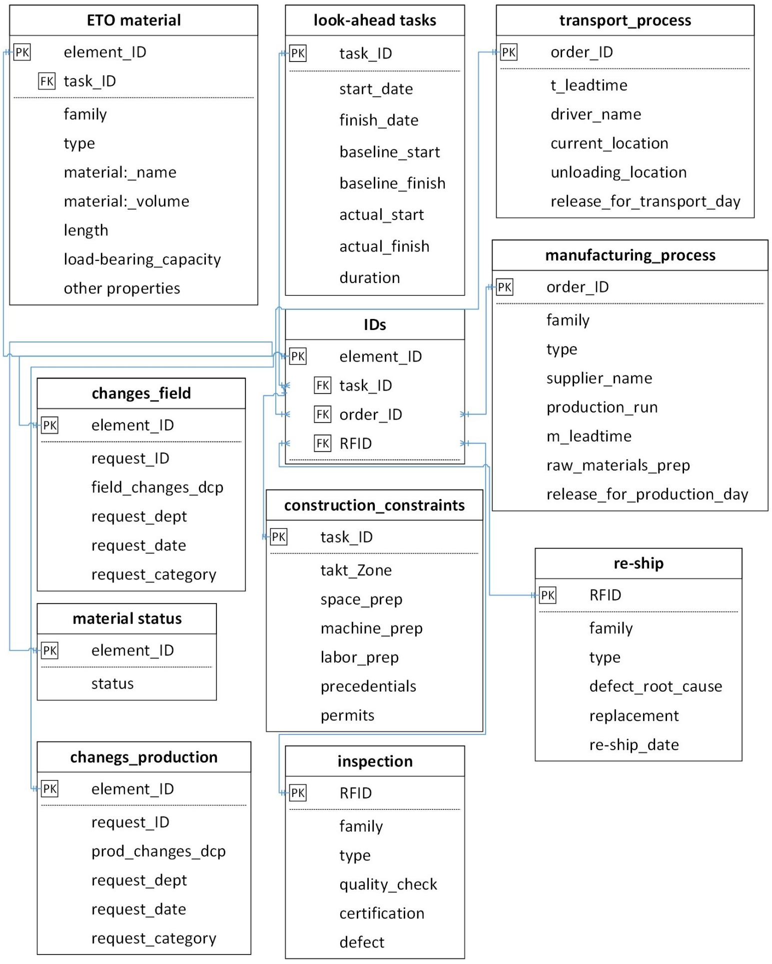


Figure 4.4: An example entity relationship diagram

from the Sqlite database.

4.3.6 Notification of project participants of decisions and construction progress

A process is required to notify project participants of decisions made and update them as to construction progress. When design or schedule changes are made, project participants are alerted and informed as to whether raw materials can be released for manufacturing, or whether manufactured materials can be released for transport. The communicated information includes whether the upcoming tasks are on track to be started according to the most recent short term look-ahead plans, and if not the reason why, as well as remedy actions to be taken. The information to be communicated to project participants is entered by the site manager, after discussions with the project participants who will be affected by the design or schedule changes. For example, if the assembly of prefabricated column on N^{th} floor is Y days delayed due to its precedential slab work, then the site manager is to enter the change of assembly date in the system. Y day delay messages will then be sent to fabrication workers so that they can postpone the fabrication, or the transportation, of those columns for Y days.

4.3.7 Differences compared to other workflows using BIM and RFID

The BIM-RFID-LAP workflow is different from a traditional workflow using BIM and RFID without the incorporation of look-ahead plans (referred herein as a BIM-RFID-TRA workflow), although both contain the same basic phases, i.e. estimation, procurement, transportation, inspection and usage of materials.

In this paper, the BIM-RFID-TRA workflow is depicted at a high level of abstraction, in Figure 4.5, with details given in the supplementary materials available online. The main differences between the BIM-RFID-TRA and the BIM-RFID-LAP workflows are the use of detailed short term look-ahead plans and identification of constraints for material production and shipping. The colored sub-processes in pink in Figure 4.5 show the major different sub-processes required to be adapted in the BIM-RFID-LAP workflow compared to BIM-RFID-TRA workflow. It is highlighted that the BIM-RFID-TRA lacks sub-processes to enable coordination of delivery schedules between the construction contractor and the supplier with respect to updated site progress (i.e., there are no clear decision points in BIM-RFID-TRA workflow). Therefore, the materials are pushed to the site and have to be stored on site until the day of use. It also shows that there is no early feedback loop to address change requests, such as a change of selection of prefabricated columns due to the geometry misfit problems during installation. When changes are detected, new delivery requests have to be sent to the supplier (USE 02-USE19 in Figure 4.5). As a result, the required materials need be re-shipped to site, leading to a waste of project time. The differences between the two workflows are summarized in Table 4.3.

Table 4.3: The differences between the two workflows

Phases	Differences	
	BIM-RFID-LAP workflow	BIM-RFID-TRA workflow
Estimation phase	Parametric models and a central database	Parametric models and a central database
Procurement phase	Freeze design and delivery times according to look-ahead plan	Order by one time
		No timely update of changing material needs to suppliers
Transportation phase	Track the release-for-transportation date	No time tracking
Inspection and storage phase	RFID inspection	RFID inspection
	No storage needed	Storage needed to buffer for unexpected site changes
Usage phase	Right material	Subject to late changes and wrong materials
		Need for reshipping materials

4.4 Example

4.4.1 BIM-RFID-LAP workflow

In order to demonstrate the usefulness of the BIM-RFID-LAP workflow, a detailed version of the workflow was developed to manage the material flow required in the repetitive manufacturing and installation of prefabricated columns on 22 floors of an office building. Though each floor is identical, it contains highly engineered prefabricated structural elements. In this case, the design coordination of the elements is complex, and therefore the coordination of the material and information flows makes it challenging to have the structural elements onsite when work is to begin. The building was modeled using Autodesk Revit software. The design data included the material properties of the building elements, i.e., the family and type, the length, the volume, and the load-bearing capacity of the prefabricated columns. The structural elements (e.g., the prefabricated structural columns) were all defined to a LOD300, including a description of the material properties. The data extracted from RFID tags were used in a simulated environment. It was assumed that the supplier and other project participants have no problems in sharing data with each other, i.e. they have a high level of mutual trust. The supplier of prefabricated structural elements provides in-house delivery service to ship the materials to site, without the need to involve a third party delivery service.

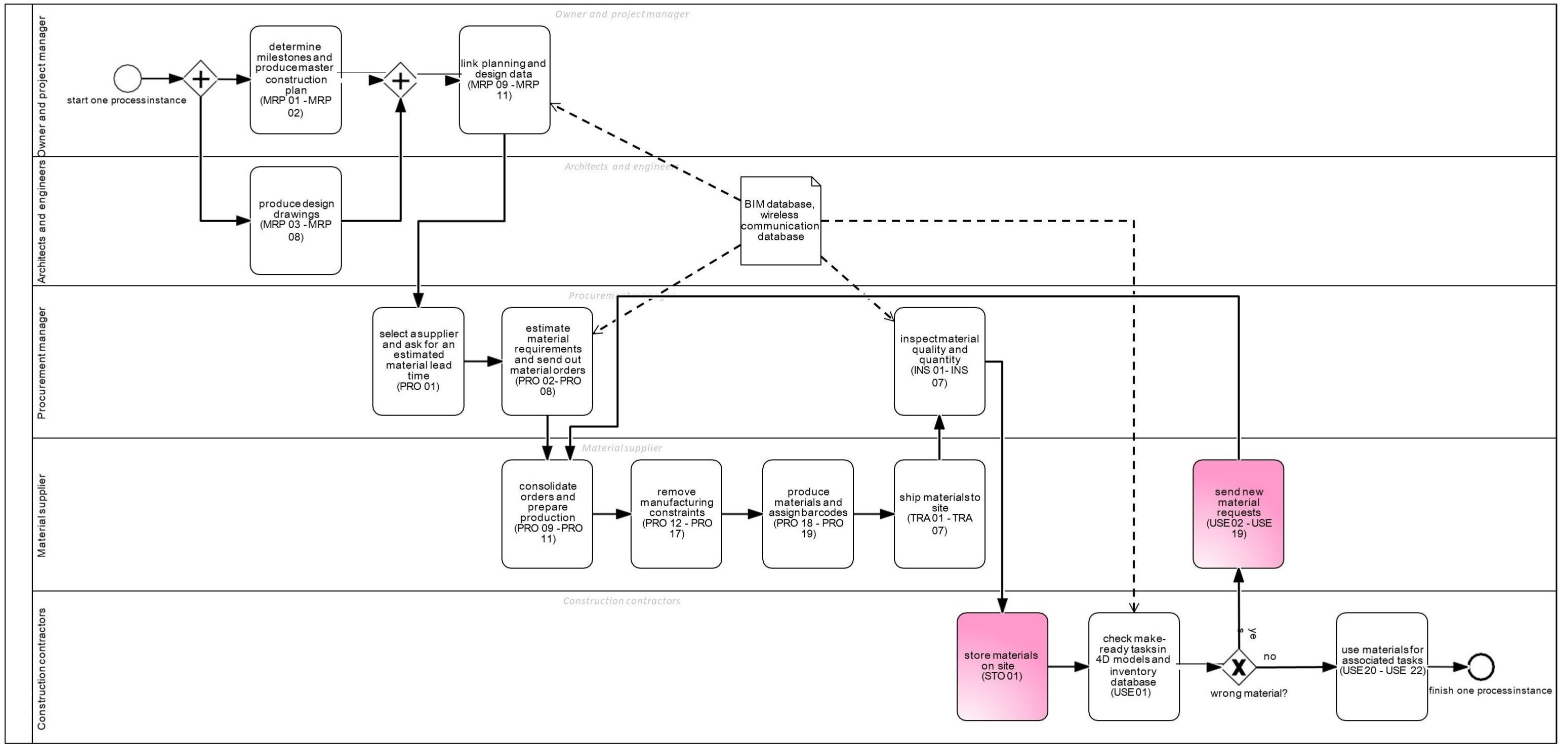


Figure 4.5: The BIM-RFID-TRA workflow at a high level of abstraction

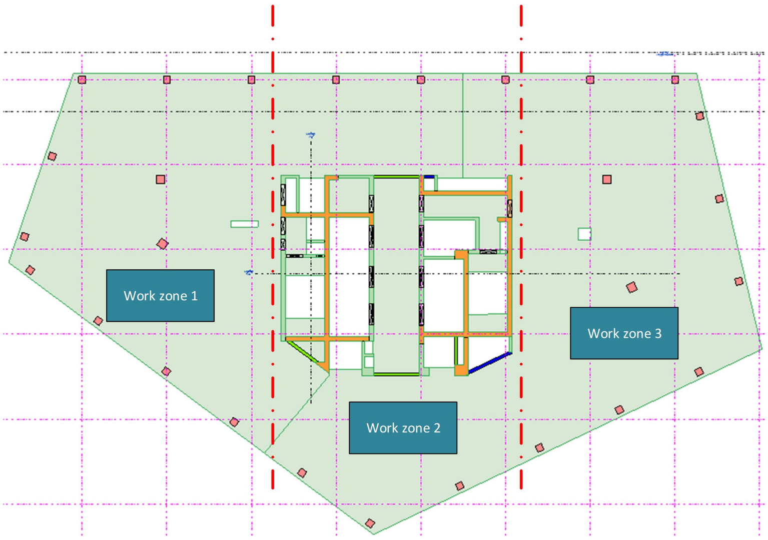


Figure 4.6: Three work zones dividing a typical floor

4.4.2 Short term look-ahead plan

Each floor was divided into three work zones (Figure 4.6), and the in situ slab construction, in situ core shear wall construction and assembly of prefabricated columns tasks were assigned to the work zones. An example 10-day look-ahead plan from the example building project is provided in Table 4.4. Once all constraints were removed from each task, all project participants were informed via a notification message that the task could be started, and arrangements were made to have the required materials delivered on the exact planned task start date. Assembly tasks were done by trades according to the look-ahead plans. It was assumed that the construction site progress was monitored via a meeting of the trades every evening after assembly tasks were finished. The short term look-ahead plan was updated based on the results of these discussions on a daily basis. It was assumed that the answers to the following questions were entered in the information exchange system, 1) Are the tasks planned for today completed? 2) Can the tasks planned for tomorrow be started as planned? The information were merely used to track the construction progress in the current look-ahead plan, which provides references for site trades to make the subsequent look-ahead plans including new material requests.

4.4.3 Material information exchange

Based on the process described in section 4.3.3, the material information for the prefabricated columns (Figure 4.7 (a)) was extracted from the BIM using Dynamo in the Autodesk Revit software using their unique element IDs. The as-

Table 4.4: An example 10-day look-ahead plan from the example building project

WBS code	look-ahead day (from 2017.Aug.04 to 2017.Aug.18)										Labor_prep	Machine_prep	Space_prep	Precedentials	Permits	Status
	1	2	3	4	5	6	7	8	9	10						
AT_OR_ST_SHC_03OG_Z1	x										-	-	-	-	-	C
AT_OR_ST_SLA_01OG_Z1	x										-	-	-	-	-	C
AT_OR_ST_PCO_01OG_Z1		x									r	r	r	r	r	O
AT_OR_ST_SHC_03OG_Z2		x									r	r	r	r	r	O
AT_OR_ST_SLA_01OG_Z2			x								r	r	r	r	r	N
AT_OR_ST_PCO_01OG_Z2				x							r	r	r	r	r	N
AT_OR_ST_SHC_03OG_Z3				x							r	r	r	r	r	N
AT_OR_ST_SLA_01OG_Z3					x						r	r	r	r	r	N
AT_OR_ST_PCO_01OG_Z3						x					r	r	r	r	r	N
AT_OR_ST_SHC_04OG_Z1						x					r	r	r	r	r	N
AT_OR_ST_SLA_02OG_Z1							x				r	r	r	r	r	N
AT_OR_ST_PCO_02OG_Z1								x			r	r	r	r	r	N
AT_OR_ST_SHC_04OG_Z2								x			r	r	r	r	r	N
AT_OR_ST_SLA_02OG_Z2									x		r	r	r	r	r	N

*(notes: r- ready, C-completed, O-ongoing, N-not started)

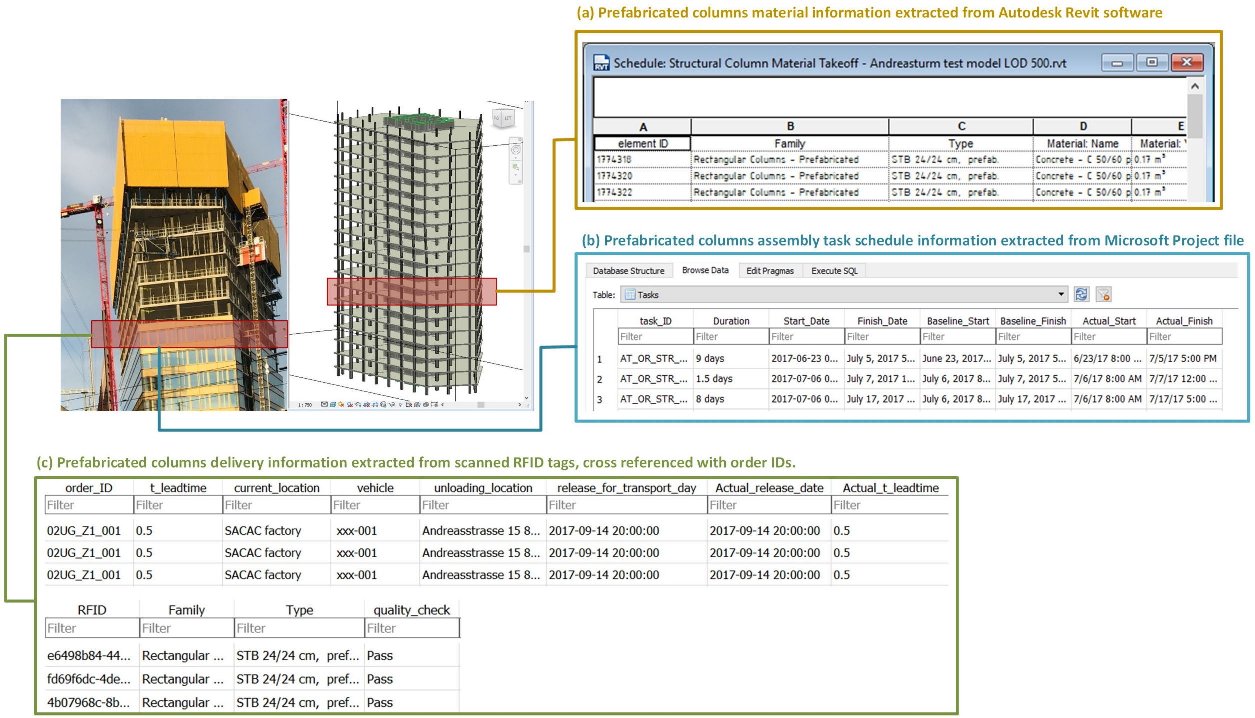
sembly task schedule information (Figure 4.7 (b)) was extracted from Microsoft Project files using work zone specific task IDs. The prefabricated column delivery information (Figure 4.7 (c)) was extracted from RFID tags. All information was entered into a Sqlite database, which could be accessed from the BIM-RFID prototype system. Once the construction contractor makes a change to the scheduling information of prefabricated column assembly tasks, the changes will be shared via central database to the supplier. In such way, the information exchange with respect to the new material need date was done efficiently between the supplier and construction contractor. Similarly, once the materials were produced and assigned with RFID tags, the supplier would enter the status information ("ready for delivery") of materials in the BIM-RFID prototype system and exchange the information with the construction contractor and site trades via the central database. Due to material information exchange process, the site needs and supply status are linked together to formulate an efficient contractor-supplier feedback process.

4.4.4 Coding system linking building object, construction and delivery information

The task ID (Figure 4.8), element ID, order ID, RFID tag ID were assigned for each of the building elements in BIM software. The different IDs were linked in the Sqlite database in order to link the column material information, column assembly task schedule information and delivery information.

4.4.5 Material requirement generation

The prefabricated columns to be delivered are monitored on a daily basis. One delivery request contains multiple types of materials for different construction tasks to be completed within the same look-ahead period, which can be identified with the same order ID. As indicated in the look-ahead plan in Table IV, both the ETO components and raw materials were needed for the planned tasks. Prefabricated columns were required for the assembly tasks such as AT_OR_ST_PCO_01OG _Z1. Also rebars and concrete were needed for casting the slabs (AT_OR_ST_ SLA_01OG_Z2) and shear walls (AT_OR_ST_SHC_03OG_Z2) on site. An example of the monitored daily material requirements is given in Figure 4.9. The latest material arrival time for the delivery of a prefabricated column was 2 hours before task start time. For example, if the arrival date for four prefabricated columns was 2017/08/04, and the transportation lead time was 2 hours, the material release date, from the factory or storage hub, was 2017/08/04.



(a) Prefabricated columns material information extracted from Autodesk Revit software

Schedule: Structural Column Material Takeoff - Andreasturm test model LOD 500.rvt

A	B	C	D	E
element ID	Family	Type	Material: Name	Material:
1774318	Rectangular Columns - Prefabricated	STB 24/24 cm, prefab.	Concrete - C 50/60 p	0.17 m³
1774320	Rectangular Columns - Prefabricated	STB 24/24 cm, prefab.	Concrete - C 50/60 p	0.17 m³
1774322	Rectangular Columns - Prefabricated	STB 24/24 cm, prefab.	Concrete - C 50/60 p	0.17 m³

(b) Prefabricated columns assembly task schedule information extracted from Microsoft Project file

	task_ID	Duration	Start_Date	Finish_Date	Baseline_Start	Baseline_Finish	Actual_Start	Actual_Finish
	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter
1	AT_OR_STR_...	9 days	2017-06-23 0...	July 5, 2017 5...	June 23, 2017...	July 5, 2017 5...	6/23/17 8:00 ...	7/5/17 5:00 PM
2	AT_OR_STR_...	1.5 days	2017-07-06 0...	July 7, 2017 1...	July 6, 2017 8...	July 7, 2017 5...	7/6/17 8:00 AM	7/7/17 12:00 ...
3	AT_OR_STR_...	8 days	2017-07-06 0...	July 17, 2017 ...	July 6, 2017 8...	July 17, 2017 ...	7/6/17 8:00 AM	7/17/17 5:00 ...

(c) Prefabricated columns delivery information extracted from scanned RFID tags, cross referenced with order IDs.

order_ID	t_leadtime	current_location	vehicle	unloading_location	release_for_transport_day	Actual_release_date	Actual_t_leadtime
Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter
02UG_Z1_001	0.5	SACAC factory	xxx-001	Andreasstrasse 15 8...	2017-09-14 20:00:00	2017-09-14 20:00:00	0.5
02UG_Z1_001	0.5	SACAC factory	xxx-001	Andreasstrasse 15 8...	2017-09-14 20:00:00	2017-09-14 20:00:00	0.5
02UG_Z1_001	0.5	SACAC factory	xxx-001	Andreasstrasse 15 8...	2017-09-14 20:00:00	2017-09-14 20:00:00	0.5

RFID	Family	Type	quality_check
Filter	Filter	Filter	Filter
e6498b84-44...	Rectangular ...	STB 24/24 cm, pref...	Pass
fd69f6dc-4de...	Rectangular ...	STB 24/24 cm, pref...	Pass
4b07968c-8b...	Rectangular ...	STB 24/24 cm, pref...	Pass

Figure 4.7: Information about the prefabricated columns. (a) Prefabricated columns material information extracted from Autodesk Revit software, (b) Prefabricated columns assembly task schedule information extracted from Microsoft Project file, (c) Prefabricated columns delivery information extracted from scanned RFID tags

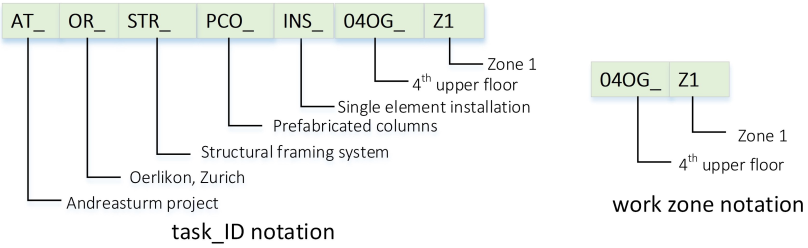


Figure 4.8: The task ID designed for the prefabricated columns

4.4.6 Notification of project participants of decisions and construction progress

The short term look-ahead plan is used to notify the project participants of decisions to interrupt work and construction progress. This timely notification process establishes the dynamic feedback cycle between the site and the supply. For example, if the assembly of prefabricated column on 03OG floor is delayed 1 day due to its precedential slab work, then the site manager must enter the change of assembly date in the system. Delay messages are then sent to fabrication workers to postpone the date of fabrication, or the transportation, of those columns for 1 day.

4.5 Potential improvements

4.5.1 Simulations

The potential improvements, in terms of the average time spent on change request feedback loops, the average floor construction time, and the average waiting time, when compared to the traditional process are shown in this section.

The construction of the 22 floors of the example building were simulated using the two workflows. One simulation represented the construction of one floor from start to end. One simulation run consisted of 22 simulations, which encompassed the 22 floors of the building. 500 simulation runs were conducted. The simulations were run using the SaaS-based simulation engine on the BIMP platform[11]. Simulations were used instead of the traditional CPM, because of their better ability to model repetitive stochastic sub-processes. Inter-arrival times were used to model the times between simulations, i.e. a subsequent simulation could only start once the previous simulation was finished. The waiting time was considered

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[11] BIMP - The Business Process Simulator, BIMP: developed jointly by University of Tartu and the Estonian Research Council, Available for use at: http://bimp.cs.ut.ee/ and https://sep.cs.ut.ee/Main/BIMPCommandLine

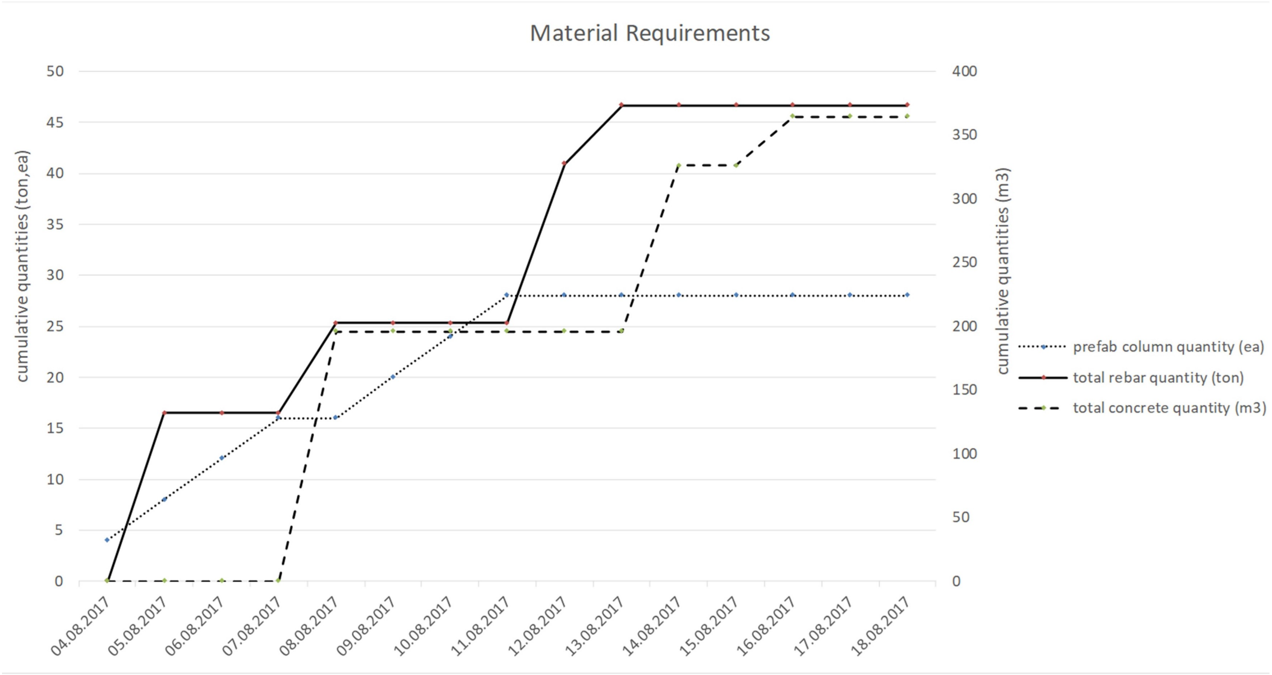

Figure 4.9: An example of the monitored daily material requirements (note that the unit for concrete is m^3, the unit for prefabricated column is ea, the unit for rebar is ton)

as an indicator of an execution bottleneck at a specific sub-process. The simulation setup was based on the 24-hour calendar time, thus the results were not scaled to 8-hour per day work schedules.

The durations of the individual tasks of each sub-process were estimated based on expert opinion obtained from 5 semi-structured interviews and one prefabrication plant site visit. The experts consisted of two construction professionals and three construction professors who have years of experience in building construction, with a focus on analyzing the details of the process diagrams. The durations of the sub-processes are provided in Table B.1 in the Appendix B.

4.5.2 Average time spent on change request feedback loops

The change request feedback loop is the repetitive series of sub-processes to identify and deal with requests to change the required materials or the time the materials are required, which requires communication among architects, engineers, suppliers and contractors. The change request feedback loop in the BIM-RFID-LAP workflow contains sub-processes PRO16 to PRO30 (i.e., 'incorporate changes in production plans' to 'give ok to production processes'). The change request feedback loop in the BIM-RFID-TRA workflow includes both USE01-USE19 (i.e., 'check make-ready tasks' to 'send new material requests to supplier'), and PRO09-STO01 (i.e., 'consolidate order and prepare production' to 'store the materials onsite').

Table 4.5 shows the average time spent on change request feedback loops using the two workflows per simulation. The BIM-RFID-LAP workflow requires 13.1% less time for change requests and information exchange processes than BIM-RFID-TRA workflow. This reduction does not, however translate entirely to the construction process, because more time is required to check and update the look-ahead plans for the material flows to proceed.

Figure 4.10 shows a probabilistic distribution representing the time spent on the change request feedback loops. The 13.1% time reduction indicates that there are benefits from the joint efforts in early identification of changes and use of the look-ahead plans for joint scheduling, which are included in the BIM-RFID-LAP workflow. In the BIM-RFID-LAP workflow, however, more time is required to address the late changes, requisition and re-shipping of the right ETO components.

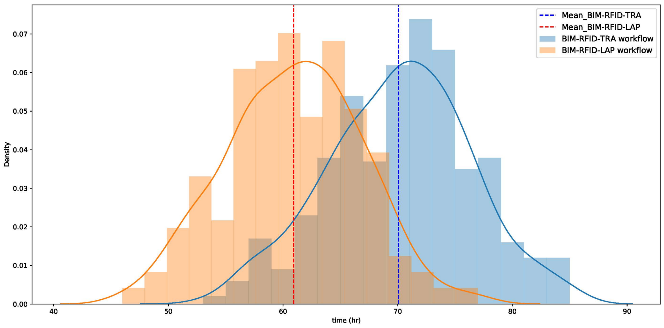

Figure 4.10: Probabilistic distribution of time spent on change request feedback loops

Table 4.5: Average time spent on change request feedback loops (notes: each simulation run contains completion of 22 process instances)

Workflow	Average time spent on change feedback loops (hrs)	Average time difference compared to the baseline
BIM-RFID-LAP	60.9	-13.1%
BIM-RFID-TRA (baseline)	70.1	0

4.5.3 Average floor construction time

The average floor construction time defined is the time required for finishing an entire material flow processes. Table 4.6 illustrates the comparison of average floor construction time between the two workflows. For the 22 floors, it takes 874.9 hours on average to complete one floor using the BIM-RFID-LAP workflow, which is 16.1% less than that of BIM-RFID-TRA. Since the only difference between BIM-RFID-LAP and BIM-RFID-TRA is whether the look-ahead plans are incorporated, it indicates that using look-ahead plans reduces the time needed for delivering the right materials to the site. The reduction of the average floor construction time is also a coherent result from exploiting the potential of BIM-RFID-LAP workflow over the holistic material flow processes.

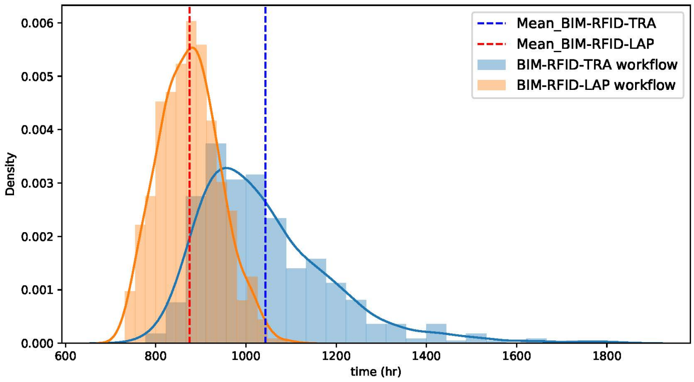

Figure 4.11: Probabilistic distribution of average floor construction time

Table 4.6: Average floor construction time in the two workflows (notes: each simulation run contains completion of 22 process instances)

Workflow	Average floor construction time (hrs)	Average time difference compared to the baseline
BIM-RFID-LAP	874.9 (standard deviation = 66.7)	-16.1%
BIM-RFID-TRA (baseline)	1042.9 (standard deviation = 149.3)	0

Figure 4.11 shows the probabilistic distribution representing the average construction time for one floor using the two workflows. The BIM-RFID-LAP workflow as a whole is subject to less variance than the BIM-RFID-TRA in the dynamic simulation environment, as can be seen from the fat-tailed distribution of the process time incurred from the BIM-RFID-TRA workflow. The fat-tailed distribution indicates the significant variability caused among complex sub-processes in the BIM-RFID-TRA workflow. In contrast, the use of the look-ahead plans in the BIM-RFID-LAP workflow reduces workflow variability.

4.5.4 Average waiting time

During each simulation run, each of the 22 simulations are only started when the previous simulation is finished. This means that each simulation, with the exception of the first, has a waiting time when the previous simulation is not complete. These are given in Table 4.7 and their representative probabilistic distributions are shown in Figure 4.12. It can be seen that there is a significant difference between the BIM-RFID-LAP workflow (222.8 hours) and the BIM-RFID-TRA (109.5 hours). The 103.5% more waiting time incurred in BIM-RFID-

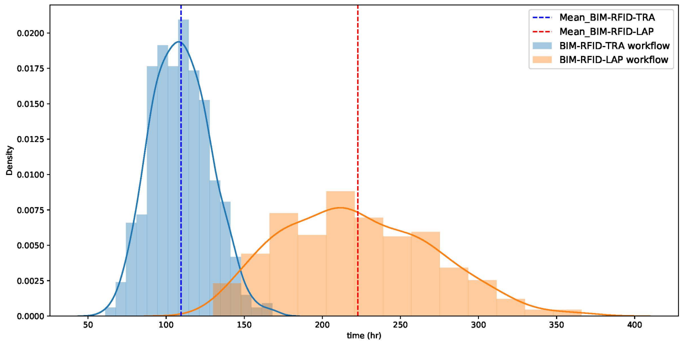

Figure 4.12: Probabilistic distribution of waiting time incurred

LAP workflow represents a relatively high frequency of resource unavailability, i.e. project participants were involved in different sub-processes that required unbalanced time, resulting in some participants having to wait longer for the availability of others. This increased waiting time is however still worth it, in terms of the reduction of the average floor construction time.

Table 4.7: Average waiting time incurred (notes: each simulation run contains completion of 22 process instances)

Workflow	Average waiting time (hrs)	Average time difference compared to the baseline
BIM-RFID-LAP	222.8	103.5%
BIM-RFID-TRA (baseline)	109.5	0

4.6 Discussion

4.6.1 Reduced construction time

The results show that the time spent for completing the construction of one floor can be reduced by 16.1% by incorporating the look-ahead plan. This indicates the possible improvement of using the BIM-RFID-workflow. Although the simulations are used, as opposed to changes on real world construction projects, the 16.1% time reduction are consistent with the test results found from relevant research. Examples of similar improvements can found in Li et al. (2017) [187], Bortolini et al. (2019) [37], Wang et al. (2017) [330] and Grau et al. (2009) [117].

Li et al. (2017) [187] 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. However, their study did not explicitly model the workflow using look-ahead plans. This research has highlighted the benefits of implementing a new workflow through complementing the state-of-the-art integrated BIM and RFID technology with concrete lean principles, e.g., the use of look-ahead plans.

Bortolini et al. (2019) [37] found that the use of a BIM 4D modelling system could help reduce person-hours spent in site logistics by 38%. Considering the stagnant construction productivity, this is seen as a significant improvement.

Wang et al. (2017) [330] and Grau et al. (2009) [117] found that the time savings through the use of integrated RFID systems could range from 70% to 90%. However, their findings mainly reflect the improvements of efficiency of logistics activities within a construction site, such as material handling and locating. Without considering the linkage between material manufacturing processes and site installation processes, the findings are limited to reflect the whole picture of material flow processes across different phases. Although there is very little evidence in other similar studies to show the time reduction of the holistic material flow processes, the impact on total project schedule duration and predictability in this research should thus be substantial.

4.6.2 Digitalisation

In the BIM-RFID-LAP workflow, the sub-processes regarding the exchange of material and lead time information are facilitated by using the central database and Dynamo scripts, where the detailed look-ahead plan is linked to the material design information in BIM authoring software. This can overcome the problems in the current industry practice that heavily relies on piles of 2D drawings, PDF documents for procurement, material lists, and a number of emails to exchange information. The change request module, ETO component estimation module and task planning module in the BIM-RFID integrated system help the participants capture the early feedbacks and be promptly notified of decisions.

4.6.3 Improved decision making

Compared to the relevant studies, such as Li et al. (2017) [187] and Bortolini et al. (2019) [37] who have focused on using digital tools either to improve accuracy of material estimation or to improve the visibility of material status, the BIM-RFID-LAP workflow distinguishes itself by adding the detailed look-ahead plan to synchronize actual site progress with the material delivery status. The decision making made through material flow processes thus becomes more accurate and reliable.

4.6.4 Change request feedback loop

The change request feedback sub-processes (PRO 15 to PRO30) requires intensive collaborative work of participants to check and update the short term look-ahead plans. The early collaboration of the supplier and the contractor decreased the amount of fragmented decision-making with respect to accurate time for production and transportation. The early feedback loops eliminated the rework (re-order of new selection of prefabricated column) to ensure a continuous flow, which accounts for the decrease in average floor construction time. The change request feedback loop in a late phase is eliminated with the BIM-RFID-LAP workflow. From this perspective, the lean principles in terms of constraint-free workflows are substantially realized by the incorporation of look-ahead plans in the BIM-RFID-LAP workflow. The features of the workflow are coherent with the lean workflows developed by Sacks et al. (2013) [265] and Abou-Ibrahim et al. (2019) [2].

4.6.5 Complex coordination problems

The incorporation of different modules into related sub-processes helped to eliminate the complex coordination problems that usually occur in the BIM-RFID-TRA workflow. The average floor construction time reductions, when the BIM-RFID-LAP workflow is used, are also partially due to the use of a single material coding system, which improves the efficiency of exchanging information between suppliers and contractors. Using the central database, sub-processes are automated to a certain level by the coding system to tie material information back to the site status. From this perspective, the BIM-RFID-LAP workflow and the system further improve the information visibility for collaborative decision making. The design of such an integrated system and the corresponding new workflow for construction projects also fulfill the future work suggested by Dallasega et al., (2018) [67] and Dallasega et al., (2019) [69], which is considered as a concrete implementation of Industry 4.0.

4.6.6 Applicability to other construction projects

Although the workflow is only shown for a single example project with repetitive construction elements, the proposed workflow can be used, modified and extended to other kinds of construction projects of various scales and types. Particularly, when the software applications are customized for projects, the new workflow has to be adapted or customized according to the functionalities and data interoperability needs of the software applications. In addition, for the development of customized workflows, the Signavio BPM Academic Initiative platform used in this research is freely available to academic institutes. Additionally, the simulations can be conducted in system dynamics or agent-based models, which can explicitly reveal the interactions and communication intensities between participants.

4.7 Conclusions and future work

This paper presented a new workflow, the BIM-RFID-LAP workflow, to improve the management of material flow processes. The new workflow is designed to systematically use regularly updated detailed look-ahead plans when using BIM and RFID technologies. Due to the incorporation of look-ahead plans, the entire material flow processes can be managed with a high granularity and information transparency into detailed construction processes. The existing gaps found in conventional use of BIM and RFID technologies have, therefore, been addressed. Its implementation will help realize the Industry 4.0 vision.

The workflow is supported by the use of an integrated database system. In this system, information on material properties and delivery status is collected from BIM software and RFID tags, and automatically linked with a short term look-ahead plan. The integrated system consists of, 1) a task planning module, 2) an ETO component estimation module, 3) a material ordering module, 4) a production module, 5) a location tracking module, 6) a delivery service module, 7) a quality inspection module, 8) a re-shipping module, 9) a material status module, and 10) a change request module, each of which facilitates an automated sub-process when planning and controlling the flow of materials in construction projects. The software system enables the contractors to better observe on-site status and differences between the actual and planned material requirements, as well as to alert suppliers if necessary. It, therefore, helps both contractors and suppliers proactively track actual material demands and supply, which eliminates the time needed for correcting wrong deliveries due to changes on the selection of materials or changes on the actual material need time.

The BIM-RFID-LAP workflow is shown by simulating how the material flow processes would be managed during the construction of repetitive ETO elements in an office building project. Through 500 discrete event simulation runs, it was found that the BIM-RFID-LAP workflow is able to reduce the average floor construction time for the example by 16.1% compared with the BIM-RFID-TRA workflow. Though more data can be collected from multiple projects for the process simulations, the simulation results derived from the stochastic simulating framework are sufficient to provide an overview of the differences between two workflows. The simulation results also provide the evidence to show the potential of using look-ahead plans to improve the existing practice of applications of integrated BIM and RFID technology. It is considered, therefore, a solid demonstration of complementing advanced Industry 4.0 technology with lean principles to fill the gaps in the state-of-the-art.

Although the BIM-RFID-LAP workflow was tested to investigate its potential to improve material flow processes on an example simulated construction project, its benefits should be investigated on other simulated and then real world construction projects. These other projects should include 1) material types, e.g. aggregates and concrete, in addition to the prefabricated elements used in this work, 2) various contractual types, 3) additional supply chain roles of participants (e.g., a third party logistic provider) and 4) different project contexts.

Additionally, with more data, future research work should also focus on improving the modelling, either in a system dynamics or an agent based model, of the interactions between multiple project participants, and investigate the costs related to the implementation of such a system and the potential cost savings. Other areas, such as data interoperability, data ownership, and legal issues related to the use of integrated Industry 4.0 technologies, should be also investigated in the future research.

CHAPTER 5

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

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This chapter corresponds to the article under review:[1]

Chen, Q., Adey, B.T., Haas C.T., Hall, D.M. (2020). Exploiting digitalization to improve the coordination of change requests in engineer-to-order materials flow management. Revised version resubmitted to journal of Construction Innovation. Status: Under review.

Abstract

The dynamic nature and complexity of construction projects make it challenging to ensure that the engineer-to-order 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. In this paper, an integrated management framework is proposed to improve communication between major stakeholders and improve engineer-to-order materials flow management. An integrated management framework is developed that integrates the use of look-ahead plans, building information models and radio frequency identification technologies to integrate business workflows. A prototype system is devised to functionally demonstrate the proposed framework to enable the quick dissemination of information emanating from changes in design, schedules, production and trans-

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[1] Please note, this is the author's version of the manuscript resubmitted to the Journal of *Construction Innovation*. For the reasons of consistency, the style of this chapter matches that of the dissertation. Changes resulting from the publishing process, namely editing, corrections, final formatting for printed or online publication, and other modifications resulting from quality control procedures may have been subsequently added. When citing this chapter, please refer to the original article found in the reference above.

portation, to major stakeholders. The system consists of four functional modules and a central database and uses a client-server architecture. The system modules are demonstrated and the usefulness of the framework is illustrated using a construction of part of a fictive but realistic high-rise building. The integrated management framework and its corresponding prototype system provide major stakeholders with the ability to coordinate their activities efficiently and make decisions collaboratively on the deliveries of engineer-to-order components. Although only a fictive example was used, it is shown that the use of the system is likely to result in substantial reduction in the time required to deal with required changes when delivering engineer-to-order materials onsite (by 18% in the example). The integrated management framework underlines the potentials of information integration in terms of agility and efficiency of supply chain coordination. 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. The proposed framework and the prototype system appear to have substantial benefits for the use of prefabricated elements, such as interior partition elements, ductwork, plumbing, and mechanical systems that typically have to be modified due to last-minute design and schedule changes. The research indicates that exploiting digitization agility in the management of engineer-to-order materials flow is possible through improved communication and the resulting improved coordination of activities that is required followed last-minute changes on site. The proposed framework combines for the first time, detailed look-ahead plans, BIM, RFID in a common data environment for supply chain collaboration to replace existing ad hoc procedures.

5.1 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 [141, 155]. These characteristics also bring great challenges to the coordination of the material flows processes[2] or their supply chain processes [73, 214, 149]. A lack of coor-

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[2] 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.

dination of material flow processes further results in incorrect material deliveries and material delays, which inevitably leads to project delays and cost overruns [193]. Researchers discovered that the problems pertaining to these issues cause over 50% of the project delays and cost overruns [43]. Therefore, successful construction projects require good coordination of material flow processes to deliver materials to site as required.

Due to inadequate dimensioning or tolerances of component geometry, ETO components are more prone to changes in design and scheduling than the make-to-stock building components [217]. Therefore, massive coordination efforts are needed for design and schedule changes to ensure the ETO components are designed and delivered as required. Coordination, in the context of dynamic material flow processes, is a managerial function responsible for aligning the decisions of major stakeholders to deal with the required changes [54]. 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 [323]. This further results in delays in material deliveries. 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 modelling (BIM) [87, 339], radio frequency identification (RFID) [16], quick response codes [143], ultra-wideband [310], Bluetooth low energy [226], near-field communication technologies [97], indoor global positioning systems (GPS) [344], and laser scanning and photogrammetry [227], etc., 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 construction management practices for supply chain coordination. In particular, the concept of supply chain agility is important for managing ETO components. Supply chain agility is derived from the concept of flexible manufacturing systems. Agile project supply chains enable contractors and suppliers to sense and enact change in response to varying demands [244, 69]. Supply chain agility requires increased visibility of 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. One emerging construction management practice to improve supply chain agility is the use of look-ahead plans. Look ahead plans are plans that include what installation tasks will be completed using which materials in which work zone and by whom, as well as start and finish dates in a short term near future [25, 69]. Look ahead plans capture changes early before they are reported too late for timely resolution [25]. They are useful to allow agile supply chain processes and reduce the rework due to late changes.

However, to date there is little research that describes how digital supply chain technologies and agile supply chain management models can be combined. To do this, this paper proposes a framework for integrated management of supply chain coordination (Section 5.3). The framework is based on the synchronization of BIM and RFID information from a construction site and a material fabrication site, which is utilized for the implementation of look-ahead planning processes for the coordination of required changes at a high information granularity level. The framework is functionally demonstrated using a prototype system that is designed with a common data environment, which allows major stakeholders (i.e., designer/engineers, supplier, and contractor) to make decisions collaboratively from design to final installation (Section 5.4). This prototype system demonstrates that supply chain information is integrated among major stakeholders and that agility is supported within a short time horizon (Section 5.5). The paper discusses the potential and limitations of the framework and concludes with proposals for future work respectively in Section 5.6 and Section 5.7.

The contribution of the integrated management framework is a novel framework that will allow BIM and RFID technologies to support look-ahead planning processes. Such a framework can help shield material flow from negative impacts due to last-minute changes, enable collaborative work of major stakeholders to better manage material flows, and replace ad-hoc coordination activities with a more structured and agile supply chain approach.

5.2 Literature review

The state-of-the-art found in the literature can be grouped as the coordination of engineer-to-order supply chain processes, the use of look-ahead plans, and the use of BIM and RFID for the coordination of the required changes. The state-of-the-art in each is synthesized in the three subsequent sections.

5.2.1 Coordination of engineer-to-order supply chain processes

Engineer-to-order (ETO) building projects and the associated supply chain processes are often regarded as complex and dynamic to manage. The primary reason is that the design, production and delivery of building elements have to meet the client needs that often vary when construction progresses [217]. 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. For example, the glass fiber reinforced concrete (GFRC) 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.

A number of 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 [317, 335]. Design changes can be triggered by various project stakeholders, such as clients, contractors, suppliers and regulatory bodies throughout supply chain processes [271]. They can affect ongoing production and installation as the change propagates to components that have already been produced and delivered to the construction site [125]. Therefore, this overlapping between design, production and installation causes significant difficulties for project stakeholders to coordinate changes and avoid delays [146, 39]. Moreover, there are often conflicting requirements and incomplete information during supply chain processes, needing more efforts to manage and coordinate the trade-offs between stakeholders. To cope with that, collaborative decision making and decentralized planning were suggested by many researchers to improve the coordination of highly complex ETO projects, such as housing projects and shipbuilding projects [217]. It is necessary to have confirmation and commitments from all stakeholders from upstream to downstream to reduce the uncertainties in design and planning activities. While many of those related studies have used qualitative research methods to identify factors or enablers to advocate for the integration of design all way down to installation, the research on the technical, tactical or operational methods was not adequately conducted to address the integration for ETO building projects.

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 [13, 350, 180, 121]. The concepts have all indicated the importance of both contractors and suppliers having 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 [21], INTELSYS.build [148], IBM Maximo [147], WebTMA [332], TotalETO [312]. These platforms partially provide the total solutions to streamline the information flow from the design to production of ETO products, with a focus to overcome the challenges of optimizing cash flow and enterprise resource planning associated with digital product design. The near-term planning of supply chain to consider the exact site status and preventive control of last-minute changes were not incorporated into the design of those platforms. Therefore, the ETO supply chain remained being managed traditionally: the contractor and the supplier coordinate information and material flows based on rough plans and standalone platforms, thus lacking the insights into the continuously changing site conditions. As a result, they have difficulty foreseeing the uncertainties from the site schedule and have to passively respond to problems when they occur.

To alleviate those problems, different approaches were proposed in mainstream academic studies, which fall into two main categories: the lean construction approach and the digital integration approach. To limit the scope of the specific approach to study, the following two subsections focus on the reviewing the use of look-ahead plans as representative of the lean construction approach and the use of BIM and RFID as representative of the digital integration approach.

5.2.2 Look-ahead plans for the coordination of changes

Considering the characteristics of ETO building projects, supply chain integration and agility to respond to changes are needed in the supply chain processes. In an endeavor to encourage this, researchers have explored the advantages of using rolling look-ahead plans. Look-ahead plans are used to facilitate the look-ahead planning process. When making look-ahead plans, every participant involved in the project needs to actively provide input (e.g., new materials to be ordered and produced, new dates possible to start the work, etc.) to activities affected by changes and interdependent activities. Look-ahead plans help project participants prevent work conflicts, ensure the right materials are ordered and delivered, ensure correct work sequences, and facilitate a fluent workflow for installation crew, preventing rework [82]. Therefore, the use of look-ahead plans is an appropriate way to resolve the challenges in ETO projects, such as housing and shipbuilding projects.

Researchers have investigated the use of look-ahead plans to improve communication between construction site and fabrication site concerning early identification of design changes and the need to re-schedule installation work. For example, Ruwanpura et al. (2012) [263] demonstrated the capability of using look-ahead plans to ensure timely delivery of materials and timely notification of approved change orders, which facilitates smooth operations on construction sites. To address the multiple changes in ETO building projects, Dallasega et al. (2019) [69] showed that using and updating look-ahead plans on a weekly basis to better synchronize material fabrication and installation tasks enabled the installation times to be reduced by approximately 2.7% through early identification of site misfit problems. In another example, an implementation KanBIM workflow resulted in increases in the percentage of planned work completed on time from 33% to 62%, primarily due to the instant information on the dynamically changing work status [265]. A recent study by Chen et al., (2020a) [51] showed that using look-ahead plans reduced the duration of a holistic material flow process by 16.1% compared with the traditional push-based workflow. In brief, without the implementation of look-ahead plans to ensure the soundness of planned work, there is little assurance that the right work is being made ready and executed at the right time to stay on schedule.

These researchers, however, show that the look-ahead planning process is time-consuming and error-prone. Typical look-ahead plans are created, updated and maintained manually and rely on a great amount of paperwork, manual documentation of workflows, and standard conference room whiteboards (e.g., 20 feet horizontal length). There is less reported use of digital information to enable the look-ahead planning processes to coordinate required changes and associated material flows. Additionally, some studies have pointed out a waste of time caused by using traditional scheduling software, such as Microsoft Project, Primavera, etc. to help identify constraints in task scheduling [313]. The extensive efforts needed for manual work creates difficulties for project participants to continuously provide up-to-date information and jointly conduct decision making on design changes or scheduling changes. Some software applications, though, are available for stakeholders to use and participate in the look-ahead planning processes, such as KanBIM [265], Visilean [324], Lean4Team [183] and vPlanner [326]; none of them have yet been able to provide suppliers with proactive planning capabilities based on the continuously changing site progress.

5.2.3 BIM and RFID for the coordination of changes

With advances in construction automation [52] and digital manufacturing [122, 105], researchers have developed various types of information communication technologies to enable supply chain integration and efficient coordination of information flows. These have included a wide range of integrated applications of BIM and wireless transmission technologies, which can be combined to formulate nD BIM for supply chain integration. Taking 4D BIM and RFID technologies as an example, researchers have focused on providing quick and reliable bi-directional communication platforms for networked project participants and have improved the efficiency of tracking and exchanging material information.

The prevalent applications of nD BIM, driven by wireless transmission technologies, have been tracking material location and real-time status. Numerous case studies have shown that the use of integrated application of BIM and RFID has particular promise, considering the parametric modelling capability of BIM authoring software and the durability of RFID tags in harsh and dirty construction sites. Chin et al. (2008) [58] integrated 4D models with RFID in an information system to support logistic and progress management. They validated the system in a real-world high-rise building project to conclude that a true win-win situation is possible between the general contractor and manufacturer through the application of the proposed system. On the basis of this framework, Shin et al., (2011) [278] 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 decision collaboratively. 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) [349], which put a specific focus on using standalone RFID information platform to improve the efficiency of logistics processes.

Some other researchers emphasized the importance of tracking precision besides the supplier integration processes. For example, Fang et al. (2016) [93] and Asadi et al. (2019) [20] have developed BIM-RFID real time image registration models to ensure that the location coordinates of the prefabricated elements were read and compared with the expected location in BIM. This resulted in time-savings, when the suppliers and site trades perform materials inspection before and after every delivery. Apart from the focus on material shipping locations, Du et al. (2017) [85] and Bortolini et al. (2019) [37] 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 3D models. Their respective case study results showed that it improves the efficiency of logistics planning through automatic collection of materials quantity take-offs.

Those numerous studies show that the integration of BIM and RFID helps contractors and suppliers work collaboratively. It further helps reduce time needed for addressing requests for information on material orders, minimizing wrong orders, and ultimately helps ensure the right deliveries. Nonetheless, the ability to actively collect data from contractors to allow near term planning is not yet readily available to suppliers. It remains challenging for the suppliers to have quick access to site progresses to respond quickly to last-minute changes requested by contractors.

5.2.4 Identification of the research gap

Existing research work has already addressed the efficiency of ETO supply chain in various ways; however, there is still room for further improvement if digital information is specifically used to support look-ahead planning processes to improve the coordination of required changes during material flow processes. A summary of the relevant works (mentioned in Section 5.2.2 and 5.2.3) is presented in Table 5.1.

Based on the literature review, the challenges of delivering materials in response to required design and schedule changes can be partially overcome by approaches to agility in the guise of the look-ahead plans. Look-ahead plans are a means to enable agility in material flow management; contractors and suppliers can rely on look-ahead plans to identify constraints for installation and detect the design and schedule changes early. Without look-ahead plans, the materials orders that are made too early may, in fact, increase the probability of not having the right material available at the time required. The use of the look-ahead plans remains however rudimentary in ETO building projects. The integration of look-ahead planning processes with digital tools opens a new way for supplier-contractor collaboration. When adequately investigated and implemented, suppliers will have the ability to actively collect data from contractors to allow near term planning and proactive decision-making processes.

Two research gaps emanating from the literature are:

1. What would be a management framework to allow suppliers to get more detailed insights into site progress through the look-ahead planning process in order to shield the material flow processes from negative impact by last-minute changes;

2. What would be the form of a prototype system to functionally demonstrate the framework?

5.3 The integrated management framework

To address research gap one, this paper develops an integrated management framework to incorporate detailed look-ahead planning processes into a digital workflow. Its theoretical foundation is the lean construction theory, 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 5.1. The schematic representation of the traditional management framework is illustrated in Figure 5.2. The unique features of the proposed framework, when compared

Table 5.1: A summary of the relevant works regarding improvement of ETO supply chain processes

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 & Rauch (2014) Mello et al. (2015) Saoud et al. (2017) Iakymenko et al. (2018) Wesz et al., 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
Ruwanpura et al. (2012) Dong et al. (2013) Sacks et al. (2013) Braglia et al. (2018) Dallasega et al. (2019) Chen et al. (2020) *Commercial platforms:* Visilean Lean4Team vPlanner	Look-ahead planning process implementation to remove constraints and site variabilities	Case studies or prototype demonstration	Visualization of constraints for near term planning, agile scheduling	Site installation	Workflow perspective on installation tasks
Chin et al. (2008) Yin et al. (2009) Shin et al. (2011) Fang et al. (2016) Du et al. (2017) Asadi et al. (2019) Bortolini et al. (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

with the traditional management framework, are described as follows. Table 5.2 summarizes the comparison of the two frameworks.

Firstly, the integrated management framework requires a common data environment so that the architects, engineers, contractors and suppliers work collaboratively to exchange the change-request forms, drawings and documentation of design changes to resolve a design change (P1). To allow collaboration, a shared database is intended to create the common data environment. Additionally, the common data environment is useful to assist fast feedback loops between the stakeholders. A feedback loop starts, and could undergo numerous iterations, before design freezes or material production starts or material transport starts (P2, P3, P5). These early iterations, in turn, reduce the uncertainties related to changes that might be requested by the construction contractors for the required installation tasks. An example of such uncertainties is the discrepancies that sometimes occur between the dimensions of the ETO components as produced and the exact dimensions of these components required on site. In contrast, the intensive and quick feedback processes are not available in the traditional management framework, and stakeholders have to work on standalone databases, including using multiple spreadsheets and relying on fragmented message flows via emails and phone calls.

Then, a look-ahead plan is used based on digital information flowing among stakeholders, instead of relying on multiple spreadsheets. It is used to know with a high level of certainty when the tasks in the upcoming weeks are to start and finish in the look-ahead planning period, which is determined based on the consensus of the project participants. In the shared database, it contains, 1) the work zone(s) in which the work will be conducted, 2) the sequencing of the tasks, 3) the constraints on the tasks (i.e., the constraints of labor preparation, machine preparation, space preparation, permits and precedential relationship constraints), 4) the daily update notifications to be sent when the tasks are pulled and changes to schedules are made, and 5) 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). Once a design change is found, BIM authoring software is used for sharing the design information to resolve the design change and conflicts (P1). Then, 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) (P2). This process is highlighted in the yellowed box in Figure 5.1, featuring a dynamic status updating of the look-ahead plan based on digital information flows. It is however not achievable using the traditional management framework due to the lack of shared information. As a result, the information in the look-ahead plan remains too static to capture the updated site changes if the traditional management framework is used.

Thirdly, the integrated management framework features the control of two

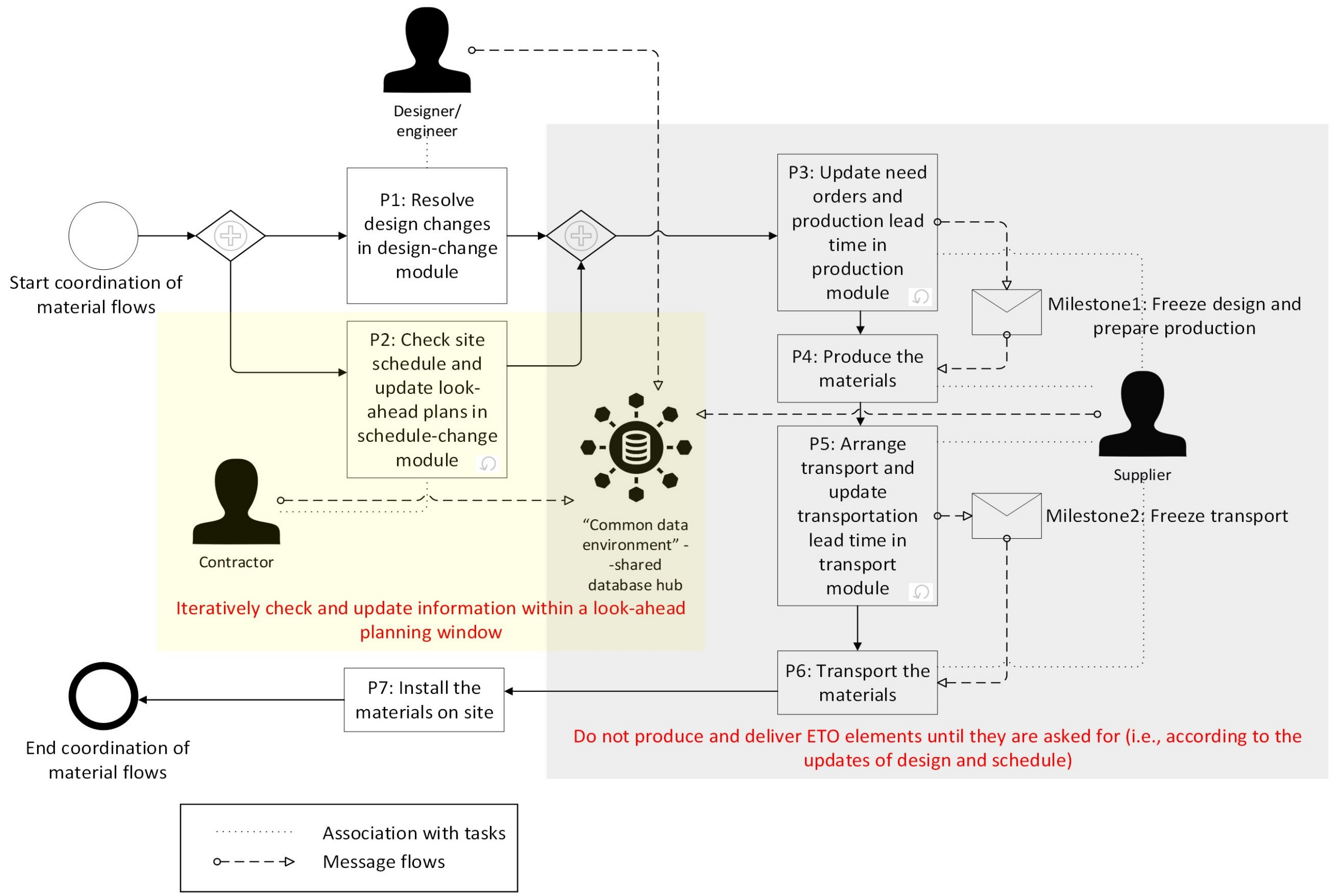

Figure 5.1: The proposed integrated management framework

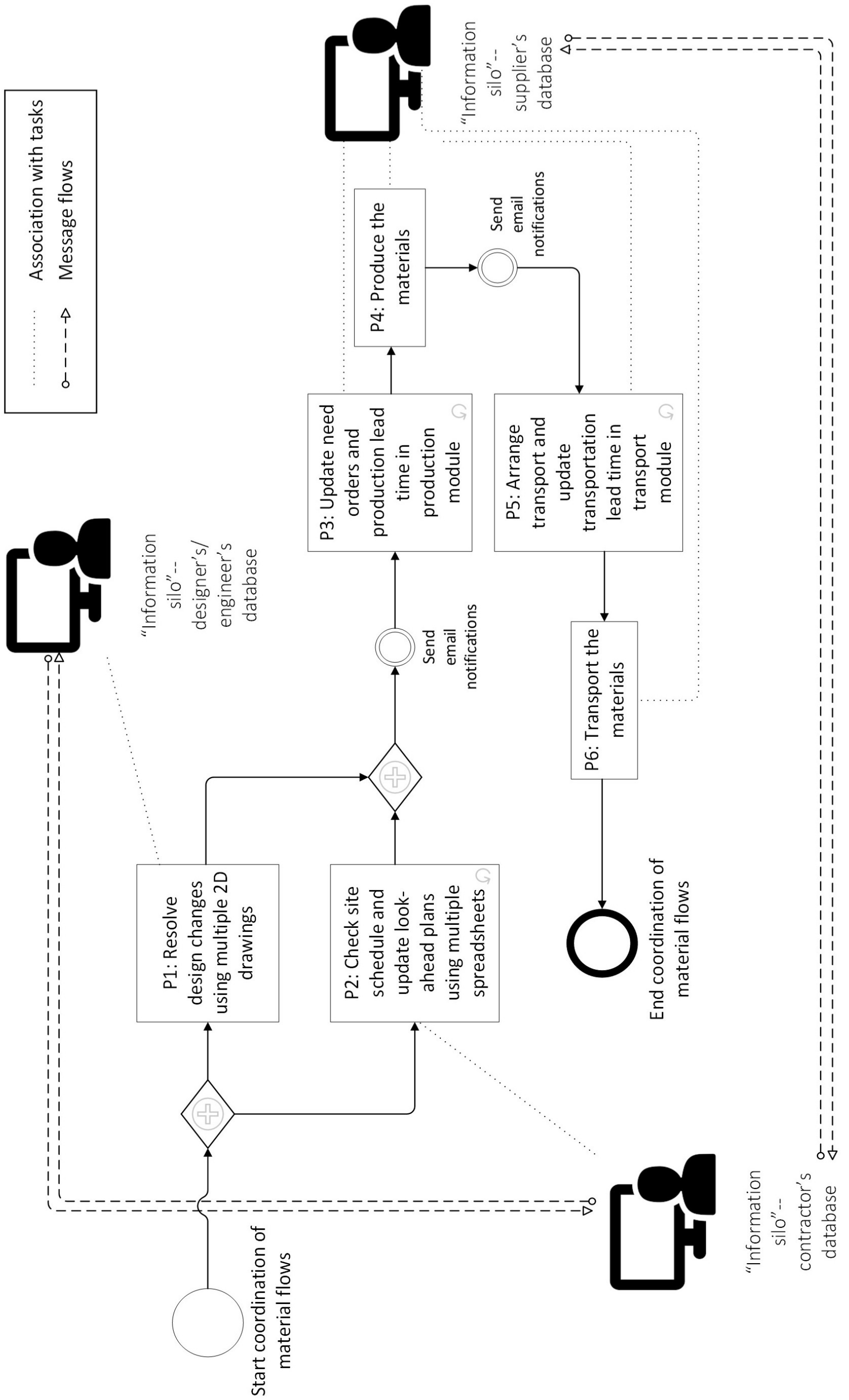

Figure 5.2: The traditional management framework

milestones to prevent the impact of last-minute changes; including milestone 1 (the time to freeze design for production) and milestone 2 (the time to freeze the transport time of materials). Once the look-ahead plans receive updates, the suppliers need to update new order information and production lead times taking into consideration the impact by design changes and schedule changes (P3). When the contractors and suppliers fix the design change, suppliers can freeze the design drawings (i.e., engineering drawings and corresponding shop drawings) for production. As 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 (i.e., for just-in-time delivery, material need-times are the continuously updated start-times of insulation tasks) (P4). This also ensures that the ETO elements will not be produced or delivered until they are asked. 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 5.1. However, the control of the two milestones is missing from the traditional management framework. As a result, the resolution of the changes is always late and reactive.

Table 5.2: The comparison of the integrated management framework and the traditional management framework

Features	Two management frameworks		Processes involved in the framework
	Integrated management framework	Traditional management framework	
A common data environment in the form of a shared database	✓		P1-P6
Information silos in the form of individually owned databases		✓	P1-P6
Collaborative way planning through the dynamic updates of the look-ahead plans	✓		P2
Fragmented way of planning through the static information in the look-ahead plans		✓	P2
Preventive control of milestones in case of changes	✓		P3,P5
Reactive resolution of changes on an as-needed basis		✓	P3,P5

5.4 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.

5.4.1 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: 1) the design-change module, 2) the schedule-change module, 3) the production module and 4) the transport module. A summary of each is provided in Table 5.3.

Table 5.3: A summary of the functional modules

Functional module	Functions	Authority to access all the functions		Processes involved in Figure 5.1
		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

Design-change module

To fulfill the required process P1 in Figure 5.1, 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 is designed parametrically as a unique element. An element 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.

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.

Schedule-change module

To fulfill the required process P2 in Figure 5.1, 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 time 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 time 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 [51]. 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 if any changes to the originally planned dates are required. Since 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 programming 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.

Production module

To fulfill the required processes P3 and P4 in Figure 5.1, 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, production status etc.).

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, milling, etc.). 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.

Transport module

To fulfill the required processes P5 and P6 in Figure 5.1, 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 minutes), 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 if any delay is notified from the transport process. For example, if there is a significant delay due to 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.

Linking the modules

The four modules are linked to support the feedback loops and coordination of the milestone dates. The link is realized by automatically calculating the dates when materials should be produced and transported to site. 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). The updates of milestone enabled by the calculations in functional modules are shown in Figure 5.3. The pseudocode to support the calculations is provided in Figure C.1 in the Appendix C. With the information shared among the contractors and suppliers, the delivery of ETO components are either expedited or postponed to accommodate the dynamically changing site needs.

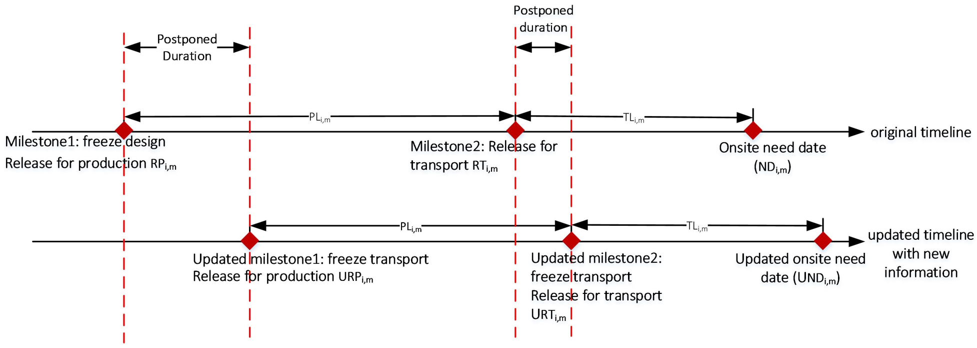

Figure 5.3: The updates of milestone enabled by the calculations in functional modules

Since the system is designed following the philosophy of the proposed framework in Section 5.3, the system is designed to allow users to trigger an update on the actual material requirements and reliable dates to release production and transport of materials. 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.

5.4.2 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 1.90GHz. In this research, Autodesk Revit is chosen as the BIM authoring software. In the system, the data of 3D models are transferred and stored by using the Dynamo programming scripts[3] 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 5.4. 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 utilizes the data retrieved from the database layer according to the functions. The presentation layer provides

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[3] Dynamo (Open source graphical programming for design), Available at: https://dynamobim.org/.

the user interface composed of Tk 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 wall, to be constructed, e.g., length, weight, color, 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, 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, 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 5.3.

In order 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 detailed processes for data integration into MySQL server are shown in Figure C.2 in the Appendix C. The data are 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.

5.5 Functional demonstration and capability evaluation

Studies have shown that the impact of the functional demonstration is considered significant for construction management research [194]. Due to the difficulties to access to real-world pilot projects, the functional demonstration was conducted

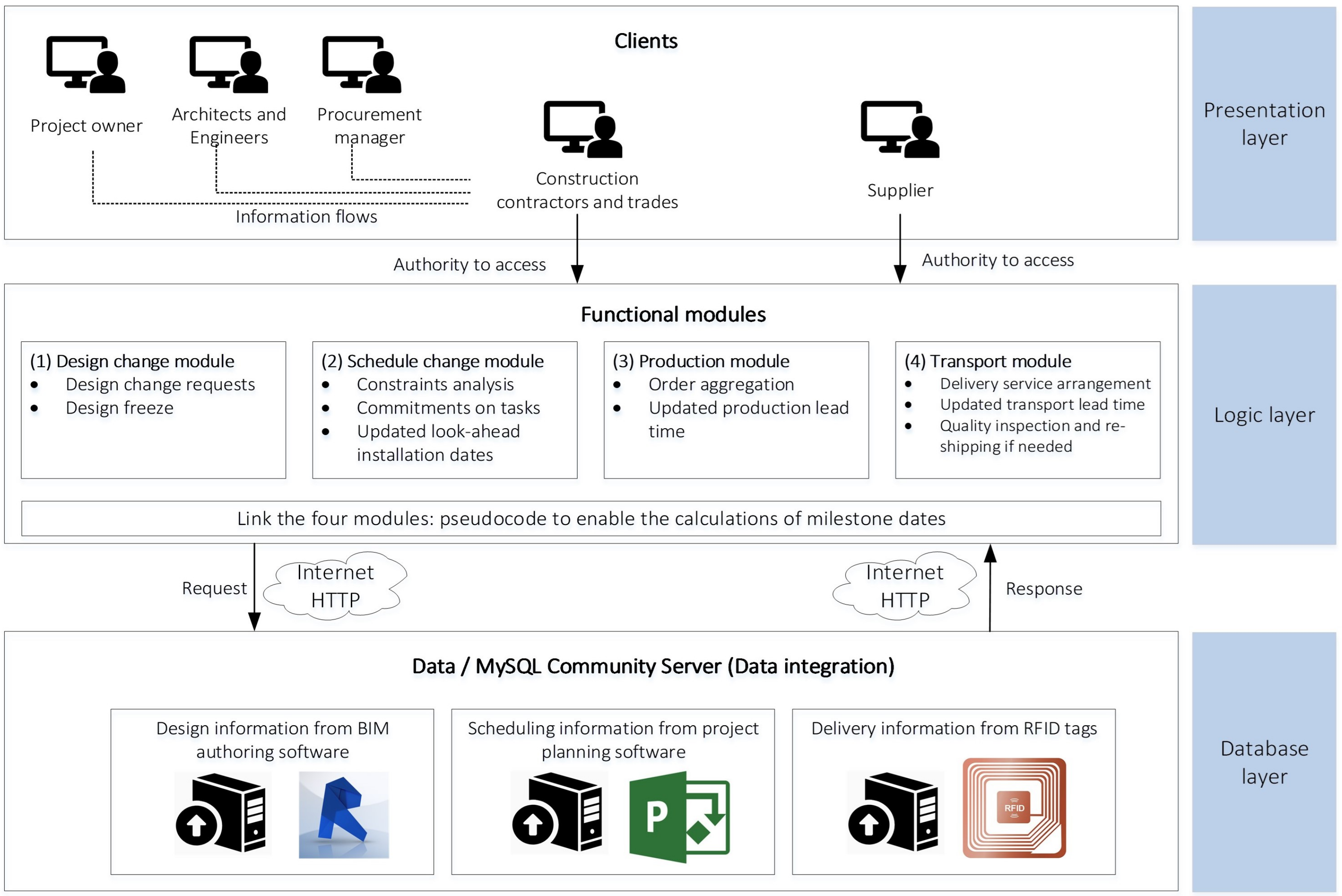


Figure 5.4: The system architecture of the prototype for the integrated management framework

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 Section 5.5.1 and Section 5.5.2.

5.5.1 Implementation of module specifics

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 5.1. Suppliers and contractors should login into the system with usernames and passwords to access the modules.

Design-change module

An example of using the design-change module is shown in Figure C.3 in the Appendix C, 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.

Schedule-change module

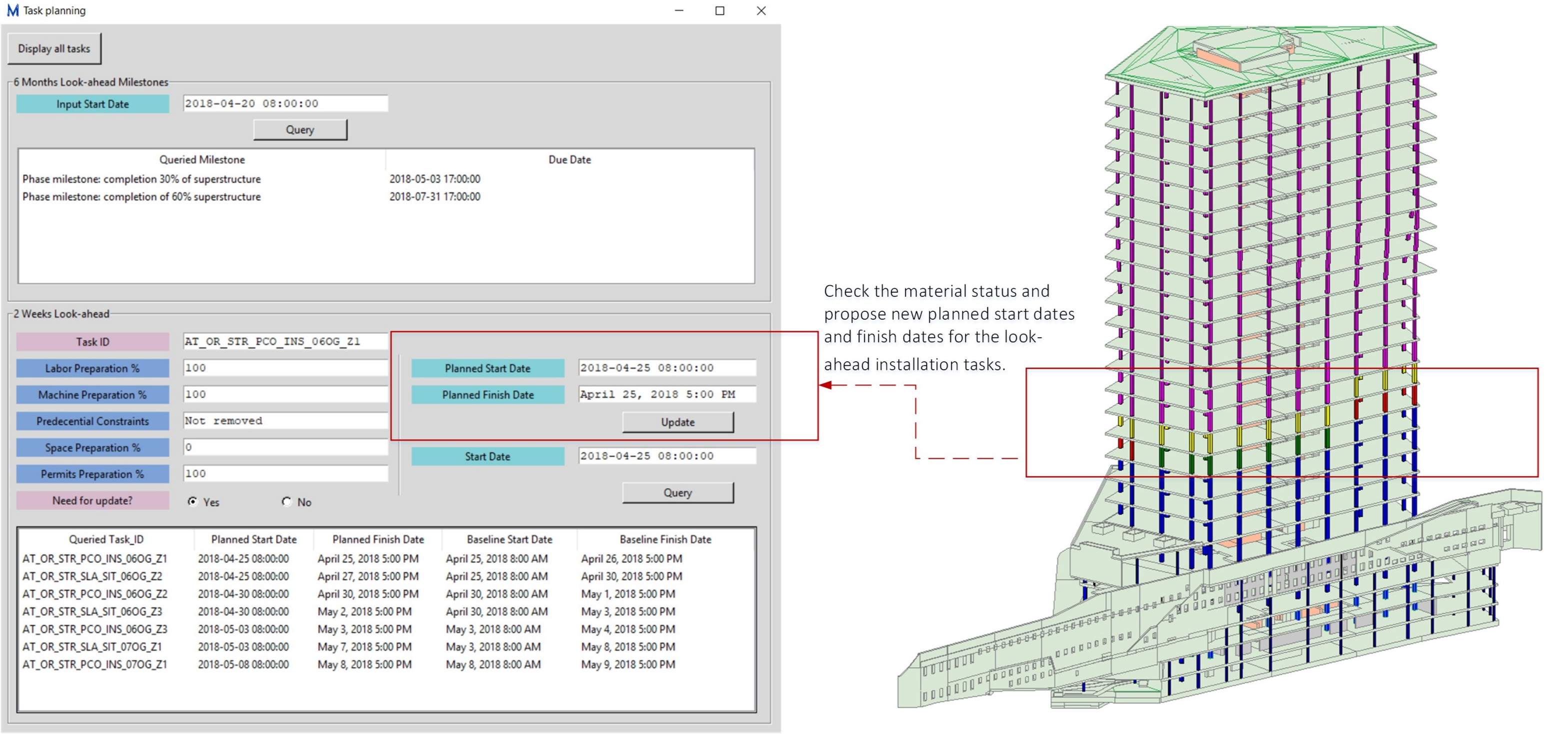
The example of using the schedule-change module is shown in Figure 5.5. As there was a design change on the loading bearing capacity of specific columns, contractors checked if the design change led to a change in the planned start and finish dates of installation tasks in the look-ahead schedules. The task ID, 'AT_OR_STR_PCO_INS_06OG_Z1', refers to the installation of prefabricated columns in work zone Z1 on the 6th 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. Since none of the preparation work was 100 percent 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.

Production module

The example of using the production module is shown in Figure 5.6. 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 6th 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.

Transport module

The example of using the transport module is shown in Figure 5.7. 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



Input Start Date: 2018-04-20 08:00:00

Queried Milestone	Due Date
Phase milestone: completion 30% of superstructure	2018-05-03 17:00:00
Phase milestone: completion of 60% superstructure	2018-07-31 17:00:00

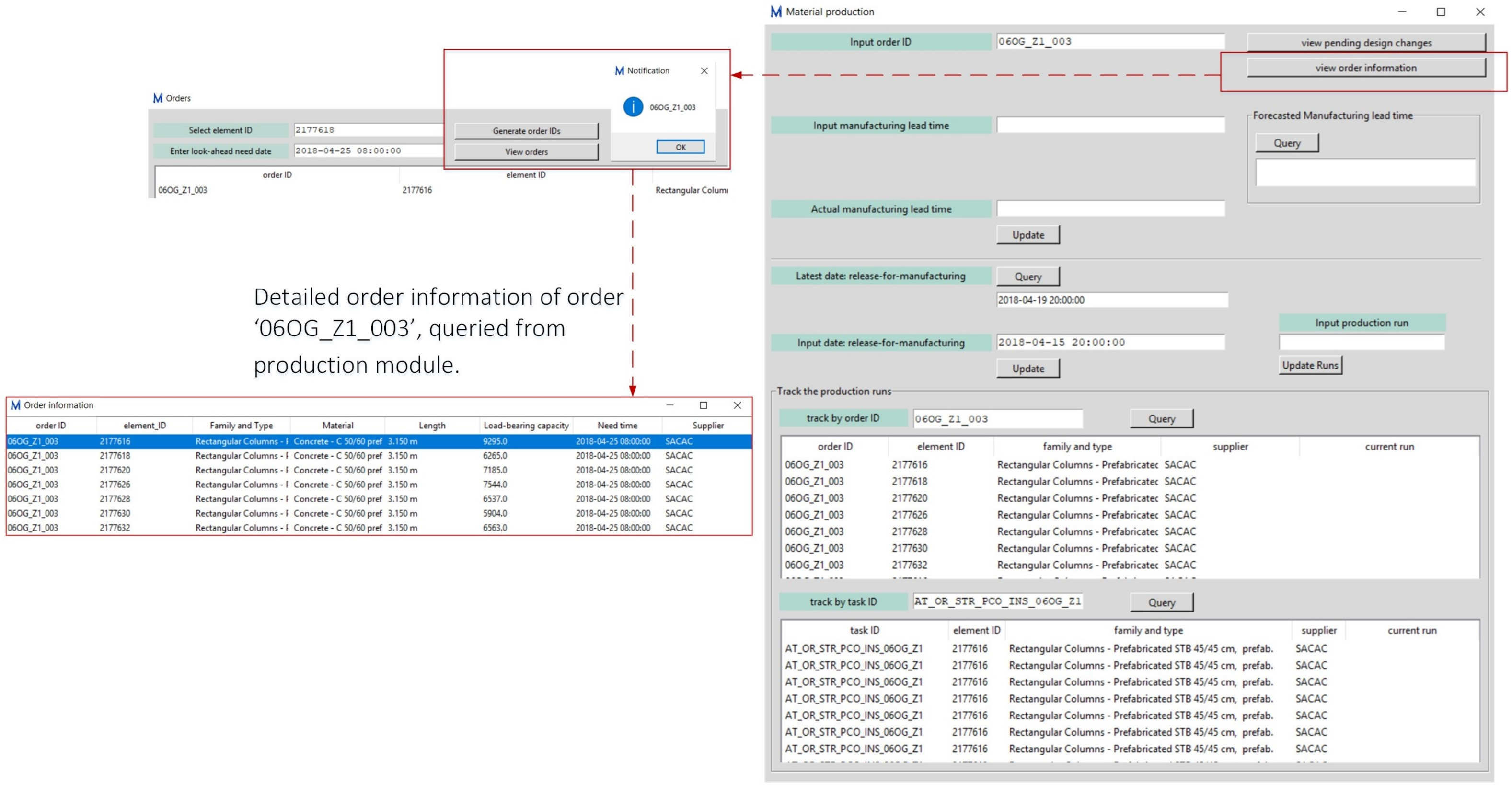
Task ID: AT_OR_STR_PCO_INS_06OG_Z1
Labor Preparation %: 100
Machine Preparation %: 100
Predecential Constraints: Not removed
Space Preparation %: 0
Permits Preparation %: 100
Need for update? ● Yes ○ No

Planned Start Date: 2018-04-25 08:00:00
Planned Finish Date: April 25, 2018 5:00 PM
Start Date: 2018-04-25 08:00:00

Queried Task_ID	Planned Start Date	Planned Finish Date	Baseline Start Date	Baseline Finish Date
AT_OR_STR_PCO_INS_06OG_Z1	2018-04-25 08:00:00	April 25, 2018 5:00 PM	April 25, 2018 8:00 AM	April 26, 2018 5:00 PM
AT_OR_STR_SLA_SIT_06OG_Z2	2018-04-25 08:00:00	April 27, 2018 5:00 PM	April 25, 2018 8:00 AM	April 30, 2018 5:00 PM
AT_OR_STR_PCO_INS_06OG_Z2	2018-04-30 08:00:00	April 30, 2018 5:00 PM	April 30, 2018 8:00 AM	May 1, 2018 5:00 PM
AT_OR_STR_SLA_SIT_06OG_Z3	2018-04-30 08:00:00	May 2, 2018 5:00 PM	April 30, 2018 8:00 AM	May 3, 2018 5:00 PM
AT_OR_STR_PCO_INS_06OG_Z3	2018-05-03 08:00:00	May 3, 2018 5:00 PM	May 3, 2018 8:00 AM	May 4, 2018 5:00 PM
AT_OR_STR_SLA_SIT_07OG_Z1	2018-05-03 08:00:00	May 7, 2018 5:00 PM	May 3, 2018 8:00 AM	May 8, 2018 5:00 PM
AT_OR_STR_PCO_INS_07OG_Z1	2018-05-08 08:00:00	May 8, 2018 5:00 PM	May 8, 2018 8:00 AM	May 9, 2018 5:00 PM

Check the material status and propose new planned start dates and finish dates for the look-ahead installation tasks.

Figure 5.5: The 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”, blue color denominates the status “installed”.)



Input order ID: 06OG_Z1_003

Input manufacturing lead time:

Actual manufacturing lead time:

Latest date: release-for-manufacturing: 2018-04-19 20:00:00

Input date: release-for-manufacturing: 2018-04-15 20:00:00

track by order ID: 06OG_Z1_003

order ID	element ID	family and type	supplier	current run
06OG_Z1_003	2177616	Rectangular Columns - Prefabricatec	SACAC	
06OG_Z1_003	2177618	Rectangular Columns - Prefabricatec	SACAC	
06OG_Z1_003	2177620	Rectangular Columns - Prefabricatec	SACAC	
06OG_Z1_003	2177626	Rectangular Columns - Prefabricatec	SACAC	
06OG_Z1_003	2177628	Rectangular Columns - Prefabricatec	SACAC	
06OG_Z1_003	2177630	Rectangular Columns - Prefabricatec	SACAC	
06OG_Z1_003	2177632	Rectangular Columns - Prefabricatec	SACAC	

track by task ID: AT_OR_STR_PCO_INS_06OG_Z1

task ID	element ID	family and type	supplier	current run
AT_OR_STR_PCO_INS_06OG_Z1	2177616	Rectangular Columns - Prefabricated STB 45/45 cm, prefab.	SACAC	
AT_OR_STR_PCO_INS_06OG_Z1	2177616	Rectangular Columns - Prefabricated STB 45/45 cm, prefab.	SACAC	
AT_OR_STR_PCO_INS_06OG_Z1	2177616	Rectangular Columns - Prefabricated STB 45/45 cm, prefab.	SACAC	
AT_OR_STR_PCO_INS_06OG_Z1	2177616	Rectangular Columns - Prefabricated STB 45/45 cm, prefab.	SACAC	
AT_OR_STR_PCO_INS_06OG_Z1	2177616	Rectangular Columns - Prefabricated STB 45/45 cm, prefab.	SACAC	
AT_OR_STR_PCO_INS_06OG_Z1	2177616	Rectangular Columns - Prefabricated STB 45/45 cm, prefab.	SACAC	
AT_OR_STR_PCO_INS_06OG_Z1	2177616	Rectangular Columns - Prefabricated STB 45/45 cm, prefab.	SACAC	

Select element ID: 2177618

Enter look-ahead need date: 2018-04-25 08:00:00

order ID	element ID	
06OG_Z1_003	2177616	Rectangular Colum

06OG_Z1_003

Detailed order information of order '06OG_Z1_003', queried from production module.

order ID	element_ID	Family and Type	Material	Length	Load-bearing capacity	Need time	Supplier
06OG_Z1_003	2177616	Rectangular Columns - I	Concrete - C 50/60 pref	3.150 m	9295.0	2018-04-25 08:00:00	SACAC
06OG_Z1_003	2177618	Rectangular Columns - I	Concrete - C 50/60 pref	3.150 m	6265.0	2018-04-25 08:00:00	SACAC
06OG_Z1_003	2177620	Rectangular Columns - I	Concrete - C 50/60 pref	3.150 m	7185.0	2018-04-25 08:00:00	SACAC
06OG_Z1_003	2177626	Rectangular Columns - I	Concrete - C 50/60 pref	3.150 m	7544.0	2018-04-25 08:00:00	SACAC
06OG_Z1_003	2177628	Rectangular Columns - I	Concrete - C 50/60 pref	3.150 m	6537.0	2018-04-25 08:00:00	SACAC
06OG_Z1_003	2177630	Rectangular Columns - I	Concrete - C 50/60 pref	3.150 m	5904.0	2018-04-25 08:00:00	SACAC
06OG_Z1_003	2177632	Rectangular Columns - I	Concrete - C 50/60 pref	3.150 m	6563.0	2018-04-25 08:00:00	SACAC

Figure 5.6: The example of using the production module

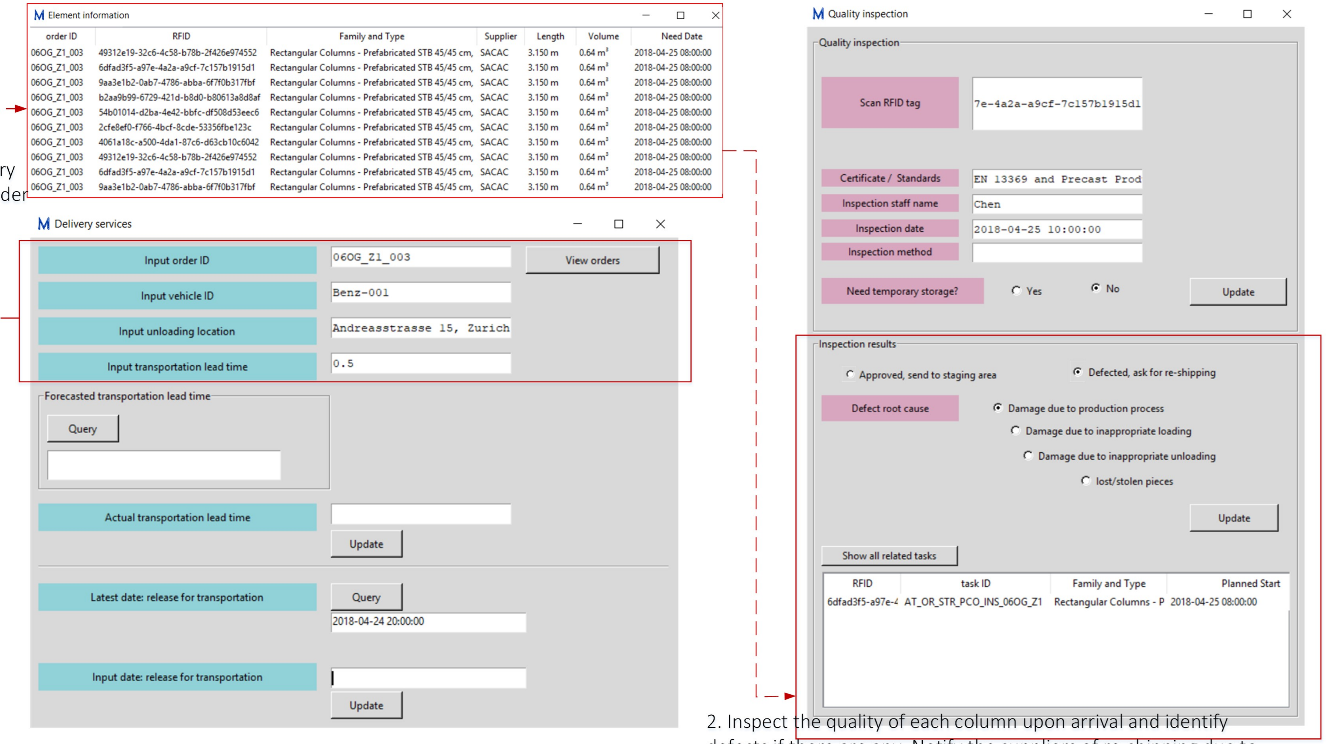
the date, the suppliers updated the transportation lead time linked with the order ID 06OG_Z1_003. Then they queried the latest date to release transport (i.e., milestone 2) based on the latest schedule change (i.e., updated start date of look-ahead tasks) and actual production time, which is '2018-04-24' 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-world projects, the data shown in Figure 5.7 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 due to 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'.

5.5.2 Process illustration and capability evaluation

To illustrate the usefulness of the frameworks shown in Figure 5.1 and Figure 5.2, Monte Carlo simulations were conducted to show and compare the durations of column deliveries in two material flow processes. One is the material flow process using the prototype system to facilitate the coordination of the changes, and the other uses the traditional management framework containing multiple spreadsheets, numerous phone calls and emails. It is worth noting that the simulations were not conducted for validation purposes, due to 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. Although capability assessment was not focusing on validating the real-world workflows, conducting simulations was a simple and effective way to approximately show the different performances of the two material flow processes and show the usefulness of the system.

Monte Carlo simulations have been successfully implemented for process simulations in several construction duration analysis studies [172, 309]. The Monte Carlo simulations with 1000 runs were conducted in this study using RiskyPro-



Element information

order ID	RFID	Family and Type	Supplier	Length	Volume	Need Date
06OG_Z1_003	49312e19-32c6-4c58-b78b-2f426e974552	Rectangular Columns - Prefabricated STB 45/45 cm,	SACAC	3.150 m	0.64 m³	2018-04-25 08:00:00
06OG_Z1_003	6dfad3f5-a97e-4a2a-a9cf-7c157b1915d1	Rectangular Columns - Prefabricated STB 45/45 cm,	SACAC	3.150 m	0.64 m³	2018-04-25 08:00:00
06OG_Z1_003	9aa3e1b2-0ab7-4786-abba-6f7f0b317fbf	Rectangular Columns - Prefabricated STB 45/45 cm,	SACAC	3.150 m	0.64 m³	2018-04-25 08:00:00
06OG_Z1_003	b2aa9b99-6729-421d-b8d0-b80613a8d8af	Rectangular Columns - Prefabricated STB 45/45 cm,	SACAC	3.150 m	0.64 m³	2018-04-25 08:00:00
06OG_Z1_003	54b01014-d2ba-4e42-bbfc-df508d53eec6	Rectangular Columns - Prefabricated STB 45/45 cm,	SACAC	3.150 m	0.64 m³	2018-04-25 08:00:00
06OG_Z1_003	2cfe8ef0-f766-4bcf-8cde-53356fbe123c	Rectangular Columns - Prefabricated STB 45/45 cm,	SACAC	3.150 m	0.64 m³	2018-04-25 08:00:00
06OG_Z1_003	4061a18c-a500-4da1-87c6-d63cb10c6042	Rectangular Columns - Prefabricated STB 45/45 cm,	SACAC	3.150 m	0.64 m³	2018-04-25 08:00:00
06OG_Z1_003	49312e19-32c6-4c58-b78b-2f426e974552	Rectangular Columns - Prefabricated STB 45/45 cm,	SACAC	3.150 m	0.64 m³	2018-04-25 08:00:00
06OG_Z1_003	6dfad3f5-a97e-4a2a-a9cf-7c157b1915d1	Rectangular Columns - Prefabricated STB 45/45 cm,	SACAC	3.150 m	0.64 m³	2018-04-25 08:00:00
06OG_Z1_003	9aa3e1b2-0ab7-4786-abba-6f7f0b317fbf	Rectangular Columns - Prefabricated STB 45/45 cm,	SACAC	3.150 m	0.64 m³	2018-04-25 08:00:00

Delivery services

Input order ID: 06OG_Z1_003
Input vehicle ID: Benz-001
Input unloading location: Andreasstrasse 15, Zurich
Input transportation lead time: 0.5
Forecasted transportation lead time
Actual transportation lead time
Latest date: release for transportation: 2018-04-24 20:00:00
Input date: release for transportation

Quality inspection

Scan RFID tag: 7e-4a2a-a9cf-7c157b1915d1
Certificate / Standards: EN 13369 and Precast Prod
Inspection staff name: Chen
Inspection date: 2018-04-25 10:00:00
Inspection method
Need temporary storage? ○ Yes ● No

Inspection results

○ Approved, send to staging area
● Defected, ask for re-shipping

Defect root cause
● Damage due to production process
○ Damage due to inappropriate loading
○ Damage due to inappropriate unloading
○ lost/stolen pieces

RFID	task ID	Family and Type	Planned Start
6dfad3f5-a97e-4	AT_OR_STR_PCO_INS_06OG_Z1	Rectangular Columns - P	2018-04-25 08:00:00

1. Arrange delivery service for the order '06OG_Z1_003'

2. Inspect the quality of each column upon arrival and identify defects if there are any. Notify the suppliers of re-shipping due to the defect information.

Figure 5.7: The example of using the transport module

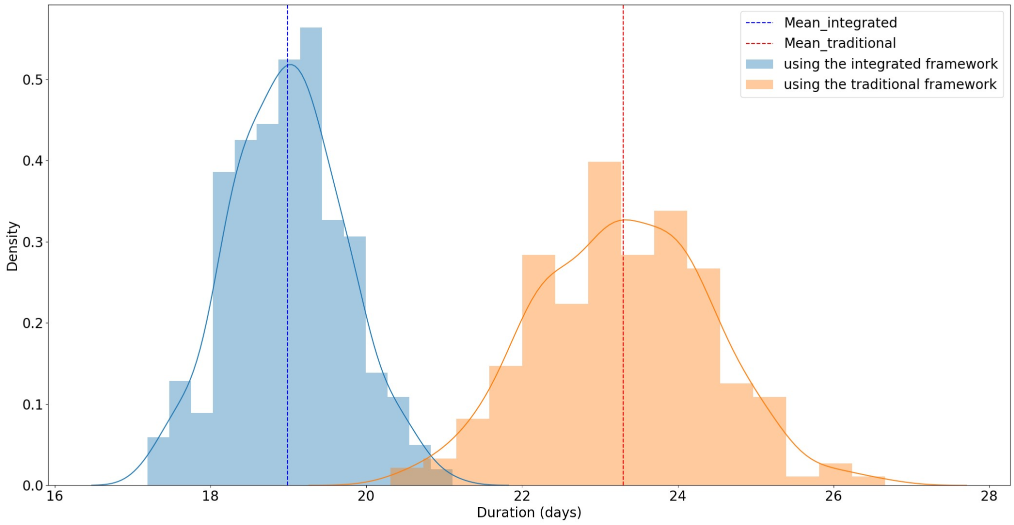


Figure 5.8: The comparison of probabilistic distribution of duration of completing the specific material flow processes between using the integrated management framework and the traditional management framework

ject7 [259], a plugin application in Microsoft Project. The details to establish Monte Carlo simulations in RiskyProject7 will not be described in this paper, however, for more details, the simulation files can be downloaded from [4].

The data collected for the simulations of the durations were based on expert opinions from two construction professionals with over five years of work experience in prefabricated building projects. The data and the scheduling charts for the simulations are presented in Figure B.1 in the Appendix B. The scheduling charts were derived from Figure 5.1 and Figure 5.2 by simply converting flowcharts into Gantt charts while maintaining the precentral relationships between steps. The data were rough estimations derived from their experience on respective daily workflows (P1 to P6) concerning the example material orders (06OG_Z1_003 and 06OG_Z2_001). The probabilistic distributions of the milestone dates (e.g., the milestone1 and milestone2) were estimated based on expert experiences, which were subjective but representative for the simulations.

Figure 5.8 shows the comparison of probabilistic distribution of duration of completing the specific material flow processes between 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’.

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[4] Monte Carlo simulation of duration of material flow processes using RiskyProject7 (2020), Available for downloading at: https://drive.google.com/drive/folders/15Rsf7FFZqRjaozkpX1Meqleao1qUzOrP?usp=sharing

5.6 Discussion

5.6.1 Agility of ETO supply chain coordination

The prototype for the integrated management framework equips stakeholders with the ability to respond fast to last-minute changes, due to 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 addressed quickly without delaying the site schedule. Using the system, the major stakeholders can be responsive and proactive to changes.

5.6.2 Efficiency of ETO 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 substantial reduction in the time required to deal with required changes when delivering engineer-to-order 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) [187] 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.

5.6.3 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) [185] and Graham et al. (2019) [116], 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 accommodate specific projects, including ones of larger sizes. Due to 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 amongst different project stakeholders could be managed most effectively.

5.6.4 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. 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 utilized 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

[121], 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 [145].

5.7 Conclusion and future work

This paper presented a framework for an integrated management system to use information from BIM and RFID to support 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, the prototype system was devised consisting of four functional modules; (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. The highlighted features of the system were the functionalities to capture change information and make materials deliveries respond quickly to changes in the near term. From the theory point of view, the development of the framework is a concrete demonstration of lean construction theories, and the system improves upon traditional processes.

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. The integrated management framework can help suppliers and contractors to reduce the burdensome work of exchanging information and improve agility in coordination.

The usefulness of the framework and system functionalities were demonstrated only in a fictive example where there were changes in the design of the prefabricated columns and in the schedule as to when they are to be delivered on site. 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. Also 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 modelling and discrete event simulations could be studied to reveal the process dynamics and the interactions between the major stakeholders during collaboration.

PART III

Improve bulk material flows

CHAPTER 6

Supplier-contractor coordination approach to managing demand fluctuation of ready-mix concrete

This chapter corresponds to the published article:[1]

Chen, Q., García de Soto, B. and Adey, B.T. (2021). Supplier-contractor coordination approach to managing demand fluctuation of ready-mix concrete. Vol 121, Article No. 103423, doi: 10.1016/j.autcon.2020.103423

Abstract

Although advancements have been made in the management of projects due to the digitalization and automation technologies, the efficient use of digital data is still lacking for the coordination of the supply chain. This paper presents an approach that allows data-driven and schedule-oriented supply chain coordination in the face of demand fluctuations. The approach consists of two main steps that contractors should take: 1) monitor the demand fluctuations based on a 4D model that captures the as-built status and updated look-ahead schedules, 2) make decisions to modify original orders to accommodate the demand fluctuations where orders are determined by a heuristic evolutionary algorithm. As a proof of concept, the coordination approach is demonstrated using an example project featuring a five-day in-situ construction of concrete walls. Results from this example show that using the approach improves the responsiveness of concrete planning and ordering. As a result, this leads to improved collaboration between suppliers and contractors in construction projects.

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[1] Please note, this is the author's version of the manuscript published in the Journal of *Automation in Construction*. For the reasons of consistency, the style of this chapter matches that of the dissertation. Changes resulting from the publishing process, namely editing, corrections, final formatting for printed or online publication, and other modifications resulting from quality control procedures may have been subsequently added. When citing this chapter, please refer to the original article found in the reference above.

6.1 Introduction

There has been a rise in the use of prefabrication and modularization processes in construction projects, the cast-in-situ concreting activities, however, remain to dominate the construction industry on account of great convenience, ease of use, and good quality of ready-to-mix concrete [336]. The global concrete (hereafter referred to as concrete) consumption in the construction industry costs was around USD 656.1 billion in 2019 [257]. Nonetheless, a significant amount of the concrete was not efficiently used as planned and, therefore, was wasted, leading to project cost overruns. Multiple reasons may explain the wastes, and one main reason is the lack of coordination of material supply and demand [298, 243]. The supply chain of construction materials, especially when it comes to perishable materials such as concrete, is usually difficult to coordinate [303]. Unlike prefabricated components that have a longer lead time for the coordination of design and delivery, concrete deliveries need much less lead time but leave little room for variability in the time for concrete placing on site [351, 196]. The quality of concrete decays rapidly during the delivery processes, which requires a highly responsive environment to coordinate its supply and demand.

In practice, project contractors and delegated concrete batch plants have to proactively coordinate information to enable good timing and reliability of concrete deliveries [311, 225]. These include time considerations such as the continuously changing speed of site installation processes, the accuracy of concrete take-offs and orders, and the communication intensity between concrete batch plants and the site [222, 19]. However, it is very challenging to achieve those aspects in current practice. On the one hand, the contractor typically orders, many days in advance, large quantities of construction materials (e.g., concrete) based on a rough static site schedule for a long planning horizon. As the construction progresses, the schedule and associated material demand have to be updated according to the current work status (i.e., as-is conditions) without the supplier being notified on a regular or timely basis. Therefore, most of the time, the supplier has to produce concrete on a static ordering plan with no systematic feedback from the site. On the other hand, the concrete batch plants have to be optimally configured to meet a number of clients' schedules to avoid idle time for production lines, trucks, and drivers. When demands are changed, the production schedules are adjusted, and the batch plants will have to quickly respond to meet the changing requirements from the contractors. Due to these complex interdependencies, the contractors and the suppliers always fail to ensure a good balance of supply and demand [195]. As a result, the concrete is delivered either too much, causing a waste of unused concrete on site, or too little to meet the changing demand. This has presented considerable challenges in the coordination processes to allow concrete supplies to be driven by dynamic site needs.

Some researchers have developed coordination theories to help stakeholders understand and improve the coordination processes. For example, Simatupang et al. [280] conceptualized coordination as the actions of decision synchronization to resolve conflicting objectives, mitigate uncertainty, redesign workflow, and allocate resources. Therefore, following this theory, the contractors and the suppliers are encouraged to share knowledge and make decisions collaboratively to sense the uncertainties quickly and ensure the schedule-driven material supplies [193, 54]. In particular, suppliers need an approach to collaborate on pulling the varying concrete demands and site schedules from the contractors.

Current ways for collaboration have been still dominated by traditional approaches, which include piles of paperwork about the account code description, field-required date, responsible supplier, and quantities of the required materials. These processes are extremely slow as they take approximately 20–30% of the feeders' daily efforts to update the actual demands [111]. To overcome these problems, researchers have advocated the use of a collaborative/common data environment that is designed based on emerging digital and automation technologies [52]. For example, Building Information Models (BIM) based platforms are ideal for handling the large quantity of information required to coordinate the material supply and demand, which would function as the information hub to enable a quick exchange of information in formats consistent with the needs of coordination [237, 266]. Furthermore, the integration of BIM with wireless transmission technologies, such as radio frequency identification and Bluetooth low energy technologies, has been investigated to achieve information visibility during material coordination [297, 51]. Other technologies have focused on construction progress monitoring and control, such as Scan-to-BIM based on laser scanning, photogrammetry, and digital image processing technologies [38, 171]. Although these technological developments are useful to automate information flows, they have not been effectively used in a way that supplies are coordinated to fulfill the fluctuating demands from the site and the value of information has not been fully exploited to support joint decision-making activities [155, 156]. The data-driven decisions to balance supply and demand have been missing from the current practices. However, great potentials would be foreseeable if the data from these integrated digital platforms could be properly used by both contractors and suppliers to support data-driven, schedule-oriented, and collaborative decision makings.

To realize that, this paper develops a two-step coordination approach for suppliers and contractors to improve concrete delivery at the minimal cost with a consideration of the demand fluctuations over the dynamic construction processes. The first step is to monitor the demand fluctuations based on 4D models that capture the as-built site progresses and updated look-ahead schedules. The second step is to make decisions to modify original concrete orders at a demand fluctuation where quantities of extra-orders and outsourcing orders are determined by a heuristic evolutionary algorithm. Since this research focuses on the method to coordinate material supplies under demand fluctuations within a 4D modelling environment, the detailed analysis of the data interoperability and legal issues are beyond the main research scope. The proposed coordination approach contributes to the current body of literature by achieving two specific objectives:

- through Step 1, the data from 4D models are organized to generate information about demand fluctuations promptly, which increases the responsiveness of contractors;
- through Step 2, the collected data are used directly in a heuristic process to calculate material supplies subject to minimal costs, which increases the reliability of joint decisions to accommodate the demand fluctuations.

The remainder of the paper is structured as follows. Section6.2 contains a comprehensive review of the literature concerning the capabilities and potentials of 4D models and heuristic models that improve the concrete deliveries with a different focus, followed by the research gaps identified in a summary of the relevant works. Section 6.3 describes the details of the proposed supplier-contractor coordination approach, which includes two steps for the contractor to manage the order quantities under demand fluctuations. Section 6.4 contains an example demonstration of the coordination approach as a proof of concept. Section 6.5 presents a discussion of the strengths and weaknesses of the coordination approach. Section 6.6 contains the conclusions of the work and proposals for future work.

6.2 Literature review

Methods related to the improvement of the construction supply chain processes can be broadly grouped in two categories: 1) the advanced technologies that facilitate the monitoring of site progress and real-time coordination of material delivery, and 2) the heuristic models that improve decision-makings on optimal material supply quantities and delivery times at minimal costs. The following subsections provide an overview of the advancements in those areas.

6.2.1 Capabilities and potentials of advanced progress monitoring approaches

Progress monitoring is an essential part of supply chain processes, which has been extensively studied together with 4D BIM. 4D BIM is favored because it provides a data-rich, object-oriented, intelligent, and parametric digital representation of the facility to associate with time (schedule) information, which could support data-driven decision making for supply chain processes [106].

One trending approach to develop 4D models is to combine recognized 3D objects during laser scans (also referred to as Lidar or LiDAR) with the planning information in BIM authoring software before construction [168]. For masonry blocks and concrete walls, Golparvar-Fard et al. [112] and Turkan et al. [314] found that this type of system can obtain over 95% accuracy for fitting scanned object point clouds to as-built 3D objects, which exceeds typical manual performance. But it relies heavily on manual interventions to perform synchronization between the two models (e.g., as-built scanned point cloud and as-planned models). The problem could be alleviated by advanced digital image processing algorithms and 3D object recognition technology. For example, Brilakis et al. [40] and Maalek et al. [206] demonstrated that the synchronization processes become less time consuming, and accuracy can reach more than 99%. As an alternative approach, Vick and Brilakis [322] used drone photography to construct 4D models from the recognition of the structural objects from the site photos.

However, previous research did not specifically highlight the conflicts between project planning and execution. To address this, Mengiste and García de Soto [219] developed the rate of color evolution of a point cloud method to monitor the performance of construction trades. To further refine the work monitoring and planning, Hamzeh et al. [123] and Goh and Goh [110] implemented a lean approach to identify a precursor to task execution. Furthermore, Sacks et al. [268] and Heigermoser et al. [134] integrated the lean approach (e.g., last planner system) with 4D models for task assignments in short-term look-ahead weeks. In this direction, Bortolini et al. [37] extended the approach with logistic information to improve site logistic planning of engineer-to-order prefabricated building systems. The combination of 4D models with lean principles could provide an amount of realistic site information, which improves the efficiency and reliability of progress monitoring of site works.

Besides the emphasis of onsite work, relevant studies on 4D models presented their potentials to help contractors automatically and accurately monitor the supply chain progresses. For example, Li et al. [187] explored the synergic interaction between the automatic quantity take-offs in the 4D models and the material delivery information from RFID tags in prefabricated construction projects. A similar study was carried out by Deng et al. [76], which focused on the optimization of the number of material deliveries and suggested the necessity of locating consolidation centers in congested regions with long material delivery distances. These studies showed the capabilities of 4D models to improve the visibility of material status and facilitate collaborative decision making between suppliers and contractors. Apart from those studies on prefabricated materials, a recent study by Sheikhkhoshkar et al. [276] with the closest alignment to the topic of 4D models for concrete planning also reveals the potentials of 4D models. They provided cost-effective design solutions that take into account the need to order and schedule the correct volumes of concrete. But their focus was to combine site operational data with concrete design considerations instead of the supply re-arrangements. The supply problems due to the material demand uncertainties remain not adequately addressed.

Though 4D models have been used to improve the supply chain processes in different perspectives, it remains challenging for the project contractors to know how to effectively use the digital data to support the coordination and navigate decision making for concrete deliveries. The data collected from 4D models could be used as an important premise to reflect the dynamically changing material demands. There is room for improvement by using 4D models in the concrete supply chain as well as developing efficient algorithms to enhance decision making considering its progress uncertainties.

6.2.2 Capabilities and potentials of heuristic models

A large body of literature emphasized on implementing various heuristic models as well as meta-heuristic models to enable data-driven decision-making processes to improve supply chain performance. In particular, these models have been extensively used to address the supply disruption and demand fluctuation problems and optimize the purchasing, tracking, and dispatch sequencing of concrete. This stream of research mainly tackles the problem of integrating concrete production (i.e., supply quantities and schedules) and truck dispatching to the site, which can be formulated as a complex NP-hard optimization problem. Many related works contain efficient heuristic optimization models or algorithms, such as the commonly used ant/bee colony algorithms, genetic algorithms, and simulate annealing algorithms. It is, however, worth noting that these heuristic algorithms differ in computational time and quality of achieved solutions for specific problem descriptions. While as indicated by most relevant studies, the basic implementation steps and effectiveness of the algorithms are pretty much similar.

To be more specific, most relevant studies considered the just-in-time delivery of concrete as a job shop problem where the construction sites send concrete orders as the jobs to be processed [348]. When they formulate the math models for the heuristics, each concrete delivery represents a job operation carried out by one of the trucks that corresponds to a workstation. The ultimate goal is to satisfy the material demand with minimal cost or minimal time. It is also worth noting that these are considered as non-convex NP-hard math problems, and heuristic models are efficient in giving good feasible optimal results. Other than the mainstream heuristic models, new methods such as augmented balance point diagrams are also available to match site progress with concrete supplies [18]. Since heuristic models received more attention in the research area, this paper would only emphasize the discussion of the potentials of heuristics.

With the advancements in the area of operations research, several heuristic models have been built available for optimizing purchasing, trucking, and dispatch sequencing of concrete. For example, Maghrebi et al. [209] developed a model based on ensemble machine learning algorithms to automatically match expert decisions for concrete dispatching. But this approach may have rejected a particular optimal solution even though it could have been made to work. Naso et al. [228] and Liu et al. [198] built a genetic algorithm model to find the best dispatch schedule and truck allocation that minimized the total waiting time for-trucks at a site while satisfying the need for deliveries to other sites without interrupting the concrete casting operation. In addition, Maghrebi et al. [208] found that the column generation algorithm can attain near-optimal solutions for concrete dispatching within the allowable time window. They also found that it was still challenging to reduce the complexity of the heuristic process for concrete dispatching problems. Besides, even though multiple heuristic algorithms have been used for different case studies, most of them were based on known demand, and thus the uncertainty in demand was neglected.

To address that, researchers have also explicitly modeled supply chain uncertainties in the heuristics processes. For example, Li et al. [188] used a heuristic cost minimization model to compare and select proactive and reactive strategies for supply disruption management. How the lead time of backup sources, disruption starting time, cost of lost sales, backup costs, and extra-order rate impact the dynamic strategies have been thoroughly explored in their study. Paul et al. [245] extended heuristic models for material supplying to be capable of dealing with multiple demand fluctuations on a real-time basis, where a new occurrence may or may not affect the revised plan of earlier occurrences. In this direction, a study by Chakrabortty et al. [46] found that project scheduling can be well optimized via heuristics under dynamic environments and highlighted the priority rules required in scheduling. Therefore, the use of the heuristic approach could provide reliable solutions to the management of uncertainties, which should be further considered in the management of demand fluctuations.

As different algorithms continue to advance in this area, a relatively new approach called Covariance Matrix Adaptation Evolution Strategy (CMA-ES) was developed by Hansen et al. [126] and considered to have potential to avoid local optimal results for engineering control cases [136]. There has yet been little evidence using this algorithm for construction supply chain optimization. Using CMA-ES in this research can be viewed as a starting point to investigate advanced heuristic approach in manufacturing domain for the supply chain optimization in construction projects.

Multiple studies presented strong evidence about the usefulness of various heuristics for optimizing concrete purchasing, trucking, and dispatch sequencing of concrete to satisfy the dynamically changing demand. Therefore, heuristic models would be considered as important and complementary means to navigate decision making when used together with 4D models.

6.2.3 A summary of relevant works

A summary of relevant works is presented in Table 6.1. The summary highlights that both 4D models and heuristic models can improve the supply chain processes from different perspectives. However, there is a dearth of research to explore the capabilities of 4D models together with heuristic models to improve concrete deliveries with consideration of demand fluctuations. Although these technological developments are useful to automate information flows, they have not been effectively used in a way that supplies are coordinated to fulfill the fluctuating demands from the site. The data-driven decisions to balance supply and demand have been missing from the current practices. The great potentials, nevertheless, would be foreseeable if the data from these integrated digital platforms could be properly used by both contractors and suppliers to support data-driven, schedule-oriented, and collaborative decision makings.

First, 4D models enable visibility of information to the construction site and supply site. Then the information could be used directly for optimal decision-making processes during supplier-contractor coordination. To utilize data in the best way, this research develops a two-step approach to focus on two objectives:

- the data from 4D models are organized to generate information about demand fluctuations promptly, which increases the responsiveness of contractors;
- the collected data are used directly in a heuristic process to calculate material supplies subject to minimal costs, which increases the reliability of joint decisions to accommodate the demand fluctuations.

On this basis, this research would contribute to the existing body of literature regarding supply chain optimization, particularly in the face of uncertainties.

6.3 The supplier-contractor coordination approach

6.3.1 General description of the approach

The design framework of the supplier-contractor coordination approach is illustrated in Figure 6.1. The complete implementation processes are illustrated in Figure B.2 in the Appendix B, which includes the specific roles and responsible workflows by the site trades, general contractor, and material supplier. Figure B.2 follows the Business Process Model and Notation (BPMN) standard[2]. The sub-processes in each swimlane represents a participant. The flows between the swimlanes (i.e., the participants) represent the information flows needed between

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[2] Object Management Group, Business Process Model and Notation, available at `http://www.bpmn.org/`

Table 6.1: A summary of relevant works

Papers	**Research focus**	**Main approach**	**Highlights of potentials**	**Supply chain perspective**	**Material Type**
This research	Cost-efficient coordination system for concrete ordering and production	Heuristic optimization and 4D BIM prototype demonstration	Improved decision-making capabilities and responsiveness for concrete deliveries under demand fluctuations	Ordering, production function, and site installation function	Ready-mix concrete
Sheikhkhoshkar et al. (2019)	Temporary structure design and concrete placing with 4D BIM	Parametric programming and 4D BIM prototype demonstration	Automation methods to improve efficiency in concrete placement designs	Site installation function	
Naso et al. (2007) Yan et al. (2011) Maghrebi et al. (2015) Maghrebi et al. (2016) Liu et al. (2017)	Cost-efficient coordination system for optimal scheduling of concrete delivery trucks	Heuristic optimization	Improved decision-making capabilities for scheduling of concrete delivery trucks	Delivery function with a focus on the site logistics	
Bosché (2010) Golparvar-Fard et al. (2011) Brilakis et al. (2011) Turkan et al. (2012) Kim et al. (2013) Vick and Brilakis (2018) Mengiste and García de Soto (2018) Bortolini et al. (2019) Deng et al. (2019) Maalek et al. (2019)	Real-time monitoring and tracking of dynamic site processes to enhance supply chain integration	4D BIM prototype demonstration	Improved information visibility and material tracking capabilities	Delivery function and site installation function	Prefabricated elements and other types of materials
Sacks et al., (2010) Hamzeh et al. (2015) Goh and Goh (2019) Heigermoser et al. (2019)	Site progress monitoring and schedule optimization through lean principles, e.g., last planner system	Lean approach and 4D BIM prototype demonstration	Improved process stability and planning reliability	Site installation function	
Paul et al. (2014) Li et al. (2017) Chakrabortty et al. (2020)	Risk hedging strategies under supply chain uncertainties (i.e., supply disruption and demand fluctuation)	Heuristic optimization	Improved decision making and risk management of supply chain behavior and performance with less cost	Ordering and production function	

two sub-processes. The design framework in Figure 6.1 is the simplification of the detailed processes in Figure B.2. With the design framework, the proposed coordination approach is formulated to manage the quantities of the materials to be ordered subject to demand fluctuations in a look-ahead X-day planning window. The changing demand should be fulfilled at a minimal cost by both the supplier and the contractor.

To build the coordination approach, several assumptions are made here to clarify its applicability:

- The two-echelon supply chain structure is considered instead of a multi-layer one. The supply chain contains one supplier and one contractor for the model simplification purpose. The contractor outsources a third party supplier on an as-needed basis.
- The supplier and the contractor have already agreed on sharing information via a central database to support collaborative decision making. The supplier needs to share production data such as the available idle time, extra-order unit cost, and production capacity. The contractor needs to

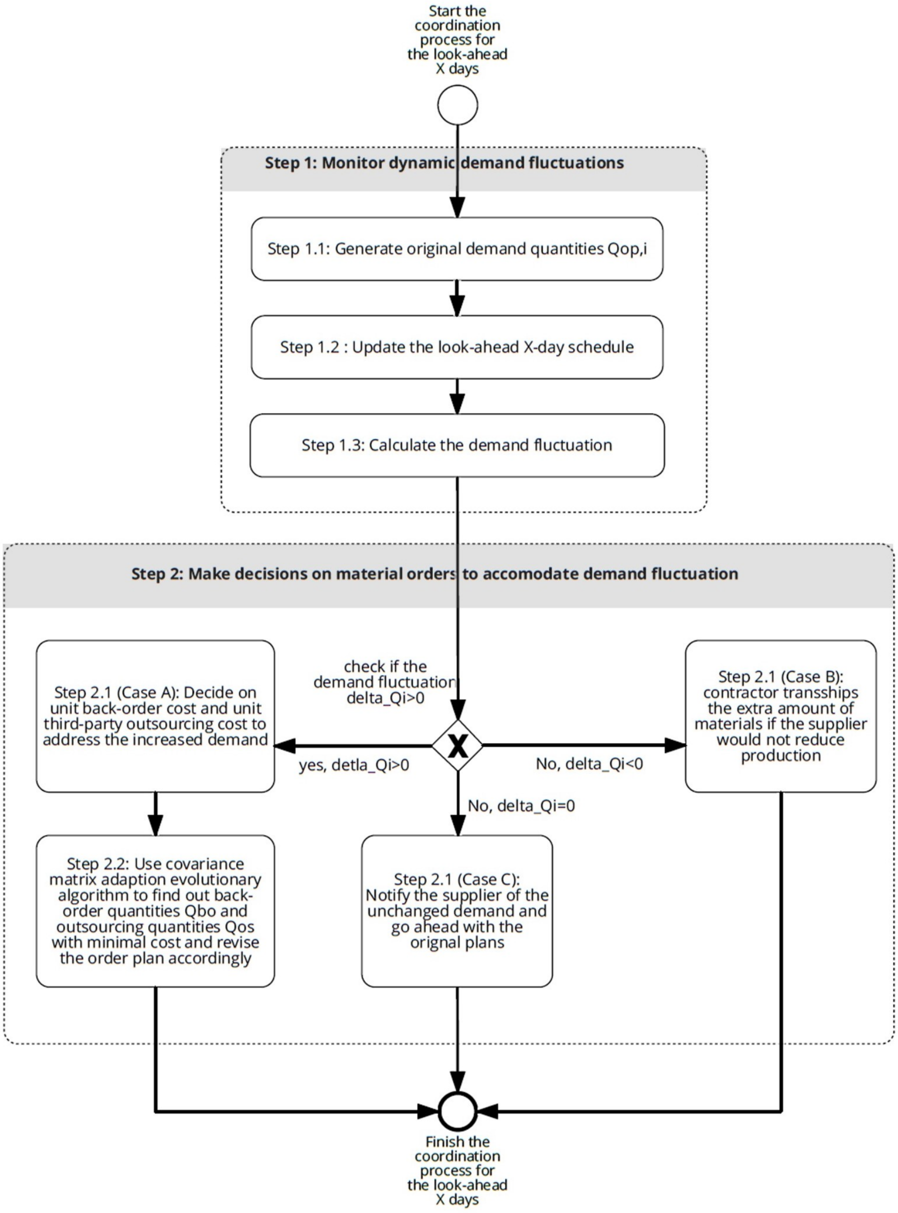

Figure 6.1: The design framework of the supplier-contractor coordination approach

share data about demand fluctuations. The specific roles and responsibilities of the supplier and the contractor have been defined for the use of the database. Besides, an integrated contractual framework is encouraged to regulate their roles and responsibilities.

- The contractor does not have onsite areas for producing the concrete; instead, the contractor tends to outsource the concrete.
- The contractor will not change the supplier for the originally ordered quantities during the material planning and coordination processes, and the extra-ordering process is done with the same supplier.
- The supply of concrete is a lot-for-lot system, which means the supplier produces and transports the whole batch of concrete at the end of a production run. A lot is associated with a task ID in this study.
- Since the look-ahead scheduling window is quite short, the cost minimization does not take into consideration the inflation rate over a specific period.

Step 1 of the approach, which is to monitor the dynamic demand fluctuations using a 4D model, requires the update of a short term X-day look-ahead schedule, which is based on a comparison between the as-built site progress captured by automation technologies and the original (i.e., as-planned) schedule. The demand fluctuations are determined from updated material quantities based on the updated schedule. In step 2, which is to decide what actions to take when the demand fluctuations are observed, three cases to be considered: 1) (Case A) when there is an increasing demand in the updated X-day look-ahead schedule, 2) (Case B) when there is a decreasing demand, and 3) (Case C) when there is unchanged demand (i.e., no fluctuations), in the update X-day look-ahead schedule. This paper focuses on the description and discussion of Case A, as it occurs more often in construction projects and is more challenging to tackle. For a better understanding of the demand fluctuation problem, the definitions of the terms used in this paper are provided below:

- **X-day look-ahead schedule**: the schedule that includes the tasks to be done and being committed in the following X-day planning window. In practice, the X-day look ahead plan is updated weekly (e.g., every Friday). The required material quantities are derived based on those tasks.
- **Revised order plan**: if demand is increasing in the updated look-ahead schedule for the following X days, the contractor has to revise the order plan and inform the supplier of the new quantities to be produced for the site. The revised order plan includes the quantities of materials to be extra-ordered, the quantities of materials to be outsourced, and the quantities of materials that are originally planned. The quantities in the revised order

plan are determined by evaluating the costs of the extra-ordering and the costs of outsourcing.

- **Extra-ordering**: if the demand is increasing, the portion of the demand that cannot be fulfilled in the original order plan, but that will be delivered after the supplier agrees to provide that additional amount due to the adaptation to their batch production line. To save time for production, the supplier will make the best use of its idling time for the production of extra-ordering quantities. The supplier and the contractor negotiate the extra-order unit cost (i.e., the unit cost for the additional portion).

- **Outsourcing**: if the demand is increasing, the portion of the demand that cannot be fulfilled in the original plan, but that will be delivered an outsourced (i.e., third party) supplier besides the extra-ordering portion. The contractor determines the third-party supplier. The outsourcing unit cost is usually higher than the unit cost by the original supplier because outsourcing suppliers may have stronger bargaining power.

- **Lost site productivity**: if the demand is increasing and the extra-ordered or outsourced quantities cannot be delivered as of the concrete need date, then the site has to delay the associated tasks and lose the productivity for a certain period. The delayed period is equal to the additional time to provide the additional quantities if the total of extra-order quantities and outsourcing quantities are smaller than the increased demand quantities

6.3.2 Nomenclatures

In this paper, the following notations (Table 6.2) are used to formulate the math model for the coordination approach.

Table 6.2: Nomenclatures for this research

Notation	Description	Unit of measure
i	The indices for the task ID, the i^{th} task ID in the X-day look-ahead schedule. To simplify the calculation, one task ID represents the one-day concrete installation of a specific type of concrete placing work.	-
M_i	The total number of element IDs that belong to the i^{th} task ID	-
N	The total number of the task IDs in the X-day look-ahead schedule	-
PD	The total number of uncompleted precedential tasks	-
Q_{ele}	The volume of an individual building element modeled in BIM authoring software	m^3
$Q_{d,i}$	The delayed quantities that are carried forward into the following X days	m^3
ΔQDC_i	The added or reduced quantities due to design changes for the non-started tasks	m^3
p	The production rate for producing concrete in the supplier's batch plant	m^3/day
t_{idle}	The idle production time that is available for the supplier to use for producing additional concrete (i.e., the extra-ordered quantities)	day
c_p	The unit cost for producing the concrete in the supplier's batch plant	USD/ m^3
c_{bo}	The unit cost for producing the extra-ordered quantities of concrete in the supplier's batch plant	USD/ m^3
c_{os}	The unit cost for producing the outsourced quantities of concrete in the third party supplier's batch plant	USD/ m^3
c_{lp}	The unit cost for losing onsite productivity that is estimated by the contractor when the increasing concrete demand is not fulfilled by either extra-order or outsourcing	USD/ m^3
TC_p	The total costs of producing the concrete in the supplier's batch plant	USD
TC_{bo}	The total costs of producing the extra-ordered quantities of concrete in the supplier's batch plant	USD
TC_{os}	The total costs of producing the outsourced quantities of concrete in the third party supplier's batch plant	USD
TC_{lp}	The total costs brought by losing onsite productivity when the increasing concrete demand is not fulfilled	USD
TC	The total costs incurred by both the supplier and the contractor to fulfill the site demand for the look-ahead X-day tasks	USD
$Q_{op,i}$	The concrete quantities calculated from the original schedule for task i for the following X-day planning of installation tasks onsite	m^3
$Q_{up,i}$	The concrete quantities calculated from the updated schedule for task i for the following X-day planning of installation tasks onsite	m^3
ΔQ_i	The differences between $Q_{op,i}$ and $Q_{up,i}$, which indicates the demand fluctuations for task i observed from the updated look-ahead schedule.	m^3
$Q_{bo,i}$	The quantities of concrete that should be extra-ordered from the supplier for task i after the occurrence of the increasing demand	m^3
$Q_{os,i}$	The quantities of concrete that should be outsourced from a third party supplier for task i after the occurrence of the increasing demand	m^3
$Q_{lp,i}$	The quantities of concrete that cannot be fulfilled other than extra-ordering and outsourcing, which inevitably leads to losing site productivity of installation tasks	m^3
$Q_{ro,i}$	The total order quantities with the same supplier, consisting of the originally ordered quantities and the extra-order quantities, which is defined as the reordered quantities with the same supplier.	m^3
γ	The production reliability at the batch plant considering the possible rejected products due to quality defects	-
α	The accuracy of automatic recognition of site progresses using the well developed Scan-to-BIM technologies	-
β	The material usage conversion factor	-

6.3.3 Step 1 - Monitor dynamic demand fluctuation from 4D models

To track the dynamic demand fluctuations, it is necessary to track the construction progress regularly. 4D models that combine three-dimensional point clouds with the 3D design model in BIM authoring software are used that particularly features X-day look-ahead schedules. The point cloud data represent the as-built status or the finished and ongoing status of a group of tasks. The 3D design model linked with the look-ahead schedule represents the as-planned status of the same tasks. Based on the as-planned status, the original demand quantities of these tasks $Q_{op,i}$ can be calculated. Based on the comparison between the as-built status and the as-planned status, the X-day look-ahead schedule should be updated. According to the updated schedule, the updated demand quantities of these tasks $Q_{up,i}$ can be computed. Therefore, the demand fluctuation for each task ID can be obtained from $Q_{op,i}$ and $Q_{up,i}$. The detailed processes are described in the following subsections.

Step 1.1- Generate original demand quantities $Q_{op,i}$

The original demand quantities $Q_{op,i}$ are derived from an original X-day look-ahead plan. The look-ahead plan contains information about the task IDs, the description of the task, the originally planned start date, and the planned finish date. Each installation task has a unique task ID, the design of which is shown in Figure 6.2. Because the look-ahead schedule is usually used for planning of tasks at a high granularity level, each task ID should be assigned to represent the required installation work on each specific day. In the BIM authoring software, building objects are modeled parametrically, and therefore each building object has a unique element ID. A task ID can be associated with a group of different element IDs in the 3D model. By mapping the task IDs to elements IDs in the BIM authoring software either manually or using a rule-based mapping method (e.g., rule-based mapping in Autodesk Navisworks), the quantities of the material (i.e., concrete) for a specific task can be automatically computed using its built-in schedule function. For each day in the following X-day planning window, which is represented by a unique day ID, the original demand quantities for each task ID can be summarized to obtain the total original demand quantities of the material on each day indexed with a day_ID. The data-entity-relationship model is presented in Figure 6.3, which shows the linkage between the X-day look-ahead schedule, the building object information in the 3D model, and the original demand quantities. The original demand quantities $Q_{op,i}$ can be obtained according to Equation 6.1.

$$Q_{op,i} = \sum_{ele=1}^{Mi} Q_{ele}; i = 1, 2, ...X \tag{6.1}$$

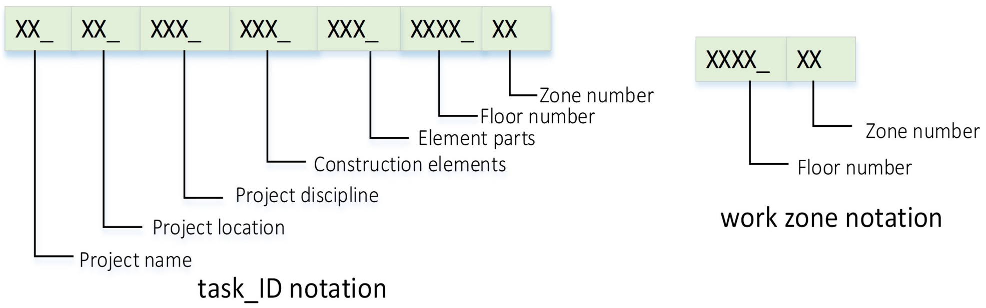

Figure 6.2: The design of the task ID

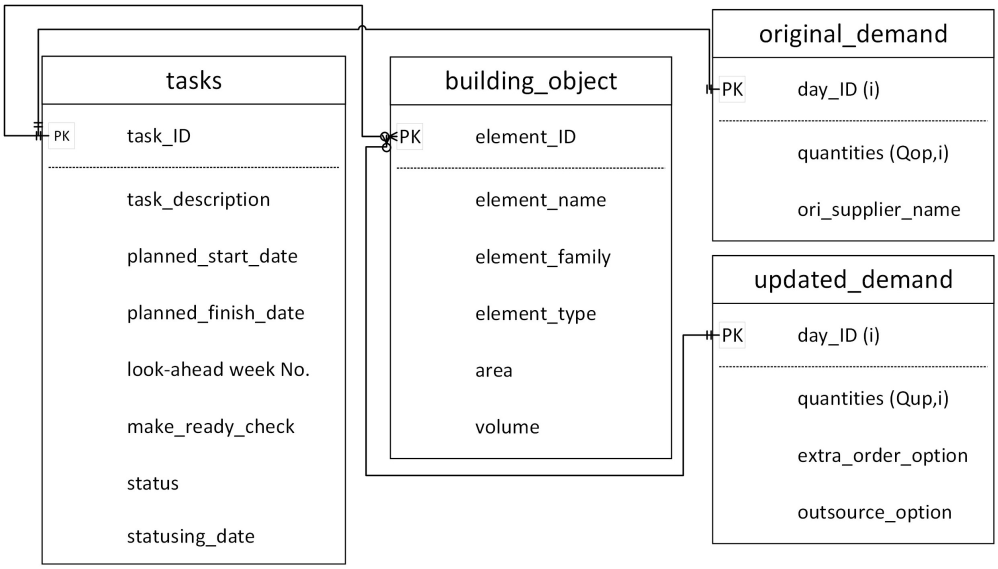

Figure 6.3: The data-entity-relationship model to show the linkage between the look-ahead schedule, the 3D model and the original demand quantities

Step 1.2- Update look-ahead X-day schedule

For each task ID, the system compares the quantities of recognized objects in the point cloud data with the quantities of planned objects, i.e., scheduled and linked with task IDs in the original look-ahead schedule. Since the object recognition based on point cloud data is not perfect due to the occluded surfaces or limited scanning ranges, the calculation of the actual site progresses incorporates an accuracy factor, α. If the quantities of planned objects for task ID i is equal to zero, then the recognized as-built progress is assigned as 0%. Otherwise, the recognized as-built progress for task ID i at the scanning date is calculated according to Equation 2. It is noted that the quantities of the planned object should be calculated according to the laser-scanned date, as shown in Equation 6.3. If the recognized as-built progress is smaller than 100%, the originally planned tasks are behind schedule, meaning there is a delay. The delayed quantities are calculated by Equation 6.4, and they need to be carried forward into the upcoming planned dates. In Equation 6.2, if $\{obj_{recog}\}_i$ is found to be greater than $\{obj_{plan}\}_i$, the originally planned tasks are ahead of schedule. The tracking of each task status can be obtained from Equation 6.5. Either for the case of delay or the case of the ahead of schedule, the contractor will discuss with the site trades to update the following X-day look-ahead schedule for the non-started activities. If necessary, the precedential relationships and critical path should be re-evaluated based on the monitored task status. The information from the updated look-ahead X-day schedule, together with the data attribute relationships, is stored in the central database (e.g., MySQL database). The database is then connected to the parametric models in Autodesk Revit through the Dynamo programming interface to enable the automatic information exchange and the updates among different stakeholders.

$$prog_{i,recog} = \frac{\| \{obj_{recog}\}_i \cap \{obj_{plan}\}_i \|}{\| \{obj_{plan}\}_i \|} * 100\%, when \{obj_{recog}\}_i \leq \{obj_{plan}\}_i \tag{6.2}$$

$$obj_{plan,i} = \frac{\| Scandate - PlanStartdate \|_i}{\| PlanFinishdate - PlanStartdate \|_i} * Q_{op,i} \tag{6.3}$$

$$Q_{d,i} = (1 - prog_{i,recog} * \alpha) * Q_{op,i} \tag{6.4}$$

$$task\_status = \begin{cases} ahead\_of\_schedule, & \{obj_{recog}\}_i > \{obj_{plan}\}_i \\ on\_schedule, & prog_{i,recog} = 100\% \\ delayed, & prog_{i,recog} < 100\% \end{cases} \tag{6.5}$$

Step 1.3- Calculate demand fluctuation

With the updated X-day look-ahead schedule, the updated demand quantities can be derived using the same process that calculates the original demand quantities based on Equation 6.1. As the delayed quantities from the previous (i.e., precedential tasks) uncompleted are carried forward into a specific i^{th} task in the following X days (represented as $Q_{d,i,pre}$), the demand fluctuation in the next day should include the total of the delayed quantities of these uncompleted precedential tasks. It is noted that the needed quantities should be calculated considering a material usage factor, β. Besides, the newly planned tasks in the X-day planning window may be subject to design changes of related elements; therefore, the originally designed quantities for that task may change, which is represented as ΔQDC_i. The delayed quantities from the uncompleted precedential tasks and ΔQDC_i constitute the total demand fluctuation for task ID i. If the total number of uncompleted precedential tasks is PD, then the demand fluctuation can be computed using Equation 6.6. The delayed quantities for previously planned tasks are carried forward together with the non-started started tasks in the following X days. Therefore, the delayed quantities constitute a part of the demand fluctuation when there are any delayed tasks in the former X-day planning window.

$$Q_{d,i} = (1 - prog_{i,recog} * \alpha) * Q_{op,i} \tag{6.6}$$

6.3.4 Step 2 - Make decisions on material orders to accommodate demand fluctuation

Step 2.1 (Case A): Increasing demand

Case one represents the scenario when the contractor and the supplier have to make decisions together to revise order plans that can fulfill the increased demand quantities. There are two options to revise the order plan, namely the extra-order option and the outsourcing option. For the extra-order option, the supplier is expected to use the idle production time in the batch plant to update the production quantities for a given period, which is defined as t_{idle}. The revised order plan will start immediately after the construction site experiences the demand fluctuation, which is forecasted and determined by the contractor in the X-day look-ahead plan to reflect real-time site progresses. A portion of the total increased demand quantities can be fulfilled by using the idle production time during this X-day look-ahead planning window. For the outsourcing option, the contractor needs to immediately find a third-party supplier who can provide the same type of concrete within the X-day look-ahead planning window. The third-party supplier is selected in the contractor's historical procurement database. After the occurrence of the increased demand fluctuation, the revised order quantities, which can include the quantities to be extra-ordered and the quantities to be outsourced, will be determined by a heuristic optimization to minimize the total costs incurred from the two options. Since the site progress monitoring and look-ahead planning are conducted weekly, the revised order plans are also generated every week, depending on the updates in the X-day look-ahead planning window. The decisions to generate the revised order plans are made to minimize the costs by all the involved participants. Therefore, the supplier quantities are always balanced with the demand quantities, which reflect the changing site needs promptly.

Math model formulation The unfulfilled demand ΔQ_i, which results from the increased demand for each task ID i, is forecasted and calculated from the monitoring process. To fulfill ΔQ_i the extra-order option and the outsourcing option are considered to bring different costs for both the supplier, the third-party supplier, and the contractor. The total extra-order cost TC_{bo} is determined as unit extra-order cost multiplied by extra-order quantities and the additional time to produce them at the batch plant [245], as shown in Equation 6.7. The total outsource cost TC_{os} is computed as the unit outsourcing cost multiplied by the outsourced quantities, as shown in Equation 6.8. If the sum of extra-order quantities and the outsourced quantities are not enough to fulfill the increased demand, the construction site will lose productivity on certain installation tasks due to the unavailability of the required concrete quantities. Therefore, the cost incurred by the lost productivity is considered as part of the total costs for coordination. The cost of lost productivity is obtained by multiplying the unit site-loss cost with the quantities that cannot be fulfilled, which is shown in Equation 6.9. Besides, with the extra-ordered quantities, the total production cost at the supplier's batch plant is calculated by multiplying the unit production cost with the sum of the extra-order quantities and the originally planned order quantities, as shown in Equation 6.10.

$$TC_{bo} = c_{bo} * \sum_{i=1}^{N} (Q_{bo,i} * \frac{Q_{bo,i}}{p}) \tag{6.7}$$

$$TC_{os} = c_{os} * \sum_{i=1}^{N} Q_{os,i} \tag{6.8}$$

$$TC_{lp} = c_{lp} * \sum_{i=1}^{N} (\Delta Q_i - Q_{bo,i} - Q_{os,i}) \tag{6.9}$$

$$TC_p = c_p * \sum_{i=1}^{N} (Q_{bo,i} + Q_{op,i}) \tag{6.10}$$

The decisions on the quantities in the revised order plan are formulated as a non-linear constrained optimization problem that minimizes the total cost of coordination, which is the summation of the total production cost, total extra-order cost, total outsourcing cost and the cost incurred by the lost productivity on site, as shown Equation 6.11. The minimization of the total cost of coordination is subject to the supplier's idle time production capacity and demand constraints. The decision variables are the extra-order quantities $Q_{bo,i}$ and outsource quantities $Q_{os,i}$, for each task ID, during the X-day look-ahead planning window. The extra-order quantities and the outsourcing quantities can neither be negative or larger than the increased quantities ΔQ_i, which is ensured by Equation 6.12 and Equation 6.13. The total of the extra-order quantities and the outsourced quantities should not be over the required increased demand; therefore, Equation 6.14 is needed to constrain the determination of the reasonable extra-order quantities and outsourced quantities. Since the extra-order quantities are only possible by production capacity during the available idle time at the batch plant during the X-day look-ahead planning window, Equation 6.15 is considered as the constraint to ensure that the time to produce extra-order quantities at a designated supplier's production rate p (with a consideration of production reliability factor, γ) is less than the idle time t_{idle}. The mathematical model formulation to minimize the total cost of coordination is as follows.

The objective function is:

$$Minimize TC = TC_p + TC_{bo} + TC_{os} + TC_{lp} \tag{6.11}$$

subject to the following constraints:

$$0 \leq Q_{bo,i} \leq \Delta Q_i; \forall i \tag{6.12}$$

$$0 \leq Q_{os,i} \leq \Delta Q_i; \forall i \tag{6.13}$$

$$0 \leq Q_{bo,i} + Q_{os,i} \leq \Delta Q_i; \forall i \tag{6.14}$$

$$\sum_{i=1}^{N} \frac{Q_{bo,i}}{p * \gamma} \leq t_{idle} \tag{6.15}$$

Implementing heuristics A heuristic process is developed to solve the mathematical model for the occurrence of the increasing demand. The determination of the extra-order quantiles and the outsourced quantities follow a stochastic process. In this study, the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) heuristic approach is selected to find the optimal value of the two decision variables. The CMA-ES approach is a relatively new heuristic process compared to the other similar heuristic approaches, e.g., genetic algorithm, bee colony, simulated annealing, etc. It is chosen for this research mainly because of its unique property, which is to exhibit invariance to invertible linear transformations of the search space to avoid getting stuck in local optimal values. Invariances are highly desirable because they imply uniform behavior on classes of functions and therefore imply the generalization of empirical results. Though other heuristics have been extensively used for ready-mix concrete deliveries and coordination problems, the use of CMA-ES in this research can be seen as a starting point for future investigations to follow in this area.

The CMA-ES defines an optimally diverse population of candidate solutions in an area that can be continuously changed. The size of the area and its location are determined based on the algorithm's previous experience with the objective function. New candidate solutions are sampled from a multivariate normal distribution, which is shown in Equation 6.16, whose mean m and covariance matrix

Σ are adapted in each generation along with the general step size σ. The number of sampled candidate solutions λ is called the population size.

$$Q_{bo,i}(k), Q_{os,i}(k) \sim m + \sigma N(0, \Sigma); k = 1, ..., \lambda \tag{6.16}$$

The heuristic process using CMA-ES for this research is coded in a Python-based evolutionary algorithm framework, called DEAP [74]. The representation scheme of CMA-ES has the same components as the other evolutionary heuristic algorithms, including individuals, populations, etc., while it differs in the updates of the search space. In DEAP, each individual (i.e., $Q_{bo,i}$ and $Q_{os,i}$) has an accompanying vector, called strategy, which is also a vector controlling its mutation. The CMA-ES heuristic process based on the DEAP framework for this research is described in Step 1 to Step 7 in Table 6.3. The respective codes are shared in Polybox repositories[3].

Table 6.3: The CMA-ES heuristic process based on the DEAP framework

Step No.	Process in each step
Step 1	initialize the decision variables $Q_{bo,i}$ and $Q_{os,i}$ using the values from the original order plan, which means they are initially set to zero.
Step 2	input the values of parameters of the mathematical model, namely the deterministic values of $Q_{op,i}(\forall i)$, c_{bo}, c_{os}, c_p, c_{lp} and p.
Step 3	initialize λ, m, and σ, set Σ as the identity matrix, and create a strategy to generate individuals based on an updated sampling function learned from the sampled population based on the mean and covariance matrix. The number of individuals while generating one population is set to 25. The number of iterations is set to 500, and therefore the number of total iterations of individuals is 12,500 (25*500).
Step 4	register 'generate' and 'update' function in the built-in toolbox of DEAP for the strategy that takes a population of one individual as the argument.
Step 5	evaluate $Q_{bo,i}$ and $Q_{os,i}$ with the objective function TC, assign a relative ranking to sort the individuals according to the evaluation results, and update the covariance matrix.
Step 6	check if the termination criterium is met (i.e., the heuristic processes converge with a good probability with the above settings); if not, go back to Step 4 and Step 5; if yes, go to Step 7.
Step 7	record the best values of $Q_{bo,i}$ and $Q_{os,i}$

Step 2.2 (Case B): Decreasing demand

If there is a decreasing demand for concrete for the following X-day installation tasks, there would be unused quantities ordered or delivered to the site. In such a case, the contractor has two options to deal with the unused quantities. The first option is to immediately negotiate with the supplier to reduce the production

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[3] The coding snippets for CMA-ES heuristic process for this research can be accessed at: `https://polybox.ethz.ch/index.php/s/FWOHO2iY2U2crSj`

quantities as ordered before. If the supplier agrees to change the production plan and reduce the production quantities, the contractor can receive the quantities just as needed without causing excess inventories or waste of concrete on site. The other option is to let the supplier deliver the originally ordered quantities to the site. Then the contractor plans to transship the unused quantities to other projects in the contractor's project portfolio. Transshipment has become an emerging solution in the manufacturing industry. It is used when products are transferred from suppliers who have sufficient supplies to others in need of those products. Therefore, it can be viewed as a potential solution for contractors with several concurrent construction projects (i.e., project portfolio) to deal with the unused or over-stored but perishable materials that can be laterally shared among projects. For ready-mix concrete, the transshipment approach has been described in the authors' another study (Chapter 7) and not discussed hereby in detail. To briefly introduce, the transshipment approach includes two main steps. First, the daily material supply and demand data are collected from a continuously updated schedule and 3D models as input for calculating transshipment quantities. Second, an evolutionary optimization algorithm is used for optimizing the transshipment quantities with minimal cost. The formulation of the algorithm contains the re-allocated quantities of unused materials and the candidate projects that would receive them with the designated transshipment costs. The evolutionary optimization algorithm can find the optimal solutions of re-allocated quantities to a group of projects that should receive the unused materials with minimal cost. These processes are illustrated as Case B sub-processes in Figure B.2 in the Appendix B.

Step 2.3 (Case C): Unchanged demand

If the project is progressing as planned and there are no demand fluctuations, then the production and delivery of the concrete would go as originally planned. The contractor will need to notify the supplier that the production should continue as originally planned for the following X-day look-ahead planning window.

6.4 Example demonstration

6.4.1 Example project information

To demonstrate the usefulness of the proposed supplier-contractor coordination approach, an example office-building project featuring a five-day in-situ construction of concrete walls was used to derive the revised order plan in a 5-day look-ahead planning window (X=5). Shear walls and exterior walls installation tasks were planned in the 5-day look-ahead schedule, and their predecessors included the in-situ installation of the floor slabs on the ground floor in different work zones. The design of an example task ID for the shear wall installation tasks is shown in Figure 6.4. The index i for the task ID range from 1 to 5, represents five shear wall installation tasks from day 1 to day 5 in the look-ahead planning window. To simplify the model, each of the task IDs represents an in-situ installation task on a single day. The look-ahead planning period covered the working week from 16-Feb to 20-Feb. Two tasks planned in the previous working week were set to be the hurdles that lead to a re-scheduling of the look-ahead planning period, which should have occurred on the 12-Feb and 13-Feb, according to the original plan. These tasks are all on the critical path. For the concrete production and delivery for these tasks, the lot-to-lot batches were coordinated and accomplished on a daily basis. The accuracy of automatic recognition of site progresses, α, was estimated to be 0.95 within appropriate confidence intervals according to some relevant empirical studies [112, 314]. The material usage conversion factor, β, was estimated to be 0.90 as the site manager indicated a waste of 10% of the material used due to material handling and poor planning of placement. The production reliability, γ, was estimated to be 0.95 based on the supplier's historical production data. Additionally, no design changes were found for the non-started tasks as planned for the following five days; therefore, the demand quantity fluctuations due to design changes are zero.

The building was modeled using Autodesk Revit software. The design data included mainly the element ID, the volume of each element, and the type of the concrete for the element. The building elements were modeled in Revit as unique elements, each of which had a unique element ID. The element IDs were manually mapped to the task ID in Revit according to the work zones specified by the site trades. Figure 6.5 shows how the element IDs in the 3D model and the look-ahead schedule were linked together. For example, the task ID 'AT_OR_ST_SHC_SIT_00EG_Z1' (i=2) was linked to 11 element IDs, including '1941250', '1941252', and so on. This means that the 11 geometric parts were designed for the walls associated with the shear wall construction in work zone 1 on the ground floor planned on the 2nd look-ahead day. The 11 elements were individually included in the BIM. Therefore, the total number of element IDs that belong to this task ID, M2, was 11. The same applies to all the tasks. The data related to the design information is listed below.

$M_1 = 71,\ M_2 = 11,\ M_3 = 20,\ M_4 = 45,\ M_5 = 22,\ \Delta QDC_i = 0; \forall i = 1, 2, 3, 4, 5$

Besides the design and scheduling at the contractor side, the supplier was assumed to provide an in-house delivery service to transport the concrete to the site, without the need to involve a third party logistic service in the material flow process. In this example, considering the limited length of the paper, only Case A is demonstrated as the most common and challenging demand fluctuation case. The data related to finding optimal revised order plans to accommodate demand fluctuation are listed as follows.

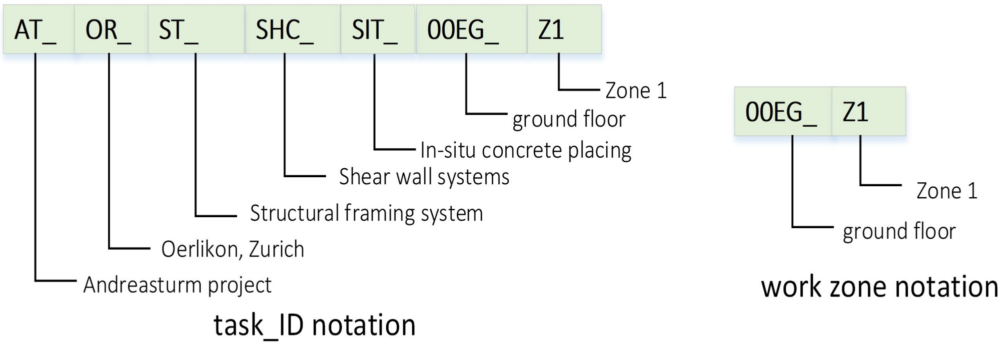


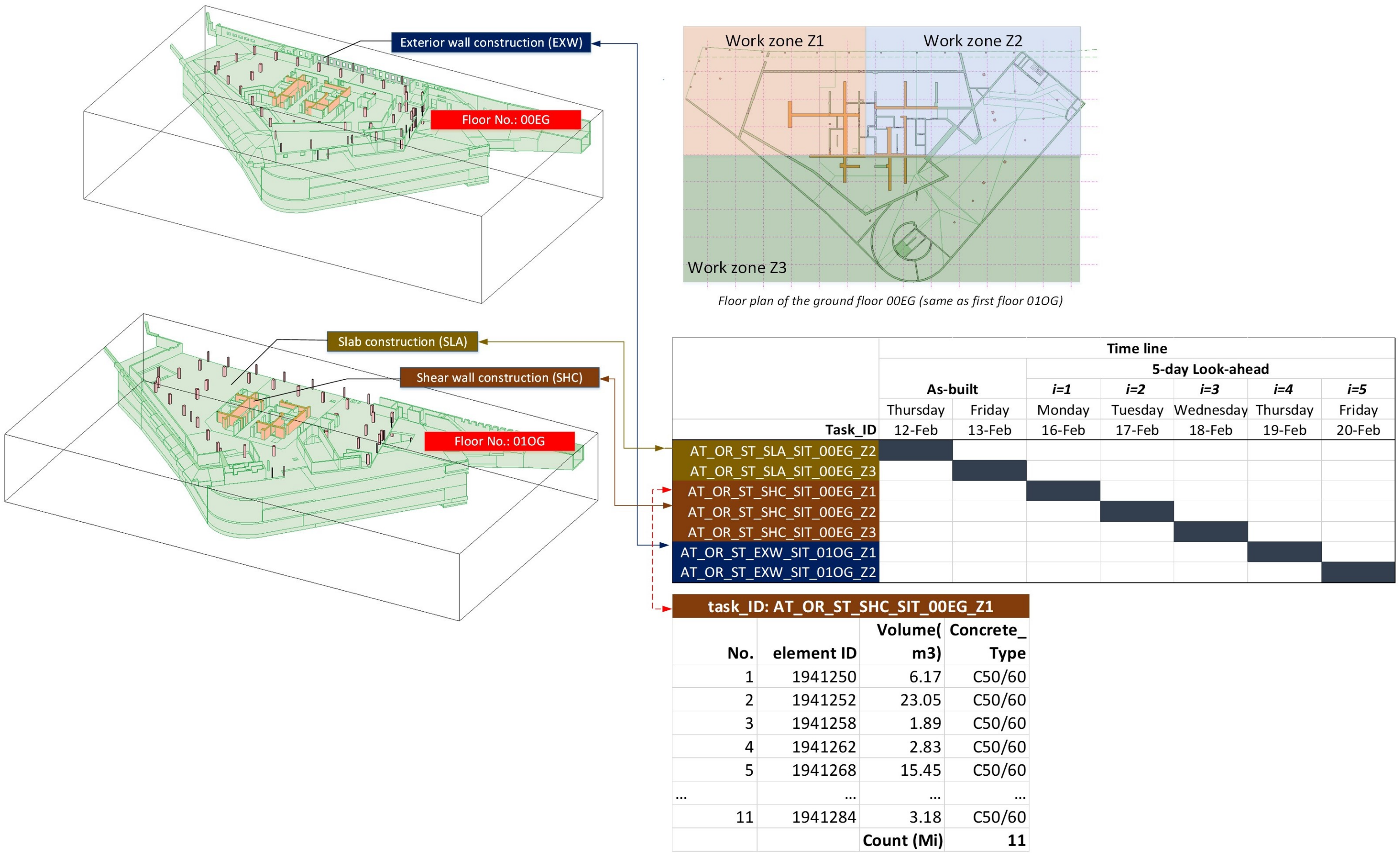
Figure 6.4: The design of an example task ID for the installation of shear walls

$t_{idle} = 0.5$, $p = 60$, $c_{bo} = 95$, $c_{os} = 132$, $c_{lp} = 260$, $c_p = 180$, $\Delta Q_i > 0; \forall i = 1, 2, 3, 4, 5$

6.4.2 Step 1 - Monitor dynamic demand fluctuation

Step 1.1- Generate original demand quantities $Q_{op,i}$

The demand quantities were obtained according to Equation 6.1, and the volume of each building element was obtained automatically from the Revit in-built quantity take-off function. Table 6.4 shows the detailed presentation of the 5-day look-ahead schedule, including those task IDs and the associated concrete demand quantities on each day (day_ID $= i$). It is noted that the schedule included the delayed quantities caused by the uncompleted precedential tasks, which would be carried forward to the following respective dates.



	Time line						
			5-day Look-ahead				
	As-built		i=1	i=2	i=3	i=4	i=5
	Thursday	Friday	Monday	Tuesday	Wednesday	Thursday	Friday
Task_ID	12-Feb	13-Feb	16-Feb	17-Feb	18-Feb	19-Feb	20-Feb
AT_OR_ST_SLA_SIT_00EG_Z2	■						
AT_OR_ST_SLA_SIT_00EG_Z3		■					
AT_OR_ST_SHC_SIT_00EG_Z1			■				
AT_OR_ST_SHC_SIT_00EG_Z2				■			
AT_OR_ST_SHC_SIT_00EG_Z3					■		
AT_OR_ST_EXW_SIT_01OG_Z1						■	
AT_OR_ST_EXW_SIT_01OG_Z2							■

task_ID: AT_OR_ST_SHC_SIT_00EG_Z1

No.	element ID	Volume(m3)	Concrete_ Type
1	1941250	6.17	C50/60
2	1941252	23.05	C50/60
3	1941258	1.89	C50/60
4	1941262	2.83	C50/60
5	1941268	15.45	C50/60
…	…	…	…
11	1941284	3.18	C50/60
		Count (Mi)	11

Figure 6.5: An illustration of how the element IDs in the 3D model and the look-ahead schedule were linked

Table 6.4: Detailed presentation of the 5-day look-ahead schedule with original demand/order quantities information

Task_ID	Description	As-built dates with delayed tasks		5-day look-ahead schedule dates				
				i=1	i=2	i=3	i=4	i=5
		12-Feb	13-Feb	16-Feb	17-Feb	18-Feb	19-Feb	20-Feb
AT_OR_ST_SLA_SIT_00EG_Z1	In-situ floor slab, Zone1, ground floor	$prog_{recog}$ = 81% $\Delta Q_i =$ 21.75	-	-	-	-	-	-
AT_OR_ST_SLA_SIT_00EG_Z2	In-situ floor slab, Zone2, ground floor	-	$prog_{recog}$ = 74% $\Delta Q_i =$ = 45.85	-	-	-	-	-
AT_OR_ST_SHC_SIT_00EG_Z1	In-situ shear wall, Zone1, ground floor	-	-	$Q_{op,1}$ = 311.73	-	-	-	-
AT_OR_ST_SHC_SIT_00EG_Z2	In-situ shear wall, Zone2, ground floor	-	-	-	$Q_{op,2}$ = 43.98	-	-	-
AT_OR_ST_SHC_SIT_00EG_Z3	In-situ shear wall, Zone3, ground floor	-	-	-	-	$Q_{op,3}$ = 77.32	-	-
AT_OR_ST_EXW_SIT_01OG_Z1	In-situ shear wall, Zone1, first floor	-	-	-	-	-	$Q_{op,4}$ = 78.79	-
AT_OR_ST_EXW_SIT_01OG_Z2	In-situ shear wall, Zone2, first floor	-	-	-	-	-	-	$Q_{op,5}$ = 79.65

Step 1.2- Update look-ahead 5-day schedule

The site trades used the laser scanner to collect point clouds data and converted the point clouds data into the as-built progress on Friday mornings. According to the registered points cloud data, the status of the precedential tasks, the installation of the prefabricated columns and floor slabs of the ground floor, were found to be delayed. The delayed quantities for tasks 'AT_OR_ST_SLA_SIT_00EG_Z1' and 'AT_OR_ST_SLA_SIT_00EG_Z1' were calculated based on Equation 6.2 to Equation 6.4, and the delayed quantities derived from the progress monitoring results are presented in Table 6.4. Therefore, the following 5-day look-ahead schedule had to be updated to include the unfinished work of the two precedential tasks.

Step 1.3- Calculate demand fluctuation

Since the in-situ concrete placing for the floor slabs added the delayed quantities to the following five days of concrete work, the contractor had to cope with Case A demand fluctuation to fulfill the increased demand. The delayed quantities of

18.6 m^3 were carried forward on 17-Feb, and the delayed quantities of 39.2 m^3 were carried forward on 18-Feb, which should be fulfilled by the respective day. Since there were no additional quantities caused by design changes, the demand fluctuation was only accounted for by the delayed quantities of the uncompleted precedential tasks. According to Equation 6.6, the updated demand quantities were finally obtained in Table 6.5.

Table 6.5: Updated 5-day look-ahead schedule with updated demand/order quantities information

Task_ID	Description	5-day look-ahead schedule dates				
		i=1	i=2	i=3	i=4	i=5
		16-Feb	17-Feb	18-Feb	19-Feb	20-Feb
AT_OR _ST_SHC _SIT_00EG_Z1	In-situ shear wall, Zone1, ground floor	$Q_{up,1}$ = 311.73	-	-	-	-
AT_OR _ST_SHC _SIT_00EG_Z2	In-situ shear wall, Zone2, ground floor	-	$Q_{up,2}$ = 65.73 (delayed quantities of 21.75 m^3 carried here)	-	-	-
AT_OR _ST_SHC _SIT_00EG_Z3	In-situ shear wall, Zone3, ground floor	-	-	$Q_{up,3}$ = 123.17 (delayed quantities of 45.85 m^3 carried here)	-	-
AT_OR _ST_EXW _SIT_01OG_Z1	In-situ shear wall, Zone1, first floor	-	-	-	$Q_{up,4}$ = 78.79	-
AT_OR _ST_EXW _SIT_01OG_Z2	In-situ shear wall, Zone2, first floor	-	-	-	-	$Q_{up,5}$ = 79.65

6.4.3 Step 2 - Make decisions on material orders to accommodate demand fluctuation

(Case A) Optimal material orders in the revised order plan

Based on the increased demand, the CMA-ES heuristic process was implemented to find the optimal values of extra-order quantities and the outsourced quantities for the revised order plan. The initial values of λ, m, and σ were set to zero. Other random values of λ, m, and σ were also tested, which did not impact the final optimization results when the CMA-ES algorithm was converging to a global minimum. After the implementation, the revised order plan with the minimal total costs to fulfill the increased demand quantities is presented in Table 6.6, which includes the extra-order quantities, the outsourced quantities, and lost site productivity. The total cost generated from the revised order plan was 126,879.8 USD. The convergence graph from the CMA-ES heuristic process is illustrated in Figure 6.6, which shows that the optimal value was found after iterating individuals in the search space around 4,000 times.

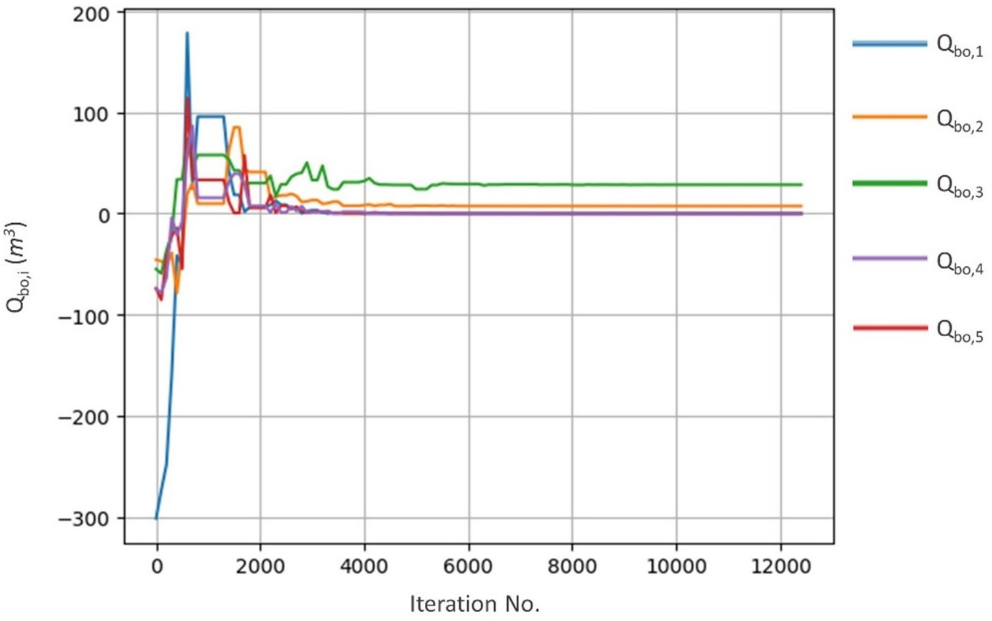
If the supplier-contractor coordination approach was not implemented and the contractor used the traditional approach to fulfill the demand fluctuations by only outsourcing the third party supplier for the increased quantities, the total cost was 132,537.8 USD. Therefore, the revised order plan saved the total cost by 4.3% (i.e., (132,537.8–126,879.8)/ 132,537.8*100%).

Table 6.6: Updated 5-day look-ahead schedule with updated demand/order quantities information

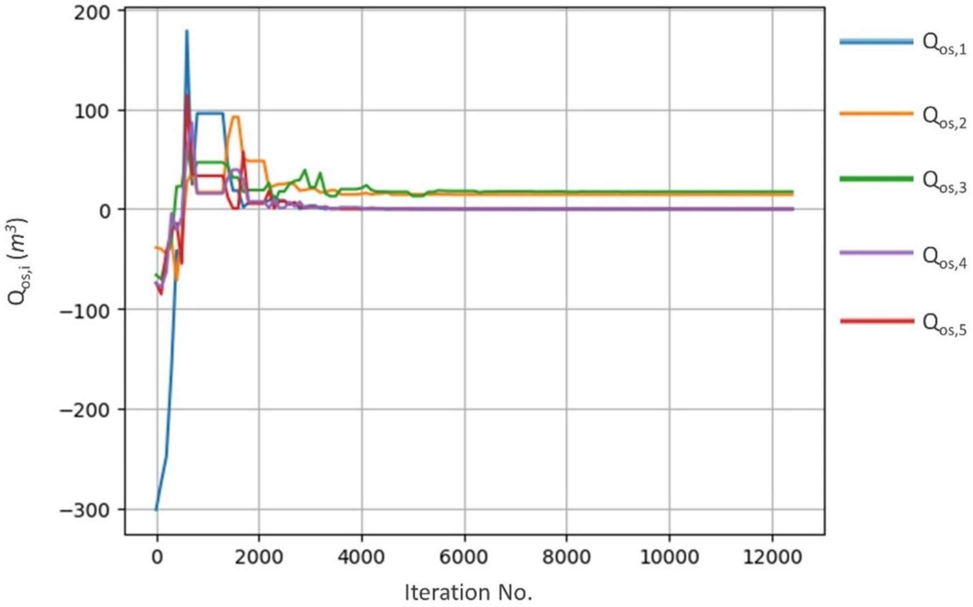
task ID	5-day look-ahead schedule dates	Updated demand quantities	New order to the same supplier	Originally ordered quantities	Extra-order quantities	Outsourced quantities	Quantities unfulfilled to cause lost site production
		$Q_{up,i} = Q_{ro,i} + Q_{os,i} + Q_{lp,i}$	$Q_{ro,i} = Q_{op,i} + Q_{bo,i}$	$Q_{op,i}$	$Q_{bo,i}$	$Q_{os,i}$	$Q_{os,i}$
AT_OR_ST_SHC_SIT_00EG_Z1	i=1, 16-Feb	311.73	311.73	311.73	0	0	0
AT_OR_ST_SHC_SIT_00EG_Z2	i=2, 17-Feb	65.73	51.33	43.98	7.35	14.4	0
AT_OR_ST_SHC_SIT_00EG_Z3	i=3, 18-Feb	123.17	105.82	77.32	28.5	17.35	0
AT_OR_ST_EXW_SIT_01OG_Z1	i=4, 19-Feb	78.79	78.79	78.79	0	0	0
AT_OR_ST_EXW_SIT_01OG_Z2	i=5, 20-Feb	79.65	79.65	79.65	0	0	0

(Case A) Effect of the model parameters on the total costs of revised order plans

The CME-ES approach provided optimal extra-order and outsourced quantities for a particular case scenario, i.e., the fixed values are set for the input parameters in the proposed non-linear constrained optimization math model. To test the robustness of the CMA-ES approach and to investigate the effect of different parameters, the sensitivity analysis was conducted respectively by changing pa-



(a)



(b)

Figure 6.6: Revised order plan based on the example settings

rameter values. This research selected five parameters to study, i.e., the available idle time for producing extra-order quantities (t_{idle}), the delayed quantities of uncompleted precedential tasks ($Q_{d,i,pre}$), the unit cost for producing outsourced quantities (c_{os}), the unit cost for producing outsourced quantities (c_{bo}), and the unit cost for losing site productivity (c_{lp}). These parameters were chosen because they have been considered as topics of great concern by researchers. The sensitivity analyses were conducted by changing one parameter with five different values during the CME-ES optimization and outputting the optimal revised order plan for each time. The total costs were generated based on the order quantities, as determined in the revised order plans. The total costs versus the changing parameter values are illustrated in Figure 6.7. The effects of the three parameters on the total costs are summarized as follows.

In Figure 6.7(a), the total cost decreased to a constant value when the available idle time increased from 0.1 to 1 day, while having the other parameter values fixed. When the available idle time was set to no less than 0.5 days, the total cost reached the minimum value. This means that the revised order plan favored the scenario when the supplier had enough idle time for producing the extra-order quantities to reduce the total costs incurred by fulfilling the increasing demand quantities.

In Figure 6.7(b), the total cost increased almost linearly with the linearly increased delayed quantities of uncompleted precedential tasks from 67.6 m^3 to 338.0 m^3 (5 times the 67.6 m^3), while having the other parameter values fixed. It was observed that the magnitude of the delayed quantities would not have a significant impact on the decision of optimal revised order plan when using the CMA-ES approach.

In Figure 6.7(c) and Figure 6.7(d), the total cost increased linearly as the unit cost for producing outsourced quantities and extra-order quantities linearly increased, respectively from 132 USD/m^3 to 228 USD/m^3 and from 95 USD/m^3 to 133 USD/m^3, while having the other parameter values fixed. The linearity indicates that the unit cost of either outsourcing or extra-ordering did not affect the decision of optimal revised order plan when using the CMA-ES approach. This also means that a high outsourcing or extra-ordering cost would not lead to a reduction in the allocation of outsourced quantities and extra-order quantities, as the increased demand quantities have to be fulfilled unconditionally.

In Figure 6.7(e), the effect of the lost site productivity on the total cost was investigated to validate to what level the site progress can tolerate material unavailability to halt installation tasks. The delay of installation tasks on the critical path normally results in a high unit cost for losing site productivity, as they allow no floating time to wait for the materials. Therefore, the critical activities allow less amount of quantities of materials to be delayed. On the contrary, non-critical activities can tolerate the delayed quantities of materials without having a high impact on the overall construction processes, where a low unit cost for losing site productivity can be assumed. In this sensitivity scenario, the unit cost for losing site productivity ranged from 50 USD/m^3 to 130 USD/m^3. It was interesting to observe that as the unit cost for losing site productivity increased to a certain level (i.e., 90 USD/m^3), the total cost increased sharply, and the tolerated delayed material quantities reduced sharply. In this example case, since all installation tasks were critical activities, the unit cost for losing site productivity had a relatively high value. The lost productivity quantities, through the heuristic optimization, were obtained as zero. This is consistent with the results from Figure 6.7(e).

6.5 Discussion

In the example demonstration, a 4.3% reduction in the total cost was observed when the proposed coordination approach was implemented instead of the traditional approach (i.e., merely outsourcing to fulfill the increased demand quantities). This cost reduction shows that, albeit small, there are benefits when the supplier and the construction contractor work together to share supply and demand information promptly. Although the approach was not tested in a real-world workflow and the material handling costs were not fully considered for cost estimation, the 4.3% cost reduction derived from the example project is consistent with the test results found in relevant research, such as Yan et al. [348]. However, they did not address the potential to complement the useful heuristic approach with structured digital data flows allowed by 4D models. This research has filled the gap by proposing the two-step coordination approach, which allows the supplier and the contractor not only to benefit from the efficiency from 4D models but also to make decisions responsively to cope with the uncertain demand changes.

From the example demonstration, it indicates that the proposed coordination approach would contribute to the current body of literature in two perspectives. First, the 4D models were incorporated to enable efficient data collection and material quantity take-offs. The material demand quantities were seamlessly connected with the onsite construction processes, which were planned and replanned in a short-term planning window. This near-term scheduling allows the contractor to quickly capture the site demand fluctuation according to the "current status" of the tasks. With the 4D models, the estimation of the site progress and the calculation of the demand fluctuations were less error-prone and less time-consuming. Second, the heuristic algorithm (e.g., CMA-ES) was implemented to help the contractor find the optimal solutions to deal with the demand fluctuations. The CMA-ES approach was sufficient to provide the extra-order quantities and outsourced quantities to formulate the revised order plan. The revised order plan ensured the contractor to fulfill the changed demand quantities with minimal costs. Therefore, the existing challenges of material coordination problems

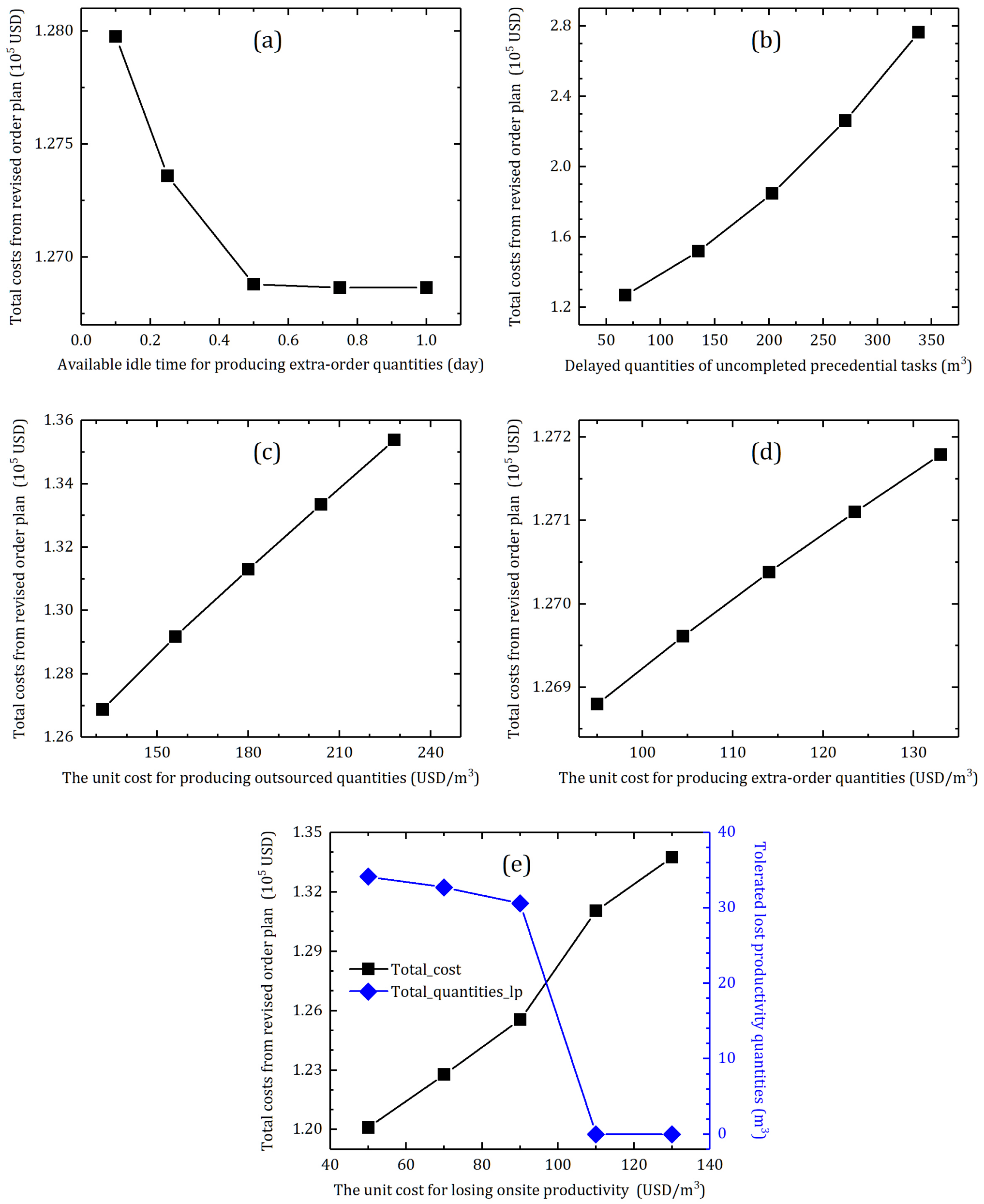


Figure 6.7: Total costs generated from the revised order plans versus the changing parameter values resulted from the sensitivity analysis

can be overcome with the potentials from both perspectives. Also, due to the parametric and computational-efficient modelling processes, both the look-ahead schedule and the optimization algorithm can be easily scaled from 5-day to an arbitrary X-day planning horizon.

According to the sensitivity analysis of the total costs, it was observed that the available idle time for producing extra-order quantities has a great impact on the determination of solutions to demand fluctuations. As a result of this, the authors suggest the contractor make the best use of the supplier's idle time to produce the additional quantities, as it will lead to the minimal costs to deal with the increasing demand fluctuations. To the best knowledge of the authors, this strategy has not been discovered by researchers in the area of construction supply chain coordination. Nevertheless, it should be considered as an optimal solution for both the supplier and the contractor to deal with demand fluctuations. Another implication was obtained from the sensitivity by unit cost for losing site productivity. It was suggested that the delay of materials for the activities on the critical path can lead to a high total cost. Therefore, extra-ordering and outsourcing options should be immediately selected without losing site productivity, which was costly for the contractor. For the other three parameters, the sensitivity results do not reveal a significant effect by the magnitude of the delayed quantities to be carried forward and the unit cost for producing the outsourced quantities. It is, however, necessary to investigate more parameters to find out how they change the CMA-ES heuristic results as well as the effectiveness of the mathematical model.

Since the proposed approach focuses on the method to coordinate material supplies under demand fluctuations within a 4D modelling environment, the data interoperability and legal issues have not been fully investigated. However, these issues cannot be avoided if the 4D models are shared among project participants, particularly among the supplier and the contractor, who usually have distinct modelling and production systems. Therefore, a common data environment is desired for the coordination of models and production processes, and stakeholders are encouraged to adopt relational contracting project delivery models to support the collaboration [122]. Additionally, cybersecurity issues cannot be neglected when the proposed approach is extensively used to involve different workflows [102]. In current practices, the supplier and the contractor are usually reluctant to share data, especially those related to cost (e.g., the unit extra-order cost or productivity data during the available idle time). With the advancement of the blockchain technology, this problem can be alleviated by its reliable distributed-ledger data structure, and the sharing of cost data between the participants becomes more transparent and proactive.

6.6 Conclusions and future work

This paper proposes a two-step coordination approach that contractors should take to help both suppliers and contractors responsively cope with the demand fluctuations with the minimal cost over the dynamic construction processes. The first step is to automatically calculate the demand fluctuations from a 4D model that monitors the as-built site progress and helps the contractor update the look-ahead schedules. The second step is to make decisions on the material orders at the occurrence of the demand fluctuation determined in the first step. The decisions on the material orders consist of extra-orders and outsourced orders, which are determined by the heuristics, the CMA-ES approach. As the coordination approach enables a data-driven and schedule-driven supply chain coordination process to address uncertain demands, it would contribute to the current body of literature not only in supply chain information visibility but also in supply chain responsiveness through efficient decisions made.

To test the usefulness of the proposed approach, an example office building project featuring a five-day in-situ construction of concrete walls was tested to derive the revised order plan in a 5-day look-ahead planning window. The 4D model facilitated the data collection on the site progress monitoring and the quick computation of the demand fluctuation quantities. In the example demonstration, the optimal revised order plan was obtained to reduce the total cost by 4.3% when the proposed coordination approach was implemented instead of the traditional approach. This reduction should be viewed as a substantial improvement for the existing practice of supplier-contractor coordination.

The sensitivity analysis was conducted to explore the effects of parameters on the CMA-ES optimization results, i.e., the total costs from the revised order plans. An interesting finding from the sensitivity analysis was that the contractor should encourage the supplier to make the best use of idle time for production. It will allow enough extra-order quantities to be supplied to fulfill the increasing demand with the minimal total cost. Additionally, the magnitude of the delayed quantities to be carried forward and the unit cost for producing the outsourced quantities do not have a significant impact on the total cost. It is, however, necessary to investigate more parameters for the sensitivity analysis.

In addition, the supplier-contractor coordination approach was tested only for one example project featuring the in-situ wall installations, whereas the construction processes consist of multiple disciplines, very complex precedential relationships, and various scheduling constraints. These all have a potential influence on the practical implementation of the proposed approach. The approach can be extended to cover all possible constraints that may affect the determination of the optimal solutions for demand fluctuations. For example, the tasks on the critical path have the highest priority to fulfill the demand, which should be modeled into the cost minimization process. Also, the success of heuristic algorithms is highly dependent on the specific problem formulation case by case. The CMA-ES approach selected for this research should be further validated for its fitness for more complex problem settings. Apart from that, issues regarding the data interoperability, cybersecurity, legal and contractual relationships should be investigated to improve the practicality of the proposed approach.

Chapter 7

Transshipment approach to coordinate materials for a contractor's project portfolio

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This chapter corresponds to the published article:[1]

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Abstract

The challenges to coordinate material supply and dynamically changing demand always lead to construction interruptions or a considerable waste of materials on-site. Mainstream research has provided various advanced digital solutions to solve these problems; however, they have not addressed how to make reliable decisions with digital models to manage the demand fluctuations of construction materials. This study proposes a transshipment approach to enable the lateral sharing of perishable materials and optimize material allocation for a contractor's project portfolio. The transshipment approach includes two main steps. First, the daily material supply and demand data are collected from a continuously updated schedule and 3D models as input for calculating unused material quantities. Second, an evolutionary optimization algorithm is used for optimizing the transshipment quantities with minimal cost. As proof of concept, the proposed transshipment approach is demonstrated by looking at a portfolio of seven building projects managed by the same contractor. The demonstration shows that the allocation of the unused materials helps to avoid waste and reduce costs

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[1] Please note, this is the author's version of the manuscript published in *International Journal of Construction Management*. For the reasons of consistency, the style of this chapter matches that of the dissertation. Changes resulting from the publishing process, namely editing, corrections, final formatting for printed or online publication, and other modifications resulting from quality control procedures may have been subsequently added. When citing this chapter, please refer to the original article found in the reference above.

from over-ordered materials by around 52%. As a result, this also leads to improved coordination between contractors and suppliers and better material flow in construction projects.

7.1 Introduction

The successful completion of construction projects hinges heavily on good supply chain management and efficient coordination of material flow. The lack of supply chain predictability, lack of planning reliability, and the dynamics of site changes usually lead to disruptions during construction processes [160, 272, 261]. These supply chain problems have brought significant challenges for project stakeholders to reduce claims, make projects stay on schedule and within budget [118, 296, 163]. The disruptions to the supplies of construction materials due to the COVID-19 pandemic have caused project delays worth about USD 32 billion [333]. For larger construction contractors, it is even more challenging to coordinate a portfolio of their projects in a way where loss can be minimized under supply chain disruptions [273, 279]. Previous research achievements to cope with supply chain disruptions have predominantly highlighted the need for inter-firm supply chain collaboration [193], the effectiveness of which could be weakened by the inter-firm communication problems due to the lockdown measures during the COVID-19. A new approach from an intra-firm perspective to overcoming the supply chain disruption is rather feasible during and post COVID-19, which allows effective and efficient material re-distribution within a contractor's project portfolio.

With the emerging concept of Construction 4.0, many researchers have explored the potentials of various digital technologies (e.g., parametric design software, integrated information platforms, or deployed sensors) to improve the information visibility and planning reliability with an ultimate goal to improve construction supply chain performance [108]. For example, Sheikhkhoshkar et al. [276] and Wu et al. [339] have addressed how to use digital data from parametric modelling software to resolve construction constraints of materials and equipment, and therefore improve the communication of site personnel. Other researchers have advanced virtual design models with ubiquitous sensors to allow the intelligent "digital twinning" of project facilities [267, 41, 107]. An example of digital twin technology used for the proactive construction supply chain in disaster response and environment uncertainties is the Flood Alert System 4 in Houston [98]. It suggested that stakeholders need to improve the number and location of sensors to collect and analyze data for coping with supply chain disruptions. Although these advanced technologies have been extensively used to improve the performance of the construction supply chain, considerable wastes and delay problems occur during the dynamic supply chain processes.

One hidden reason, as found by many researchers, is the lack of a tactical approach to enable data-driven decision-making processes to resolve project demand fluctuation issues. Simatupang and Sridharan [279] pointed out the importance of fast and collaborative decision making processes to integrate material supply and demand through a critical analysis of industry practices. A more comprehensive review of this postulation was given by Le et al. [182], who suggested lean procurement with information technologies and third-party logistics be leveraged in material procurement processes. They also identified the potential of advanced technologies together with collaborative planning to avoid wasted material storage to improve supply chain integration.

Mainstream research, however, has not explicitly addressed how to make reliable decisions with digital models to manage the demand fluctuations of construction materials. Appropriate data-driven decision-making processes, however, are essential and helpful to address problems arising from site dynamics, changing schedules, and changing demands [202, 34, 156]. Given the volatility of site demand for perishable materials, to efficiently accommodate the changing demands of these materials is not trivial. Typical examples of perishable materials in construction projects include the ready-mix concrete, fluid cement, and asphalt, whose freshness should be retained during delivery and installation processes. It is common that perishable materials are delivered but cannot be used as planned due to a changing demand caused by various daily hurdles on site. As a result, it may lead to a considerable waste of materials.

Transshipment has become an emerging solution in the manufacturing industry, from which the construction industry could learn and adapt. It is used when products are transferred from suppliers who have sufficient supplies to others in need of those products [28]. It can be viewed as a potential solution for contractors with several concurrent construction projects (i.e., project portfolio) to deal with the unused or overstored but perishable materials that can be *laterally* shared among projects with increasing demands [153]. Furthermore, its potential to reduce the amount of wasted material makes the transshipment approach a practical implementation of lean construction principles [264].

As most construction contractors have to manage large portfolios of projects, transshipment opens the opportunity for the contractors to optimize the material flow among different projects to meet the fluctuating site demands. There has been a limited amount of studies in relevance to the use of transshipment methods in the construction supply chain. For example, Chen et al. (2017) [49] suggested that transshipment is effective in coping with the demand variability in production schedules in the precast fabrication supply chain. Nevertheless, the topic should have received more attention and be investigated with advanced information communication technologies, such as Building Information modelling (BIM) platforms. Would it be possible to combine the idea of transshipment with digital workflows, which not only improves information visibility and collaboration between stakeholders but also opens a new opportunity for projects to share unused materials within a project portfolio and avoid waste of perishable materials?

To allow the efficient use of BIM-based data flow for the implementation of the emerging transshipment approach within the construction context, this research systematically develops a two-step transshipment approach to help project contractors to balance supply and demand of materials within a multi-project portfolio. The first step aims to collect data of material quantities for transshipment from a BIM authoring software. The second step uses the data in an evolutionary heuristic process to optimize the quantities that should be transshipped among projects with minimal material transportation and handling cost. The remainder of the paper is structured as follows. Section 7.2 contains a literature review concerning the different approaches to improve the coordination of the supply chain or the material flow. Section 7.3 describes the details of the two-step transshipment approach. Section 7.4 provides an example demonstration of the approach as a proof of concept. Section 7.5 discusses the potentials and limitations of the approach, and Section 7.6 contains the conclusions of this research and proposals for future work.

7.2 Literature Review on Construction Supply Chain Coordination

Methods related to the improvement of the coordination of material flow in construction projects can be broadly grouped into two categories in the state-of-the-art: 1) advanced technologies to coordinate material supply and demand, and 2) algorithmic decision-making models to coordinate material supply and demand.

7.2.1 Advanced technologies to coordinate material supply and demand

Over the past decade, BIM has been studied extensively to improve the planning and monitoring of construction projects. BIM is a data-rich, object-oriented, intelligent, and parametric digital representation of the facility, from which views and data are appropriated and analyzed to generate information that can be used to make decisions and improve supply chain processes [52, 87, 181]. Material selection and procurement processes have been more efficient when suppliers' product catalogs are integrated with BIM authoring software and efficient decision-making algorithms [95, 104, 108]. There are a substantial number of benefits of BIM adoption in the construction supply chain, as verified by Le et al. (2018)[182], Ahankoob et al. (2019)[7], Bonanomi et al. (2019)[36], and Le et al. (2019)[181], that BIM brings a closer collaboration between architects, contractors, and suppliers.

When adding a time dimension to 3D models in BIM, it becomes a 4D BIM that can be used for monitoring the status of construction tasks and material flow. Crowther and Ajayi (2019)[65] investigated the impacts of 4D BIM on construction projects and found that using 4D BIM enhances the planning reliability. In view of supply chain coordination, Irizarry et al. (2013)[150] and Deng et al. (2019)[76] extended the capabilities of 4D BIM with geographic information systems to optimize the number of material deliveries and proved the necessity of locating consolidation centers in congested regions with long material delivery distances. To allow information exchange online, Matthews et al. (2015)[213] developed a cloud-based BIM for real-time tracking of construction processes and material needs. A similar study by Chen and Nguyen (2019)[50] investigated web-based 4D models to optimize the selection process of materials through real-time updates of material location information. To focus on linking site logistics information with site installation processes, Bortolini et al. (2019)[37] developed a 4D BIM platform and demonstrated its lean potentials to allow just in time deliveries of prefabricated steel elements. Rameezdeen et al. (2015)[251] operationalized the lean potentials by following a reverse logistics concept, which realized just-in-time delivery and helped reduce wasted material storage. On that basis, Chen et al. (2020)[51] improved the reliability of 4D BIM-based material flow processes by incorporating look-ahead plans that could be updated by both suppliers and contractors. These intelligent and digital methods are efficient for data collection and communication.

Many of those studies, unfortunately, have focused on the technological aspects to improve the context-aware information exchange and information visibility for decision making of material deliveries. They have not been used for transshipment arrangements of materials when the supply plan and usage plan do not fit, which leaves materials unused after delivered to the construction site. For unused perishable materials, this would lead to considerable waste [242, 211]. For example, ready-mix concrete requires much less lead time but leaves little room for variability in the time for usage on-site. Chen et al. (2017)[49] pointed out in their research that transshipment practice could help re-allocate the unused materials and maximize the expected fill rate, improving the flow of materials between project locations at the same echelon. The idea of transshipment should be extended to include digital technologies to balance supply and demand.

7.2.2 Algorithmic decision-making models to coordinate material supply and demand

Apart from digital models, decision-making algorithms are essential to developing data-driven construction supply chain processes [182, 54]. Simatupang and Sridharan (2016)[279] further demonstrated the importance of fast and collaborative decision-making processes. In both construction and manufacturing industry, some research has focused on the development of mathematical optimization models to address the supply disruption and demand fluctuation problems, with the ultimate goal of optimizing the purchasing, tracking, and dispatch sequencing of materials [202, 340]. To emphasize that the material supply is matched with the demand, Kar and Jha (2020)[163] developed an ANP-TOPSIS based decision-making tool to combine material criticality and construction activity criticality and reduced unnecessary material waste.

Among different types of materials, ready-mix concrete has received considerable attention due to its perishability and dynamically changing demands [19, 18]. It is also worth noting that most researchers, for example, García de Soto et al. (2017)[106] and Liu et al. (2017)[198], considered modelling processes for concrete supply chain optimization are regarded as non-convex NP-hard problems, and heuristic models are efficient in giving good feasible optimal results. Many studies, e.g., Yan and Lai (2007)[347] and Liu et al. (2017)[198], show that genetic and evolutionary algorithms are useful to find delivery solutions to match site progress with concrete supplies to achieve minimal procurement and transportation costs. Other than heuristics, Fazeli et al. (2019)[95] investigated the potential of multi-criteria decision-making algorithms and developed a BIM-integrate TOPSIS-fuzzy framework to optimize the selection of sustainable material to meet changing demands at low costs. Another multi-criteria method was developed by García de Soto et al. (2018)[108], namely the cased based digital building system that improved the planning of materials in the early stages of the supply chain. These different algorithmic decision-making methods can resolve cost overrun problems for material planning, coordination, and deliveries, but potential over-ordering and over-storage problems, after contracts are settled, have not been fully addressed.

While some researchers, e.g., Park and Tucker (2016)[242] and Mahamid (2020)[211], qualitatively deducted material waste reuse strategies, there is a lack of tactical approach for contractors to use to reduce risks of excess material supplies. The possibility of lateral movement of over-ordered materials among different projects in one portfolio, which is emerging in the manufacturing industry, was not explored by the construction industry. Using heuristics for transshipment problems is currently very common among researchers in the manufacturing industry. For example, Ghorbanzadeh et al. (2019)[109] and Tarhini et al. (2020)[302] modeled the transshipment problem as a network flow model subject to minimal transportation costs and demonstrated that collaboration between buyers was made possible by allowing transshipments from one buyer to another. In contrast, this topic has been less frequently discussed in the construction industry. Transshipments provide an effective mechanism for correcting discrepancies between the project locations' observed demand and their available inventory without increasing the individual location's replenishments [356, 28, 109]. As transshipment emphasizes the lateral sharing of supplies between projects to minimize cost, the heuristics to solve the transshipment problems usually have an objective cost function to be jointly convex in the shipment quantities flowing among a contractor's project portfolio [302]. The heuristics algorithms, such as a genetic algorithm or evolutionary algorithm, can find the optimal number of shipments between the networked project locations.

When combining digital technologies with the transshipment supply chain network, heuristics can reinforce its potential by quickly collecting data to find optimal solutions for transshipment problems. While as indicated by many of those studies, the necessary implementation steps and effectiveness of heuristic algorithms are pretty much similar [198, 109]. The detailed discussion of the characteristics of different heuristic algorithms is beyond the scope of this study. It is essential to find out how heuristics could be used with digital data to support decision making and alleviate volatility problems in the construction supply chain.

7.2.3 Identification of research gaps

By reviewing the relevant body of literature, it was found that there is a dearth of research to explore the capabilities of BIM together with heuristic models to allow the transshipment of materials among projects. A summary of relevant studies is provided in Table 7.1, which indicates two specific research gaps. They are described as follows:

1. Various digital and communication technologies have been used to enable process automation and to allow information visibility and accuracy for construction planning. However, using these technologies to support decision-making processes was not thoroughly investigated to address construction supply chain volatility issues. Integrating supply chain decision-making algorithms with 4D BIM will account for this research gap.

2. There are a variety of algorithmic decision-making tools to improve the coordination of the construction supply chain in terms of matching material supply and demand to avoid material over-ordering and over-storage problems. The problems could be further alleviated by a new approach learned from the manufacturing industry. For example, the emerging transshipment approach opens a new way to resolve over-ordering and over-storage problems. It features the lateral sharing of materials among projects to correct discrepancies between the project's real-time demand. This transshipment approach yet could be further investigated by supply chain stakeholders in the construction industry.

While 4D BIM and transshipment decision-making models have been investigated independently by many researchers, their combination could not only improve information visibility and collaboration between stakeholders but also opens a new opportunity for projects to share unused materials within a project portfolio and avoid waste of perishable materials. To realize this potential, this

Table 7.1: A summary of relevant works

Papers	**Research focus**	**Main approach**	**Highlights of the research potentials**
This research	Introduce the transshipment approach, which emerged from the manufacturing industry, into the construction supply chain context to coordinate materials among projects and reduce waste	Use the data from BIM authoring software to support transshipment decision making and model the transshipment problem as a network flow model	Enable collaborative decision making and lateral sharing of materials without increasing inventories
Irizarry et al. (2013)	Develop technological approach or technological strategies to improve supply chain planning and material logistics	Use digital models, e.g., BIM-based approach, prototype demonstration and qualitative analysis of case studies	Enable automation and improving information visibility and accuracy for construction planning
Matthews et al. (2015)			
Rameezdeen et al. (2015)			
Ahankoob et al. (2019)			
Bortolini et al. (2019)			
Chen & Nguyen (2019)			
Crowther & Ajayi (2019)			
Deng et al. (2019)			
Fazeli et al. (2019)			
Le et al. (2018)			
Le et al. (2019)			
Low & Wu (2005)	Develop algorithmic decision-making models to coordinate material flows to match supply and demand	Use a heuristic approach and multi-criteria evaluation methods to solve math modeling problems	Enable reliable decision-making processes to balance the demand and supply over supply chain processes
Yan & Lai (2007)			
Wu & Low (2014)			
Park & Tucker (2016)			
Simatupang & Sridharan (2016)			
García de Soto et al. (2017)			
Liu et al. (2017)			
García de Soto et al. (2018)			
Kar & Jha (2020)			
Mahamid (2020)			
Zhao et al. (2006)	Develop algorithmic decision-making models to coordinate material flows among different projects and reduce waste in the manufacturing industry	Use a heuristic approach to solve network flow modeling problems	Enable reliable decision-making processes to balance the demand and supply among different projects and reduce waste
Belgasmi et al. (2008)			
Ghorbanzadeh et al. (2019)			
Tarhini et al. (2020)			

research developed a BIM-based and heuristics-based two-step transshipment approach. The research contributes to the existing body of literature regarding perishable construction materials that need precise and timely coordination of supply and demand. It is also considered as the complementary work in Chapter 6 [53].

7.3 The transshipment approach

7.3.1 Assumptions and nomenclatures

Before describing the transshipment approach, it is necessary to identify the assumptions for its implementation. A supply chain network for transshipment

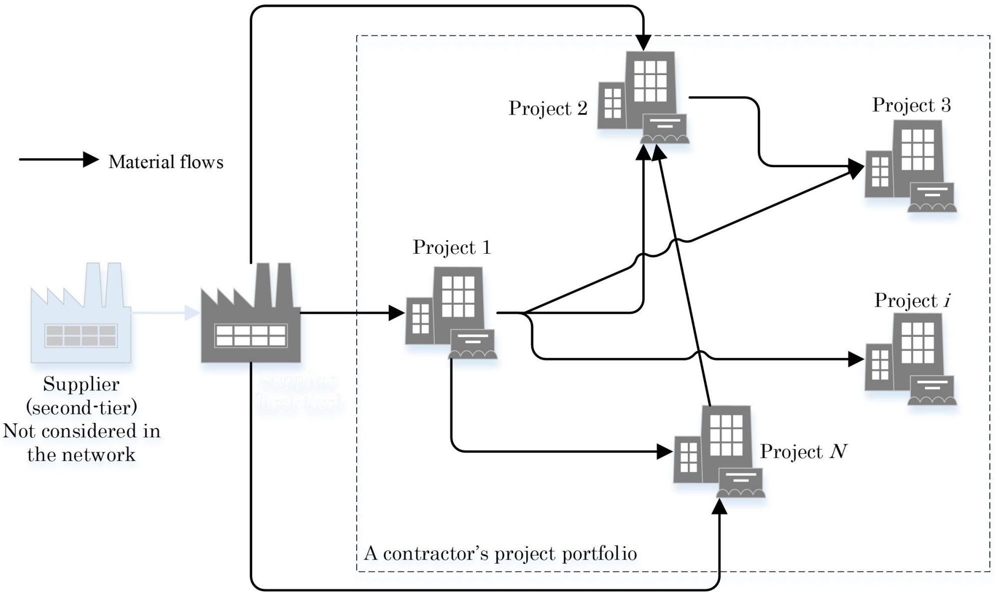

Figure 7.1: Example of transshipment supply chain network diagram (One supplier and N project locations)

was modeled in which materials flow from one supplier to N project locations via one "distributor" project. The transshipped materials were defined as proactive and strategic inventories in one project to buffer against the variability in the demand of the other projects in the same echelon level during supply chain processes, without increasing inventory levels. The relationships between the supplier and different projects are shown in Figure 7.1.

Based on the network diagram, the main assumptions of the approach are summarized as follows.

- The approach only applied to a two-echelon supply chain model, meaning that it considered a direct first-tier supplier and the customer (i.e., the project contractor). The second-tier or other extended tiers of suppliers were not considered in the transshipment supply chain network.
- The construction contractor operated more than one construction project (i.e., a total of N projects) in the same planning horizon; therefore, the transshipment of unused materials from one project to another was possible.
- A coordinator was designated by the construction contractor to be in charge of the planning of transshipment quantities that could be re-allocated to potential candidate projects.
- The coordinator had access to the material information of the other projects,

including project location, the unit material transportation cost, daily supply, and demand quantities.

Since the main objective is to study the transshipment of perishable materials, the delivery and consumption of the materials should be balanced on a daily basis. This means that there was zero inventory of the materials on project sites. The two-step transshipment approach was developed considering these assumptions, and the detailed description of the approach is provided in Section 7.3.2 and Section 7.3.3. The following notations (shown in Table 7.2) are used to formulate a part of the transshipment approach.

Table 7.2: Notations

Notation	Description	Unit of measure[2]
$D(N, A)$	A directed network with n nodes and m arcs, where N and A are the sets of nodes and arcs, respectively.	-
i	A node that represents a project, i=1,2,. . . ,N	-
$(i, j) \in A$	An arch from node i to node j, which belongs to A.	-
d_i	The daily demand quantity of project i based on the daily work plan	m^3
s_i	The daily supply quantity of project i based on the daily delivery plan	m^3
$c_{i,j}$	The unit transportation cost from node i to node j along the arc (i,j)	$USD/km/m^3$
$x_{i,j}$	The amount of materials being transported from node i to node j	m^3
$l_{i,j}$	The minimum amount of materials being transported from node i to node j	m^3
$u_{i,j}$	The maximum amount of materials being transported from node i to node j	m^3
$d_{i,j}$	The transportation distance between node i and node j	km
b_i	It means the available amount of net supply (i.e., unused materials) if $b_i \geq 0$; It means the net demand that should be fulfilled by node i if $b_i < 0$	m^3
N_d	A set of nodes that need to fulfill the demand of b_i	-
N_s	A set of nodes that are able to supply b_i	-
$Hc_{i,j}$	The unit handling cost to load materials onto the trucks at node i and to unload materials off the trucks at node j	USD/m^3

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[2] NB: '-' means not applicable.

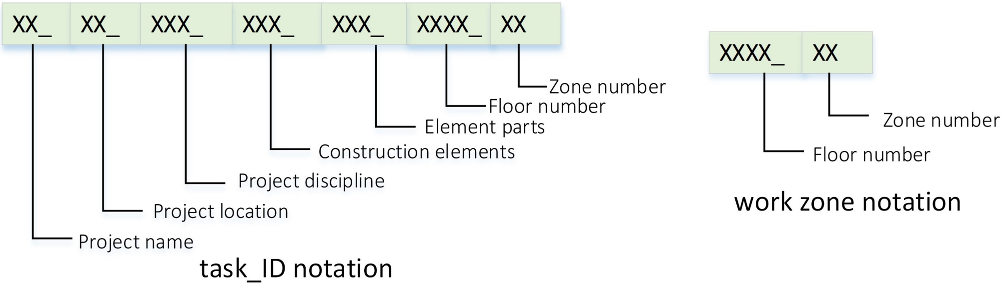

Figure 7.2: The design of a task ID for this research

7.3.2 Step 1 – Calculate material quantities for transshipment in a project portfolio

The first step was to calculate and retrieve the data of material quantities for transshipment, including the demand quantities for on-site installation tasks planned in a daily work plan and the quantities of unused materials if the delivered materials were not used up on a specific day. The unused materials could be shipped to candidate projects (i.e., any project within the contractor's project portfolio) that were in shortage of the same type of materials on the same day.

Calculate daily material demand quantity of each project d_i

The material demand quantity for each project was determined by the installation tasks as committed in the respective project's daily work plan. The daily work plan showed the detailed work assignment for designated trades to complete, which contained task IDs, planned start time, planned finish time, work description, etc. Each work assignment had a unique task ID (shown in Figure 7.2), and it was linked with the building elements in the 3D models designed in BIM authoring software. For perishable materials that should be installed immediately after delivery to the site, the task IDs should be prepared to the level of detail that indicates the tasks to be done within one day. The linkage between the task IDs and the building elements is represented by an entity-relationship diagram, as shown in Figure 7.3. It is worth noting that linking the building elements with the task IDs could be automated using rule-based mapping functions. For example, the contractor can define a rule based on the element names and floor numbers to connect building elements with the task IDs. The quantity of a specific type of material can be automatically calculated using the built-in quantity take-off function in the software.

As the contractor had N projects in the project portfolio, it was intended that each project had a 3D model designed in the BIM authoring software, a specific daily work plan, and task IDs. The material demand quantities of the N projects

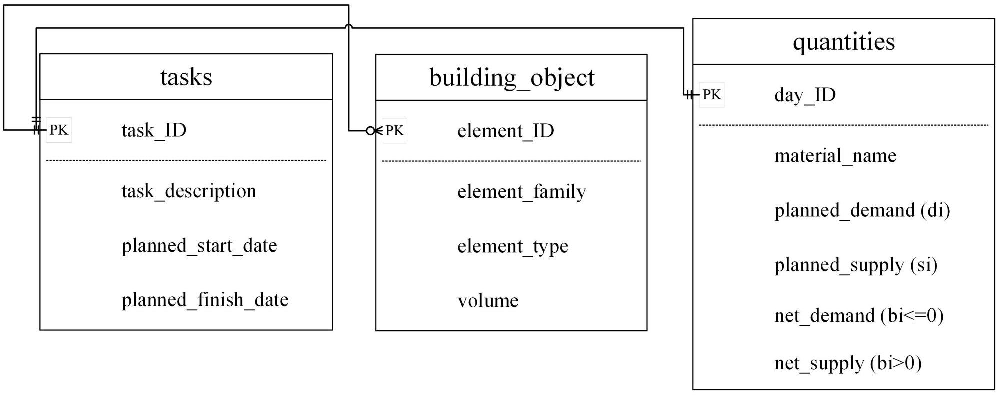

Figure 7.3: Entity-relationship diagram that shows the linkage between the task IDs and the building elements

can be quickly obtained in the same way. The coordinator designated by the contractor had access to the demand information of all of the N projects, which could be shared via a BIM cloud system with a multi-project review dashboard.

Calculate net supply and net demand quantities for transshipment b_i

Each project i had a daily material delivery plan, which should be agreed by both the project contractor and the supplier a few days before the commencement of associated installation tasks. The daily delivered quantities, or the supply quantities s_i in the N projects, were also accessible by the coordinator.

As the site condition was always dynamic and work plans have to change continuously, it was difficult to align the daily demand of materials with the daily delivery plan. Each project site should be aware of the variation of the material demand and supply quantities on a daily basis. The difference was also understood as the net supply quantity or the net demand quantity b_i in each project. It is given in Equation 7.1. If the actual daily supply was less than the demand as specified in the daily work plan, then b_i was a negative value, meaning that the project would experience a shortage of materials and demand extra quantities (i.e., net demand). On the contrary, the project would have unused materials (i.e., net supply) if the delivered quantities were more than the demands. To avoid the waste of unused materials, they would be planned to be transshipped to the projects that needed extra quantities in the meantime.

$$b_i = s_i - d_i \tag{7.1}$$

In the project portfolio, the net demand quantities by a group of projects N_d could be balanced out by the net supply quantities by the other projects in N_d.

How much (i.e., what quantity) of unused net supplies could be transported to which projects to fulfill their extra demand with minimal transshipment cost will be answered in Step 2.

7.3.3 Step 2 - Optimize transshipment quantities using the evolutionary algorithm

Formulation of the math model

The total cost incurred during the transshipment supply chain processes, that is, the objective function to optimize the quantities to be transshipped among the candidate projects, is determined as:

$$minimize \sum_{(i,j)\in A} c_{i,j}x_{i,j}d_{i,j} + \sum_{(i,j)\in A} Hc_{i,j}x_{i,j} \tag{7.2}$$

Subject to the following constraints:

$$d_{i,j} \geq 0 \tag{7.3}$$

$$0 \leq \sum_{(i,k)\in A} x_{i,k} - \sum_{(j,i)\in A} x_{j,i} \leq b_i, i \in N_s, b_i \geq 0 \tag{7.4}$$

$$\sum_{(j,i)\in A} x_{j,i} - \sum_{(i,k)\in A} x_{i,k} \geq |b_i|, i \in N_d, b_i < 0 \tag{7.5}$$

$$l_{i,j} \leq x_{i,j} \leq u_{i,j} \tag{7.6}$$

The unit transportation cost from project node i to project node j along the arc (i,j), $c_{i,j}$ and the unit material handling cost $Hc_{i,j}$ could be different due to the variety of logistic providers available for transporting the materials. The cost data for each transport were accessible by the coordinator to be used together with the net supply and net demand data.

The total transportation cost was the multiplication of the unit transportation cost with the distance between project locations and the transported material quantities. Equation 7.4 ensured that one project should have non-negative outflows of materials when it had unused materials. Besides, the quantity of materials flowing or being transshipped to other projects should not be larger than its net supply quantity. On the contrary, when one project asks for additional quantities, Equation 7.5 needed to be met to ensure that the project can receive transshipped materials greater than its net demands quantity. This means that the project node should only have net inflows.

Besides, the quantity of each shipment depended on the capacity of the type and size of vehicles as well as the transportation regulations. Additionally, it would not be meaningful to transship a very small amount of materials from one project location to another. The transported material quantities along each arc, $x_{i,j}$, had a lower and an upper limit, which was ensured by Equation 7.6.

The objective function and the constraints constituted the math model, where $x_{i,j}$ was the decision variable to be optimized to achieve the minimal transshipment cost. The values of the parameters, i.e., $d_{i,j}$, $c_{i,j}$, $l_{i,j}$ and $u_{i,j}$ were given based on the specific project conditions in the project portfolio. The values of b_i were derived from Step 1. How this model was solved to obtain the optimal value of the decision variable, $x_{i,j}$, is explained in the evolutionary heuristic algorithm in Section 7.3.3.

Heuristic process of the evolutionary algorithm

The evolutionary heuristic algorithm was used to find the optimal material quantities for transshipment because the math model was formulated as a non-linear constrained optimization problem. This research used the evolutionary solving function of Microsoft Excel Solver for the heuristic computations. The Excel files for all the computations are shared online[3].

Similar to other heuristic algorithms, the evolutionary algorithm evaluated the fitness of members of the current population of trial solutions, where a new candidate solution was better than other solutions found earlier. This heuristic process stopped and returned a solution either when the results converged to a constant value for decision variables (i.e., the Excel solver cannot improve the current solution), or when a certain stopping criterion was met. In the Excel Solver, the stopping criteria for our math model were determined to consider the following parameters:

1. Population size was set as 100,
2. Mutation rate was set as 0.075,
3. The convergence threshold, which represented the maximum percentage difference in the objective function values that Excel Solver should allow to search for optimal solutions, was set as 0.0001.

To ensure that the evolutionary algorithm yielded a reliable result, it was required that the evolutionary solving function restarted from a previously derived optimal solution, and checked if it can find an even better solution in a reasonable amount of time. Besides, the population size and the mutation rate

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[3] The Excel files used for evolutionary heuristic computations are accessible and shared online via: `https://polybox.ethz.ch/index.php/s/9CCMai8RFLBKPrJ`

should be increased to restart the function. This would take more time to finish the heuristic process, but it could tend to increase the diversity of the population and the portion of the search space to be explored.

7.4 Example demonstration

7.4.1 Description of example project portfolio

To test the usefulness of the proposed approach, the project portfolio of a contractor was used as an example. The contractor had seven (N=7) building projects located in the Canton of Zurich in Switzerland. The seven projects were taking place simultaneously. The geographical distribution of the seven projects and the relationship of the transshipment supply chain network are depicted in Figure 7.4. The seven projects all needed the ready-mix concrete to complete in-situ construction tasks within the same planning week. The seven projects were located relatively near each other so that the time of re-distribution of ready-mix concrete between project sites did not exceed the concrete hardening time. These preconditions ensured the representativeness of the selected projects to study. In the directed network, 'Project_A' had unused materials that could be transshipped to candidate projects, such as 'Project_Q', which demanded extra quantities of materials. A project could be receiving transshipped materials or transshipping materials out, depending on the optimized decision variables $x_{1,2}$, $x_{1,3}$,..., and $x_{7,6}$. The unit transportation cost and the transportation distances between projects are provided and saved online[3]. A coordinator was designated to arrange the transshipment of the ready-mix concrete among the projects.

7.4.2 Step 1 – Calculate material quantities for transshipment in a project portfolio

Each of the seven projects had a 3D building model designed in Autodesk Revit software. The task IDs (shown in Figure 7.5), which represented in-situ floor-concreting tasks on a specific day in one project location, were registered as a shared parameter in Revit. Each floor slab element was associated with the respective task ID. The linkage between the floor-concreting tasks and the material demand quantities for one project is shown in Figure 7.6. The same task ID assignment and linkage were applied to all of the projects. Then the demand quantities as planned in the daily work plan, d_i, were extracted by using the built-in quantity take-off function in Revit.

As the coordinator was able to access the daily delivery plans of the seven projects, the delivered quantities of ready-mix concrete were collected to be further compared with the daily planned demand quantities. The net supply and

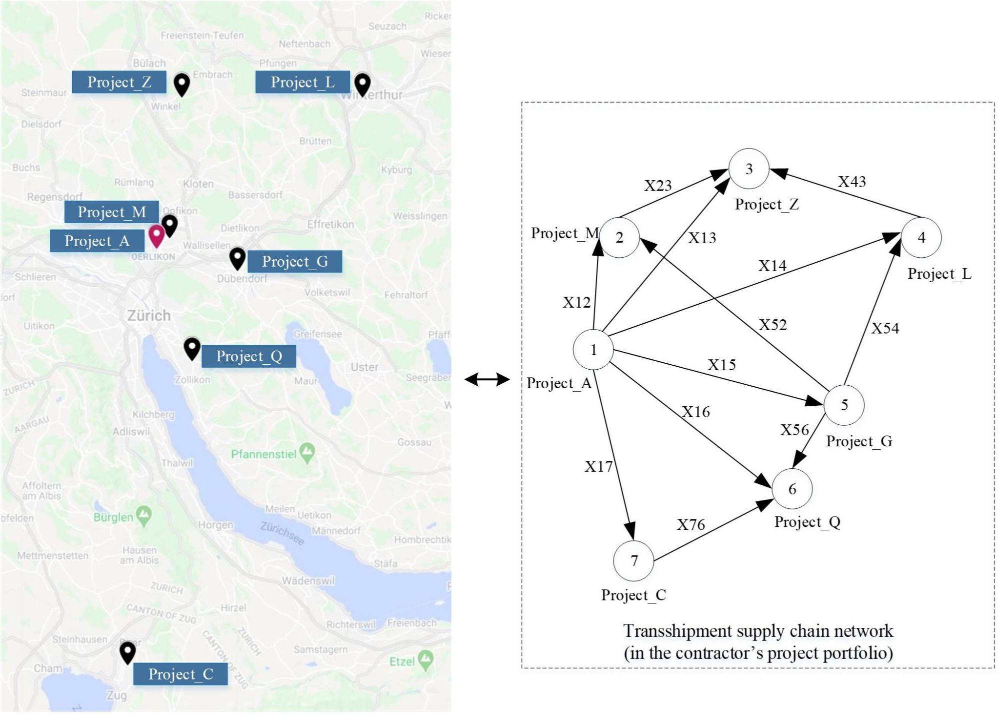

Figure 7.4: Geographical distribution of the seven projects (left) and relations of transshipment supply chain network (right). Node 1 represents 'Project_A'

net demand values could be calculated based on Equation 7.1. The results are summarized in Table 7.3.

Table 7.3: The net supply and net demand of the seven projects on a specific day (m^3)

Project	Node	s_i	d_i	b_i[4]
A	1	300.2	217.7	82.5
M	2	56.8	40.5	16.3
Z	3	50.4	86.6	-36.2
L	4	36.1	52.4	-16.3
G	5	78.5	22.3	56.2
Q	6	44.1	100.3	-56.2
C	7	32.5	16	16.5

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[4] a positive value of b_i means a net supply; otherwise, it means a net demand

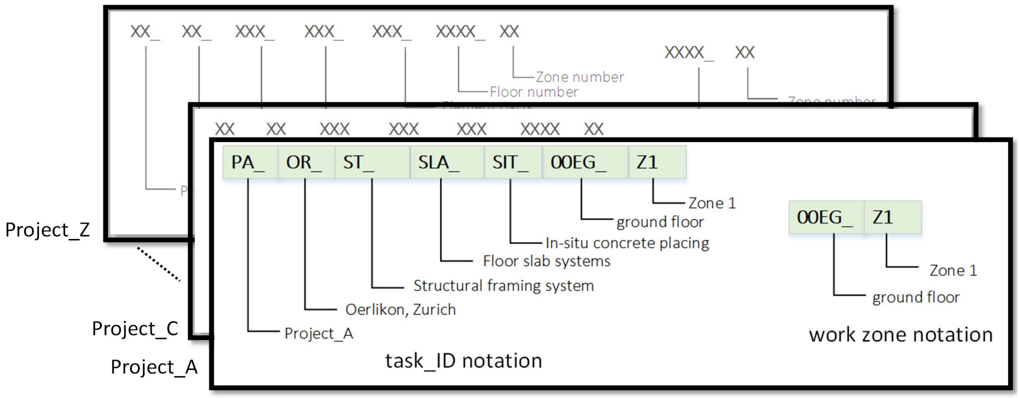


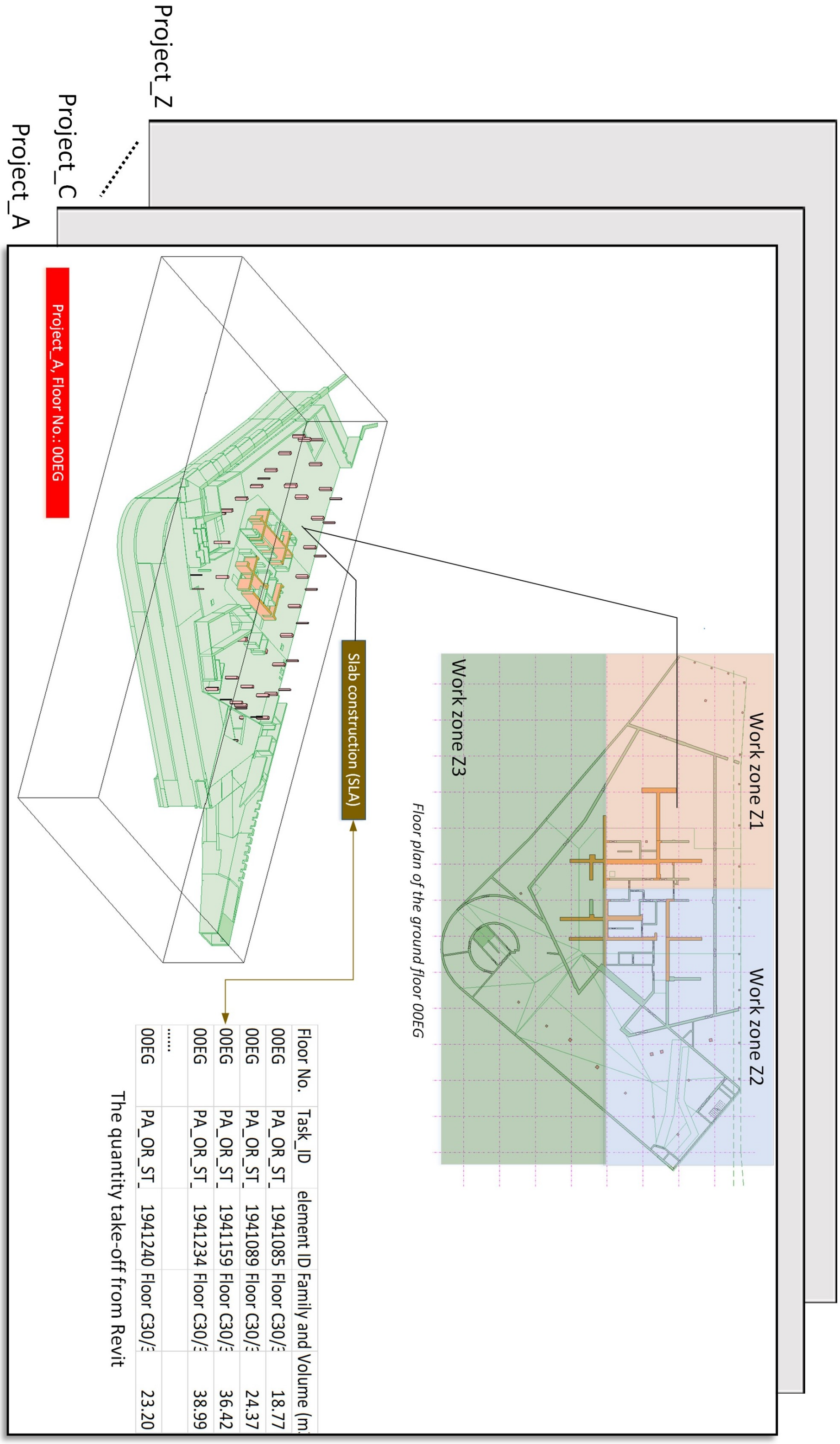
Figure 7.5: The task ID designed for the daily in-situ floor-concreting task

7.4.3 Step 2 - Optimize transshipment quantities using the evolutionary algorithm

To formulate the model, the coordinator collected the data for parameters, i.e., $d_{i,j}$, $c_{i,j}$, $l_{i,j}$ and $u_{i,j}$, which were shared online[3]. The upper limit of one shipment was 100 m^3, and the lower limit was 10 m^3, for any pair of the project nodes. In Excel Solver, its evolutionary heuristic process successfully converged the optimal values of decision variables, which are summarized in Table 7.4. Table 7.4 indicates that the candidate projects to receive the transshipped materials were 'Project_Z', 'Project_G', 'Project_Q', and 'Project_L'.

The total cost for the transshipment of ready-mix concrete based on the optimal solution was 12076 USD. If the proposed approach was not implemented to deal with the unused ready-mix concrete, the concrete would have started to cure and eventually become unusable (i.e., wasted) on-site.

If the unit price for producing and delivering the ready-mix concrete was 150 USD/m^3, the total cost incurred from the waste should be 25,725 USD (150 * [82.5 + 16.3 + 56.2 + 16.5]). Since the role of a coordinator was added to ensure the information flows between project sites, the labor costs were added to the total cost for the transshipment, which was estimated to be 300 USD per transshipment arrangement for the example. The total cost for the transshipment was 12376 ([12,076 + 300]). In the example project portfolio, the contractor could save around 52% ([25,725-12,376] / 25,725) of the cost material that otherwise would be unused or wasted ready-mix concrete on site.



Floor No.	Task_ID	element ID	Family and	Volume (m
00EG	PA_OR_ST_	1941085	Floor C30/3	18.77
00EG	PA_OR_ST_	1941089	Floor C30/3	24.37
00EG	PA_OR_ST_	1941159	Floor C30/3	36.42
00EG	PA_OR_ST_	1941234	Floor C30/3	38.99
......				
00EG	PA_OR_ST_	1941240	Floor C30/3	23.20

The quantity take-off from Revit

Figure 7.6: The linkage between the floor-concreting tasks and the concrete demand quantities

Table 7.4: The optimal values of decision variables

Decision variable	Supplying node	Receiving node	Optimal transshipped quantity (m^3)
$x_{1,2}$	1 (A)	2 (M)	0
$x_{1,3}$	1 (A)	3 (Z)	29.9
$x_{1,4}$	1 (A)	4 (L)	0
$x_{1,5}$	1 (A)	5 (G)	10.0
$x_{1,6}$	1 (A)	6 (Q)	66.2
$x_{1,7}$	1 (A)	7 (C)	0
$x_{2,3}$	2 (M)	3 (Z)	26.3
$x_{4,3}$	4 (L)	3 (Z)	0
$x_{5,2}$	5 (G)	2 (M)	0
$x_{5,4}$	5 (G)	4 (L)	26.3
$x_{5,6}$	5 (G)	6 (Q)	10.0
$x_{7,6}$	7 (C)	6 (Q)	0

7.4.4 Sensitivity analysis

A sensitivity analysis was done to validate the reliability of the optimal solutions for transshipment quantities and get a better understanding of the impacts caused by the change of the transportation capacity. Figure 7.7 shows the results of the transshipment quantities between projects versus the changes in the lower limit of the transportation capacity. The range of the lower limit of the transportation capacity was set between 10 m^3 and 30 m^3. The results indicate that the predefined evolutionary algorithm could always converge to optimal solutions of transshipment quantities with the changing parameters, and these solutions were almost statistically robust and stable. Besides, the impact by changing the upper limit of transportation capacity was negligible. This is because the extra material needs from receiving nodes were relatively low in this specific example demonstration.

7.5 Discussion

7.5.1 Cost-efficiency through lateral sharing of materials

From a perspective of supply chain efficiency, the contractor could save 52% of the cost by avoiding waste when using the proposed two-step transshipment approach instead of using the normal approach that ignores the unused ready-mix concrete on site. The cost-saving shows that there are benefits when a contractor (or a coordinator) can allocate the unused materials to candidate projects who need additional materials of the same type. Considering the average cost reduction figures mentioned in other research related to supply chain optimization, such as 10% [347], 27% [302] and 60% [37], the 52% of cost reduction in this research is relatively a substantial improvement. It is also foreseeable that considerable cost reduction is possible for the transshipment of non-perishable type

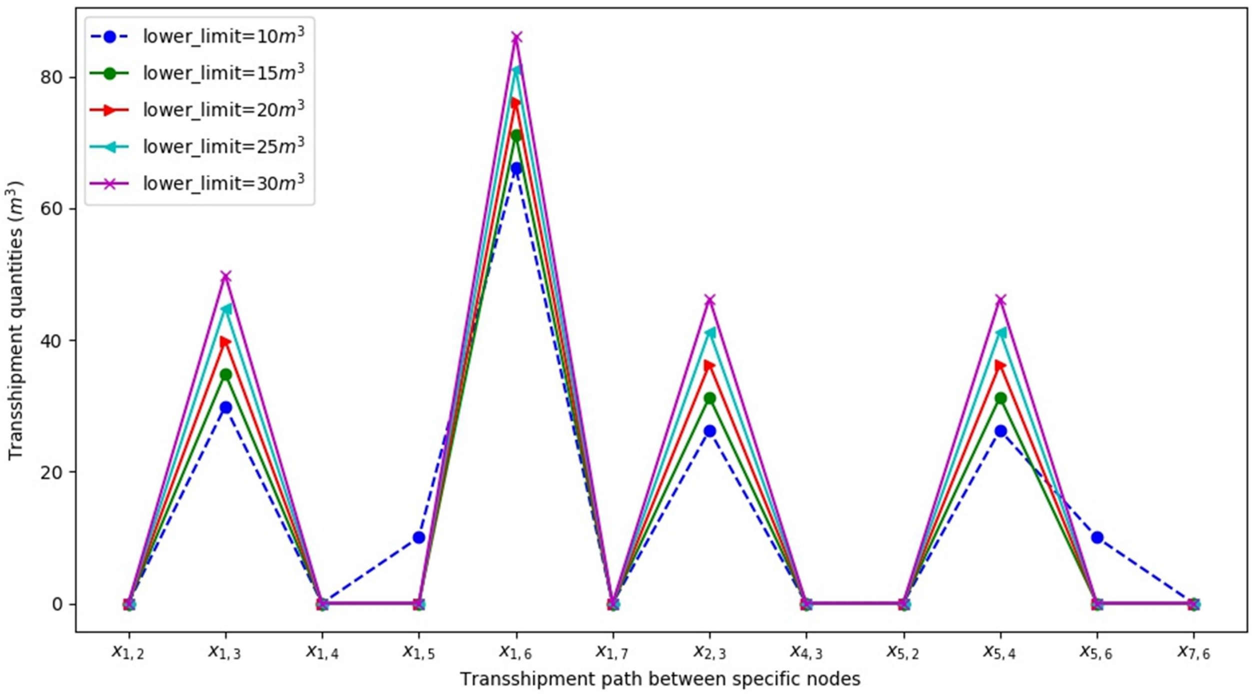


Figure 7.7: Sensitivity analysis result: the transshipment quantities between projects versus the changing lower limit of transportation capacity (Color figure available online)

of materials, including the prefabricated elements and dry bulk commodities that do not deteriorate quickly (e.g., steel, rebar, sand, etc.).

If the maximum surplus from one project site exactly meets the maximum deficit from another, the lateral sharing strategy is as simple as one-on-one material exchange. This is also the most cost-efficient scenario. In most situations, the combination of surplus and deficit status is more complex, making it difficult to coordinate material flow among projects [198]. The difficulty could be efficiently overcome by the proposed approach as it provides solutions for a broader range of surplus-deficit scenarios among projects. Although there has been very limited relevant research to validate the consistency of the test results, a group of sensitivity analysis was sufficient to show the robustness and reliability of the approach and the results.

The proposed approach could fill the gap in the current construction supply chain by providing a cost-efficient lateral sharing strategy for a contractor to manage a group of projects. The approach also allows the contractor to make the best use of unused materials in a project portfolio.

7.5.2 Agility of material planning

From a perspective of supply chain agility, this research contributes by automating information collection to support the decision making processes for transshipment planning. The supply chain agility was debated as an important part of lean construction principles to pursue automation and waste reduction [264, 37]. This research could be viewed as a concrete implementation of lean construction principles. First, using BIM authoring software enables quick and accurate data collection of material quantity take-offs. Next, the evolutionary heuristic algorithm is sufficiently built for the collected data to enables the quick generation of transshipment solutions. These two steps automate the whole process of transshipment planning to a certain level so that all the project sites can respond quickly to each other's needs.

The evolutionary algorithm, however, does not rely on derivative or gradient information, so it is possible to get stuck in a local optimal solution [28, 19]. Many other heuristic algorithms, such as covariance matrix adaption algorithms and genetic algorithms, should be experimented to solve the same math model and to evaluate the respective solutions. Nonetheless, common practices of using these heuristic-based optimization models have focused on planning and scheduling on delivery times and material quantities for a single project considering the flow of materials from multiple suppliers. They are limited to extending the material flow to a network of projects to be managed by an individual contractor. In comparison to conventional practices, the proposed approach specifically advanced the planning of materials within a contractor's project portfolio to reduce material wastes internally. It, in turn, improves the contractor's agility to respond to material demand changes among different project sites without relying too much on the suppliers.

7.5.3 Scalability of the transshipment approach

The proposed transshipment approach was designed based on a two-echelon supply chain structure. For a portfolio of complex projects, the entire supply chain structure could be composed of multi-layer suppliers, which increases the chances of the bullwhip effect – the phenomenon in which information on demand is distorted as when the moving up a supply chain. This brings additional challenges for the contractor to stabilize the information and material flow across different construction projects and various suppliers. Due to the potentials of a BIM-based shared data environment, the proposed approach could be easily extended to incorporate the functions of bi-directional data exchange between suppliers and the contractor. By doing so, the site demand information could be fed into the suppliers' databases quickly to reduce the information asymmetry caused by the bullwhip effect.

Apart from the two-echelon structure, another important prerequisite to implementing the approach was the full control of information at the coordinator's side. Although the design of a digital platform is beyond the scope of this research, it is essential to regulate the data use and information control when managing a portfolio of projects. The integration of the transshipment math model and the 4D BIM platform can be further adapted to include clear definitions of stakeholder roles and data accessibilities. This is also highly relevant to data protection and legal issues to have a significant impact on the efficiency of the implementation of the approach. With the advancement of blockchain technology, it is possible that these problems could be alleviated by its reliable distributed-ledger data structure [135]. If the blockchain technology is used to develop an automated system of transshipment planning, the sharing of cost data and dynamic demands between the participants will become more transparent and proactive.

Another possibility to scale up the proposed approach is to relax the assumptions to allow transshipment of non-perishable type of materials. The current model requires the immediate re-distribution of materials within the same planning time window. This is because the perishable materials have little tolerance for quality loss with time, e.g., being stored for a while on site. On the contrary, for non-perishable materials, the site storage is more common and feasible. For example, the unused additional precast steels could be stored in the laydown areas and transshipped at a later time to meet specific needs from other projects. To allow the transshipment of the non-perishable materials, the transshipment mathematical model needs to be reformulated to incorporate a time variable for the temporary storage of unused non-perishable materials.

7.6 Conclusions and future work

This study proposes a two-step transshipment approach to help the contractor to conduct lateral sharing of unused perishable materials in a project portfolio, where the supply and demand fluctuation could be well managed with minimal cost. The first step is to link 3D models in BIM authoring software with task information to calculate the daily net material supply and demand quantities regarding transshipment. The second step is to use this data to construct a math model, which aims to optimize the material quantities to be transshipped within the project portfolio. The evolutionary heuristic algorithm is used to solve the math model and find optimal solutions under minimal material transportation and handling cost. To test the usefulness of the approach, an example project portfolio of seven building projects was used to derive the transshipment quantities of unused materials between projects. Results indicate an approximate 52% of cost-saving compared to a normal situation when unused perishable materials are wasted on site. This cost-saving should be viewed as a substantial improvement for the existing practice of coordination of material flow. The sensitivity analysis of model parameters also indicates that the optimal solutions found from the proposed approach were statistically robust and stable.

The transshipment approach could open a new way for contractors to cope with over-ordered and unused perishable materials. It helps develop contractors' preparedness and responsiveness to supply chain disruptions and demand fluctuations during dynamic construction processes. Ultimately, this could accelerate the project timeline and reduce material costs for an overall portfolio of projects. More real-world projects should be tested in the future to validate the usefulness of the approach. Important operational constraints, such as the complex contractual relationships and stakeholders' willingness to share cost data, should be thoroughly investigated case by case to improve the practicality of the approach. Additionally, the success of the heuristic algorithms is highly dependent on the specific problem formulation case by case; therefore, a variety of heuristic algorithms need to be experimented to validate their fitness for different problem settings.

Chapter 8

Conclusions and outlook

This chapter provides the synthesis of the research objectives, main contributions of this dissertation, and main limitations along with future research work areas. This chapter concludes the entire dissertation work with reflections on the importance and the potential of the proposed systemic approach to enabling digital supply chain coordination in construction projects, which support project stakeholders with an ultimate goal to improve project performance.

8.1 Introduction

The dissertation aimed to develop a systematic approach and the corresponding techniques to improve the coordination of material and information flows in construction projects, considering the integration of lean workflows, digital technologies, and optimization algorithms, with a special focus on stakeholders' collaborative decision-making processes. The dissertation intends to achieve two review objectives and four research objectives. To establish a foundation of knowledge, two literature reviews were conducted on the topic of advanced technologies and enablers for coordination of the construction supply chain. The different technologies and enablers were summarized and categorised based on the authors' interpretation of the main contextual information from the selected literature. The dissertation addressed the research gaps by fulfilling four major objectives:

1. design a lean workflow to enable the digital integration of all supply chain phases from upstream (design phase) to downstream (installation phase) considering the need to pull installation demands into upstream material design and production activities;

2. devise an integrated management system to support the lean workflow specifically on the coordination of required changes, such as changes to the material design and installation schedules during construction processes;

3. develop a collaborative approach based on digital information that allows the project stakeholders to deal with demand fluctuations and make reliable decisions on material ordering plans to achieve minimal costs;
4. develop a multi-project coordination technique to help project contractors or owners collect digital information on material supply and demand, and optimize material flows among a network of projects to reduce waste, considering the site progresses of all the ongoing projects on a short-term basis.

The work in Chapter 4 and Chapter 5 focused on improving ETO material flow processes, which were primarily the increased visibility, agility and reliability in material planning and delivery considering the design and schedule changes. The work in Chapter 6 and Chapter 7 focused on improving bulk material flow processes, which were primarily the increased efficiency of material planning and reduced waste of materials (sustainability) during construction processes. The lean-digital paradigm was demonstrated useful when the data-driven decision-making processes were applied to the coordination of both types of materials.

The following sections summarize the results of achieving the objectives stated in Section 1.3, indicating their importance and impact.

8.2 Scientific contributions (synthesis of the objectives)

8.2.1 Design of a lean workflow to align the use of the integrated BIM-RFID system

To add value to the processes of implementing digital and information communication technologies, a lean workflow was introduced in Chapter 4 that incorporates the use of look-ahead planning processes into the conventional technological implementation of BIM and RFID technologies. The lean workflow was in turn supported by the digital data flow allowed by BIM and RFID technologies, in the form of an integrated management system as described in Chapter 5. The proposed lean workflow was characterized by two decision points to monitor the accurate releasing time for material production and transportation, which were tightly associated with the material installation tasks in the designated look-ahead planning window. Its potential was complemented by the advantage of the integrated BIM and RFID database system, which facilitates efficient information exchange between involved project stakeholders. The lean workflow was designed to align the design of the integrated BIM and RFID database system, where the two decision points were embedded in the database to allow immediate warnings and message notifications. Not only the daily workflow could be streamlined by the newly designed lean workflow, but also the traditional change management practices could be innovated by implementing the digitally supported lean principles.

Specifically, this work advanced the state-of-the-art in the field of construction automation and digitalization as follows:

- The use of look-ahead planning processes helps regulate the information flow support by BIM and RFID technologies. Compared with the traditional way of using multiple phone calls or email correspondence on a occasional basis, the integration of regular updates of information with efficient data collection and transmitting technologies allows the users quickly use information, get structured information and make reliable decisions on material deliveries. For example, in Chapter 4, the information of prefabricated columns installation needs and deliveries was collected and updated on a weekly basis, so that the design change could be finally fixed within a week before production of the columns. For materials that have a shorter lead time, the information updates among relevant stakeholders could be more frequent, for example in Chapter 7, the transshipment information about the over-ordered ready-mix concrete should be exchanged between project sites on an hourly basis. The proposed BIM-RFID-LAP workflow could be easily scaled and re-configured to satisfy the needs for managing different materials with different lead times.

- Example demonstration of the lean workflow design is sufficient through stochastic process simulations. The proposed lean workflow is shown by simulating how the material flow processes would be managed during the construction of repetitive ETO elements in an office building project. Through discrete event simulation runs, it was found that the proposed workflow can reduce the average floor construction time, for example, by 16.1% compared with the BIM-RFID-TRA workflow. Though more data can be collected from multiple projects for the process simulations, the simulation results derived from the stochastic simulating framework are sufficient to provide an overview of the differences between the two workflows. The simulation results also provide the evidence to show the potential of using look-ahead plans to improve the existing practice of applications of integrated BIM and RFID technology. It is considered, therefore, a solid demonstration of complementing advanced Industry 4.0 technology with lean principles to fill the gaps in the state-of-the-art.

- To break the fragmentation problems, the integrated management system enables the contractors to better observe on-site status and differences between the actual and planned material requirements, as well as to alert suppliers if necessary. This system helps both contractors and suppliers proactively track actual material demands and supplies, which eliminates the time needed for correcting wrong deliveries because of changes on the selection of materials or changes on the actual material need time. Because of the incorporation of look-ahead plans, the entire material flow processes can be managed with high granularity and information transparency into detailed construction processes. The existing gaps found in the conventional use of BIM and RFID technologies have been addressed. Its implementation will help realize the Industry 4.0 vision.

- To overcome the challenges of addressing the required changes, the integrated management system provides construction contractors and suppliers with the ability to coordinate change information efficiently and make decisions collaboratively on the deliveries of ETO components. The system consisted of four functional modules to facilitate the coordination of changes regarding material design and site schedule, including the: (1) design-change module, (2) schedule-change module, (3) production module, and (4) transport module. The information needed for coordination was collected from BIM and RFID and then integrated into a central database system. 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. The highlighted features of the system were its functionalities to make material deliveries more adaptable to respond to inevitable changes in the near-term pull schedule. From the theory point of view, the development of the system is a concrete realization of the look-ahead planning processes (i.e., from lean construction theories) in a digital manner, which improves upon traditional processes.
- The lean workflow can be generalized and adapted to apply to different project settings and workflow requirements. The integrated management system can also be easily maintained and configured to accommodate specific projects, including ones of larger sizes. It can be reconfigured to a cloud service architecture, which improves collaborative working culture for the integration of suppliers and contractors. For example, the proposed system could be built on Microsoft Azure, so that it would be easily scalable, and synchronization amongst different project stakeholders could be managed most effectively.

8.2.2 Development of a general framework to allow object-based supply chain management with a high granularity of information

Besides the stakeholder integration driven by the digitally supported lean workflow, the proposed lean workflow also featured the data-driven and object-based supply chain management. Both Chapter 4 and Chapter 5 used the ETO components to demonstrate the usefulness of the workflow, which is considered suitable for object-based supply chain processes. Each ETO component was modeled as an individual and unique building element in the BIM environment along with a unique RFID tag. Therefore, the status of ETO components could be tracked individually to allow high precision of material status tracking. This makes the coordination of the material and associated information flows much easier for both the suppliers and the contractors.

Specifically, this work advanced the state-of-the-art in the field of supply chain management as follows:

- Using an integrated BIM and RFID database system ensures that each ETO component is modeled and managed as a unique component, which is precisely linked with the associated material installation time. This helps solve the problems during traditional change request processes, where design models are neither kept up to date with changes made on-site nor updated as specific products are procured and installed. Using the digitally supported lean workflow, these design drawings and schedules have maintained the object intelligence and parametric capabilities of the model.
- To address the problem of inaccurate information delivery, the object-based supply chain management processes focus on the production, delivery, and management of as many specific BIM objects as possible to integrate into a digital model, right up until the installation of the building object. The regular use of the integrated management system allows all the stakeholders to save time because all the available information of required components, particularly the time for producing and transporting the components, is centralized in the integrated database. Therefore, the purchasing department will be able to optimize its time and will know exactly what to order. Also, the installation work on the construction site is optimized.
- The high granularity of information, provided by the integrated management system based on the lean workflow, is viewed as a solid foundation for collecting production, site installation, and handover documentation. The contractors can use the integrated database and the visual aspects of the model to assign responsibilities, track the status, and make it easier to connect documentation to the correct part of the building structure. Digital documentation in the form of BIM objects can be automatically delivered by the supply chain the same way they deliver order confirmations and invoices.

8.2.3 Integration of digital information flow with emerging heuristics to support decision-making in construction supply chain processes

To overcome the challenges of coordinating material demand and supply in a highly uncertain and dynamic construction environment, Chapter 6 focused on the integration of lean principles and intelligent algorithms to support data-driven stakeholder decision-making. Compared to the traditional decision-making processes where stakeholders heavily relied on the rule of thumb experience and written documents, the two-step coordination approach described in Chapter 6 provided new ways for stakeholders to solve problems regarding supply disruptions and demand fluctuations. The main feature of this approach was the ensured responsiveness of material planning and ordering through efficient automatic process monitoring, the quick generation of modified orders with minimal costs, and immediate warnings. Therefore, this approach is considered as an innovative solution to automate the current practices of supply chain coordination with high reliability of decision-making.

Specifically, this work advanced the state-of-the-art in the field of stakeholder's decision-making science as follows:

- The integration of look-ahead planning processes, heuristic algorithms, and digital data flows allows the suppliers and the contractors not only to benefit from the efficiency from 4D models but also to make decisions responsively to cope with the uncertain demand changes. The 4D models were incorporated to enable efficient data collection and material quantity take-offs. The material demand quantities were seamlessly connected with the on-site construction processes, which were planned and re-planned in a short-term planning window. This near-term scheduling allows the contractors to quickly capture the site demand fluctuation according to the 'current status' of the tasks. With the 4D models, the estimation of the site progress and the calculation of the demand fluctuations are less error-prone and less time-consuming.

- The traditional evolutionary heuristics were no longer explored for construction supply chain problems. Keeping an eye on advanced algorithms from the computer science discipline, the CMA-ES heuristic algorithm was carried out to solve real-world problems. The algorithm was implemented to help the contractors find the optimal solutions to deal with the demand fluctuations. The solutions generated were sufficient to provide the extra-order quantities and outsourced quantities to formulate the revised order plans. The revised order plans ensure the contractors to fulfill the changed demand quantities with minimal costs. Therefore, the existing challenges of material coordination problems can be overcome with the potential from both perspectives.

- Sensitivity analysis was conducted, which implied that the available idle time for producing extra-order quantities has a great impact on the determination of solutions to demand fluctuations. Therefore, it is sensible to suggest the contractors make the best use of the suppliers' idle time to produce the additional quantities, as it will lead to minimal costs to deal with the increasing demand fluctuations. This strategy has not been discovered by researchers in the area of construction supply chain management, so the suggestions recommended in Chapter 6 are considered a new starting point for stakeholders to reconfigure the modelling of supply chain problems.

8.2.4 Application of the emerging manufacturing supply chain approach to reduce material wastes in the construction supply chain network

Apart from the decision-making within one single project to address supply chain uncertainties, Chapter 7 provided a methodology from a multi-project portfolio perspective. The major attention was given to the application of an emerging transshipment approach to construction supply chain networks, which could help reduce material waste during the deliveries of perishable bulk commodity. This approach is viewed as an extension to the work in Chapter 6, as it also features the two-step coordination approach involving smooth data flowing in a digital environment for optimal decision-making processes. Considering the value of using digital data flow, the transshipment approach was combined with a BIM database to formulate a two-step approach to increase the efficiency and reliability of making material-reallocation decisions. This research contributes to supply chain agility by automating the process of retrieving material information and determining the optimal transshipment decisions for multiple projects.

Specifically, this work advanced the state-of-the-art in the field of construction project portfolio management as follows:

- To overcome the inaccurate workflow in traditional project portfolio management, the proposed approach suggested the use of BIM authoring software to enable quick and accurate data collection of material quantity take-offs. The information could be flowing smoothly from 3D modelling into the decision-making processes without significant information loss. This allows the project portfolio owner to rely on quick and accurate information to balance material deliveries on different projects to avoid material waste.

- The emerging concept of “lateral sharing” was first adopted in the construction supply chain network. To model the lateral sharing processes for different projects, a network flow math model was constructed and the evolutionary heuristic algorithm was used to enable the generation of reliable results of transshipment quantities to achieve minimal transportation cost. Therefore, this approach is considered as a starting point to drive the transformation of traditional site inventory management to reduce material waste. The emergence of carriers that deliver items to geographically dispersed destinations quickly and at a reasonable cost, combined with the low cost of sharing information through networked databases, has opened up new opportunities to better manage inventory.

- The supply chain network from a project portfolio perspective was modeled as a network flow model problem, where each construction project was considered as a node. This allows the simple abstraction of the supply chain network design, which makes it easier to approximate an optimal solution of optimizing the lateral sharing of materials. The optimal solution is also helpful for the project portfolio owner to obtain better decisions than making decisions based on the rule of thumb experience.
- Although the proposed transshipment model can be directly solved with a linear programming process, it is suggested to use evolutionary heuristic process instead. This is mainly because the network flow model will be expanded with polynomial complexity to be a non-linear model, which is more realistic to reflect the complex real-world scenarios, for example, the current math model will need to incorporate the various presidential relationships between site installation tasks.

8.2.5 Summary

In summary, this dissertation contributes to the field of construction supply chain management and construction management by providing a systematic approach and corresponding techniques to optimize the coordination of material and information flows in construction projects, considering the integration of lean workflows, digital technologies, and optimization algorithms, with a special focus on stakeholders' collaborative decision-making processes. Construction supply chain management normally receives less attention than design management or construction process optimization; however, it requires a novel methodology to advance the current practices of supply chain processes in construction projects. More precisely, this thesis contributes by explaining how the material demand and supply can be coordinated to enhance stakeholder's decision-making capabilities, minimize material waste and make sure the right materials are delivered to site needs at the right time with the appropriate costs. Upon finishing this dissertation, the involved research contributions not only extend the state-of-the-art in this field but also help to provide solid decision support tools and a management framework for project stakeholders, particularly for the contractors and suppliers.

8.3 Practical contributions

The dissertation aimed to develop a systematic approach and the corresponding techniques to improve the coordination of material and information flows in construction projects, considering the integration of lean workflows, digital technologies, and optimization algorithms, with a special focus on stakeholders' collaborative decision-making processes. Four research objectives were proposed and achieved in a way that all the necessary research steps were included from problem identification, system design, process design and process simulation, math modelling to methodology demonstration. These steps allow project stakeholders to build a deeper understanding of the synergies of lean principles, advanced digital and automation technologies, and intelligent algorithms to support decision-making activities over supply chain processes.

The different techniques have been demonstrated consistently using real-world construction projects. Each technique was designed keeping in mind that the granularity of material planning and coordination depends on the different levels of detail. While the demonstration of the techniques was based on one specific office building project consistently, the techniques provided are sufficiently general to be applied to other projects of a similar type. To make such implementation as simple as possible, special considerations should be given to legal aspects, data access rights, project organizational structure, and project culture. Nonetheless, these techniques can be generalized and adapted to apply to different project settings and workflow requirements. For example, the integrated management system can be easily maintained and configured to accommodate specific projects, including ones of larger sizes.

Apart from the material coordination perspective, the techniques or methodologies involved in this dissertation will aid the stakeholders in tracking site performance so that the status of installation tasks can be shared among the stakeholder's network. The immediate status feedback provides clues about the potential risks of project delay and cost overrun. This also sheds light on how stakeholders transform their traditional logistic view of managing material flows and move toward a more integrated and collaborative paradigm.

8.4 Limitations

The dissertation has made relevant contributions to the field of construction project management and supply chain management; however, there is room for improvement. The limitations of the current work are pointed out as follows.

8.4.1 Data sharing

The case studies presented in Chapter 4 - Chapter 7 have focused on the sharing of material procurement data between contractors and suppliers, which was not at the highest level of granularity found in some BIM authoring software. For example, the detailed design data, the data from fabrication drawings and specifications to a level of definition of 500, may be available to architects, engineers, contractors, and suppliers in some personalized BIM software. Nonetheless, the selection of the modelling data at a level of definition of 300 and Autodesk Revit software was sufficient to illustrate the usefulness of the proposed methodologies. The comparison of proposed methodologies to the traditional approach was unaffected by these limitations. However, more detailed data could increase the reliability of decisions made during the coordination of material and information flows. Some implications for this limitation include:

- The information requirements from different project stakeholders are usually different, causing inconsistencies of stakeholders' requirements in the level of definition of modelling files. The interpretation of the modelling details could be also inconsistent leading to misunderstandings, which could be overcome by a certain level of standardization. The proposed lean workflow in Chapter 4 already standardized and streamlined the data requirements; however, a wider scope of standardization would be more helpful. Not only do the processes need to be standardized, but they also require flexibility for the stakeholders to cope with variability in material design and production [255]. It is particularly important that suppliers quickly respond to the changing design requirements from clients to maintain market competitiveness. Virtual reality technologies could also be integrated to build a common understanding of material elements by project stakeholders.

- A data-rich model is useful only when the data interoperability is ensured for the communication of different types of software or platforms. Standard data formats were not the focus of this dissertation, but the importance of data standards should not be neglected. The investigation of an open, international, and vendor-neutral data formats should be further studied together with the proposed digitally supported lean workflow to allow information to flow smoothly across a wide range of hardware devices, software platforms, and interfaces for many different use cases.

- When project stakeholders share data, data ownership and legal constraints become unavoidable issues. The existing legal frameworks for professional service delivery in architectural, engineering, construction, and operations industries have not been adapted to the needs of open data sharing through e-business platforms. This is considered a major concern against the adoption of innovative information communication technologies. Although this dissertation did not focus on solving these issues, the design of the digital prototypes should take into consideration the data security and clear definition of roles of users. Specifically, considerations should be given to who owns the data, who can access the data, who authorizes the changes to the data, etc.

8.4.2 Supply chain network design

The supply chain network design is rather ideal in this dissertation when compared to real-world situations. One major assumption for the application of the methodologies in Chapter 4 - Chapter 7 is that no multi-layer or the multi-echelon suppliers are considered in the construction supply chain network. This means that only one layer of suppliers directly connected to the contractors is modeled in the digitally supported lean workflow system. While many other studies in the literature indicate the importance of a systematic analysis of all the supply chain members and the structural dimensions, the proposed methodologies in this dissertation could be easily extended to include the multi-layer suppliers' involvement. Some implications for this limitation include:

- Transshipment approach has lacked the capability to deal with projects that require different mix-design situations. Currently, the assumptions were proposed to consider only one scenario that all the project sites, managed by one general contractor, use the same design mix of the concrete, determined primarily by the same contracted architecture or engineering company. However, this is not very common in real-world situations. Particularly, all ready-mix concrete producers strive to find the perfect proportions of the ingredients of water and cement in order to optimize concrete mixes and give their concrete strength, durability, work-ability, and other desirable properties. Additionally, the different contractual processes have a big impact on the practicality of the transshipment approach. If the material producers or suppliers are not managed through one general contractor but are directly contracted with architecture or engineering company, the transshipment approach would face more challenges of collecting information for decision making of material reallocation and permitting processes to redistribute materials.

- Considering a wider scope of the supply chain network that may include the suppliers of the suppliers, a global optimization perspective is needed to ensure a more efficient but less complex supply chain coordination processes. The design of the lean workflow and the two-step coordination approach may further incorporate game-theoretic modelling, which is helpful to coordinate the material costs and ordering decisions for every layer or echelon and find the minimal costs for the entire supply chain network. Nevertheless, the design of the lean workflow and the two-step coordination approach is sufficient to address the two-echelon scenario and can be easily generalized to serve the multi-layer supply chain coordination proposes.

- Most of the other optimization methodologies mentioned in the literature have put attention on risk factors to affect the supply chain coordination efficiency. For example, risk factors have been identified and managed to hedge the dynamically changed production lead time. This perspective of risk management was beyond the scope of this dissertation. The uncertainties regarding the demand fluctuations and supply disruptions, however, have been adequately addressed in this dissertation. Two methodologies have been provided in Chapter 6 and Chapter 7 to explicitly find optimal solutions of material order quantities when site demand changes occur. They were demonstrated useful to manage the risks onsite during the dynamic construction processes.

- The lean workflow presented in Chapter 4 and Chapter 5 were tested using the discrete event simulations and Monte Carlo simulations. While there are a variety of other methodologies in the literature to serve the same purpose, for example, the use of the agent-based modelling and simulations, the results of testing workflows from this dissertation were sufficient to prove that the proposed lean workflow has reconfigured or redesigned an optimal supply chain network.

8.4.3 Lean and continuous improvement

Although lean principles contain several different specific tools and techniques, the look-ahead planning processes chosen specifically in this dissertation are considered useful to balance demand and supply during supply chain processes. There are many other useful techniques in the manufacturing industry to implement lean principles, which have not been adopted and tested for construction supply chains. For example, the takt planning technique, the Plan-Do-Check-Act technique, and the Key Performance Index system may be integrated into the research techniques developed in this dissertation. The potential of these useful techniques should be further investigated. Some implications for this limitation include:

- To establish a link between material information and the associated installation tasks, the work breakdown structure and task IDs were designed and consistently used in Chapter 4 - Chapter 7. There are other solutions mentioned in the literature to establish the link. For example, some researchers proposed the concept of intelligent planning units and takt planning units to link material information with the task unit at a detailed information level to reduce the variability in installation processes [170]. While this concept opens a new way to facilitate the coordination of materials with very structured detailed information, the solution in this dissertation is equally useful. It can be applied to achieve the same detailed level of planning and coordination without overloading stakeholders with information.
- In the manufacturing industry, continuous improvement has been a significantly important philosophy in lean management, which requires that stakeholders identify changes and take actions continuously in the business

processes. While some researchers have suggested a systematic and iterative Plan-Do-Check-Act framework for the implementation of lean principles, this four-stage framework was not explicitly followed by the main scope of this dissertation. Additionally, re-use of materials as a prospect part of continuous improvement in supply chains [270] was not addressed by this dissertation. The overall research objectives in this dissertation, however, included the Plan, Do, Check, and Act which were the most essential parts to allow responsiveness and agility in supply chain coordination. In particular, Chapter 5 addressed the iterative feedback processes for the project stakeholders to deal with design and schedule change requests, which fully reflected the requirements of this four-stage framework.

- The focus of designing the proposed lean workflow and system prototype was to re-engineer the traditional business processes, roles, and responsibilities in the supply chain network, while the final project performance assessment in terms of the cost performance was not investigated within the scope of this dissertation. Instead of the cost performance related to the implementation of the new workflow, the schedule performance was fully investigated to reflect the overall project performance. As the schedule is highly relevant to cost, the key performance indicators of the schedule used in this dissertation were adequate to support the usefulness of the proposed lean workflow and system prototype.

8.5 Outlook

Despite the contributions made in this dissertation, the understanding of coordination in the construction supply chain remain in its infancy. Based on the understanding of the limitations in Section 8.4, the following subsections provide possible future steps to this topic that will help improve overall construction project performance. The main themes include future data-sharing practices, the future supply chain network design possibilities, and the extensive lean implementation and continuous improvement.

8.5.1 Further data sharing

The proposals for future data-sharing research topics include the use of industrialized supply chain and configurators, automated object classification methods, and smart contracts. The relevant ideas are presented as follows:

- **Industrialized supply chain and configurators** To facilitate data standardization, the concept of “Industrialized supply chain” could be incorporated into the design of the lean workflow. Industrialization regarding construction started several years ago and is an important trend within the construction industry. The major benefits are the results of industrialization partially shifting activities from a construction site to remote locations. Reports and case studies from different parts of the world have shown that prefabrication and on-site assembly are becoming common practices, and consequently, the industrialized supply chain for construction projects opens a new way for the coordination of material and information flows. While the construction projects are subject to a variety of design needs and customization, configurator platforms are important elements to be studied together with supply chain management to ensure not only the standardization but also the possibilities of mass customization.

- **Automated object classification methods** To address the data interoperability issues, future research should emphasize improving data representation schema. IFC is widely accepted as the future of BIM to take on the challenge of BIM interoperability and enable its support of various automation tasks. However, it is not uncommon to see the misuses of IFC entities during the creation of BIM. Such misuses prevent successful automation of BIM-supported tasks because misclassification of objects in BIM can lead to significant negative consequences in downstream applications due to incorrect semantic information provided. A promising trend to allow better interoperability is the use of automated object classification methods for BIM objects. Some researchers have already developed new data-driven and iterative methods that can be used to develop an algorithm to automatically classify each object in an IFC model into predefined categories.

- **Smart contracts** To overcome the limitation caused by the legal constraints, new contractual schemes should be advocated. For example, smart contracts based on blockchain technology can help build trust between stakeholders. Blockchain technology provides decentralized consensus and potentially enlarges the contracting space through smart contracts. Meanwhile, generating decentralized consensus entails distributing information that necessarily alters the informational environment. With the help of fast-developing real-time communication technologies among decentralized record-keepers, a carefully designed protocol on blockchains can reduce an individual's incentive to manipulate and misreport, allowing more efficient information aggregation. Compared to traditional contracting, blockchains have the potential to produce a consensus that better reflects the "truth" of contingencies that are highly relevant for business operations, thereby enhancing contracting on these contingencies. These potentials particularly benefit the fragmented and adversarial contractual relationships in the construction supply chain processes.

8.5.2 Future supply chain network design

The proposals for future research topics in supply chain network design include the use of game theory, risk-hedging methods, and agent-based modelling. The relevant ideas are presented as follows:

- **Game theory** The importance of designing a supply chain network to ensure a balance of demand and supply among different entities is remarkable. Some studies in the literature explored the use of game theory to achieve this purpose. For example, one specific implementation is the Stackelberg game among the members of the chain, which aims to analyze the coordination behavior of the members of the proposed chain. The biggest potential is to maximize the total profit of the supply chain by employing the optimal pricing and ordering decision policies where the order quantities of a contractor and the selling prices of a supplier are the decision variables. Furthermore, the closed-form solutions of the decision variables can be generated from the method, which is more reliable than the results given by heuristic methods.

- **Risk hedging methods** In the financial domain, risk hedging is commonly used by investors to strategically offset the risk of any adverse price movements through the use of financial instruments or market strategies. The same concepts apply to the construction supply chain domain, where the supply chain network design could be aligned with the uncertainties, namely the demand fluctuations and the supply disruptions. Although there are many new supply chain concepts designed to exploit the advantages of the advanced information technologies, the right supply chain network design is dependent on several risk hedging factors, e.g., the condition of a supplier's physical facility and financial status, which must be fully investigated.

- **Agent-based modelling** In most traditional practices, each supply chain entity optimizes its operation without considering the impact on other entities. This often results in a larger variety of material supply and demand in the entire supply chain network. Many researchers have modelled construction supply chain in the agent-based modelling environment, and their studies have shown that this modelling approach helps managers detect and remove bottlenecks to reduce overall system cost throughout the supply chain. No matter which specific network modelling techniques are used, global optimization is always the central issue of systems thinking. All managers are motivated to ensure that the overall cost is reduced and operations among various systems are integrated through supply chain coordination.

8.5.3 More lean and continuous improvement

The proposals for future research topics in lean and continuous improvement include the use of intelligent planning units, continuous learning and improvement methods, and target value design. The relevant ideas are presented as follows:

- **"Leagile"** The leanness and agility could be investigated together to achieve "Leagile" benefits. For example, Last Planner System and Scrum share several principles related to the way the teams collaborate to organize the work and increase the value delivered to the customer [248]. Current construction supply chain practice has a special focus on design-construction integration, therefore, it would be useful to implement the concept of "Scrum Increment" into Last Planner System, and this may contribute to coping with the increased uncertainty, speed, and complexity inherent to the iterative design process, particularly in projects requiring considerable amount of change orders. Besides, a Scrum manager could be designated to regularly and continuously monitor the performance of the design and construction processes.

- **Intelligent planning units** The theory of an intelligent planning unit was recently designed by researchers to enable the complex built environment system to be more intelligent, standardize the complex physical entities and processes at a modular scale, and provide the decision-makers with timely and accurate information to improve decision-making processes. This is particularly useful for implementing lean material flows with structured and more detailed information. At an element level, a built environment system can be composed of special bricks that can sense all the environmental conditions during project life cycle and supply chain needs including the possibility to achieve construction circular economy. To extend the lean workflow with the intelligent planning unit concept would bring more potential to the coordination of material flows in the Construction 4.0 era.

- **Continuous learning and improvement** The basic conceptual framework of Plan-Do-Check-Act was proposed by many lean researchers to identify and tackle the problems on the assembly processes. To reinforce the potential of other specific lean methods, such as the look-ahead planning processes described in Chapter 4, this conceptual framework could be considered for integration to bring the view of the whole construction processes and conditions to prevent material waste. The look-ahead planning windows should be repeated each time after stakeholders essentially learn from the errors. In this way, the system-level continuous improvement could be realized.

- **Target value design** A popular stream of research in construction management is the target value design method. Its application is highly relevant to the key performance indicator system as project stakeholders could easily monitor and control critical performance metrics. The main principle of target costing is to make cost and value drive the design process instead of calculating the cost after a design is complete. Target costing is an effective management technique that has been used in manufacturing for decades to achieve cost predictability during new product development. Adoption of this technique could promise benefits for the construction supply chain processes as it struggles to raise the certainty of material deliveries in terms of cost, quality, and time. Despite potential benefits, there is little evidence of this practice being taken up specifically for the improvement of coordination of supply chain processes. Future research efforts should explore this path.

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Appendix A

Appendix: Literatures

This Appendix provides the supplementary information relevant to literature review processes in Chapter 2 and Chapter 3.

A.1 Construction automation

For the review on the topic of construction automation, the unstructured texts were retrieved from the 35 relevant publically available construction blogs of the top 50 determined by Feedspot using Web Scraper. Feedspot provided the most popular and influential websites that can indicate the developments in practice. The 50 social media webpages related to construction automation are shown in Table A.1.

Table A.1: 50 social media webpages related to construction automation

Item No.	Name of Webpage	Website	Applicable for data retrieval?	Category
1	Engineering News Record (ENR)	`http://www.enr.com/`	NO	online news
2	The Construction Index	`https://www.thecons-tructionindex.co.uk/all-construction-news`	YES	association webpage
3	Reddit Construction Blog	`https://www.reddit.com/r/Construction/`	YES	blog
4	Buildings: Smart Facility Management	`http://www.buildings.com/magazine/issue/672`	NO	online news
5	Equipment World	`http://www.equipmentworld.com/`	YES	online news
6	Construction News (CN)	`https://www.constructionnews.co.uk/`	YES	online news
7	Construction Enquirer	`http://www.constructionenquirer.com/`	YES	online news
8	Construction Dive	`http://www.constructiondive.com/`	YES	online news

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Table A.1 – continued from previous page

Item No.	Name of Webpage	Website	Applicable for data retrieval?	Category
9	Contractor Magazine	http://www.contractormag.com/	YES	online news
10	Professional Builder - Housing Zone	https://www.probuilder.com/	YES	online news
11	Sourceable	https://sourceable.net/	YES	blog
12	Capterra Construction Management Blog	http://blog.capterra.com/articles/construction-software/	YES	blog
13	Tiny House Blog	http://tinyhouseblog.com/	NO	blog
14	Construction Junkie Blog	http://www.constructionjunkie.com/	YES	blog
15	Construction Technology Blog	https://conappguru.com/blog/	YES	blog
16	Sage Construction and Real Estate Blog	http://blog.sagecre.com/	YES	blog
17	Commercial Construction & Renovation	http://www.ccr-mag.com/	NO	online news
18	ConstructConnect	http://www.constructconnect.com/	YES	association webpage
19	Aconex	https://www.aconex.com/blogs/	NO	association webpage
20	Sandvik Construction	http://construction.sandvik.com/news-media/	NO	association webpage
21	Build Blog	http://blog.buildllc.com/	YES	blog
22	Dexter + Chaney Blog	http://www.dexterchaney.com/news/blog/	NO	blog
23	ModSpace Blog – Construction News, Updates & Insights	http://blog.modspace.com/	NO	blog
24	Construction Specifier (The official magazine of CSI)	https://www.constructionspecifier.com/	YES	online news
25	THELIENZONE	https://www.thelienzone.com/	NO	association webpage
26	Extranet Evolution	http://extranetevolution.com/tag/eadoc/	NO	blog
27	AUTODESK - Industries	https://www.autodesk.com/solutions/bim/construction\-management-soft-ware	YES	association webpage
28	CONSTRUTECH	https://constructech.com/	YES	online news
29	Talking Construction	http://talkingconstruction.gateleyplc.com/	YES	blog
30	SHIEL SEXTON Blog	http://www.shielsexton.com/blog/	NO	blog

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Table A.1 – continued from previous page

Item No.	Name of Webpage	Website	Applicable for data retrieval?	Category
31	The UK Construction Blog	http://ukconstructionblog.co.uk/	YES	blog
32	Winnipeg Construction Association	http:winnipegconstruction.ca/news	NO	association webpage
33	WOHLSEN CONSTRUCTION	http://www.wohlsenconstruction.com/	NO	association webpage
34	GRANGER Blog	http://www.grangerconstruction.com/blog/	YES	blog
35	The Construction History Society (CHS)	http://www.constructionhistory.co.uk/	NO	association webpage
36	Alberta Construction Association	http://albertaconstruction.net/	NO	association webpage
37	Planting Acorns	http://plantingacorns.com/	YES	blog
38	Hard Hat Chat	http://commercialconstructionblog.com/	NO	blog
39	Stahl Construction	http://www.stahlconstruction.com/	NO	association webpage
40	Mates in Construction	http://matesinconstruction.org.au/	NO	blog
41	McKinsey&Company: Capital Projects and Infrastructure	http://www.mckinsey.com/industries/capital-projects-and-\infrastructure/our-insights	YES	online news
42	OAC Services	http://oacservicesinc.com/who-we-are/blog/	NO	association webpage
43	Jetson Green Projects	http://www.jetsongreen.com/	NO	association webpage
44	BuildingRadar	https://buildingradar.com/de/	YES	blog
45	Construction Industry Federation	http://cif.ie/news-feed/blog.html	YES	association webpage
46	CORE Construction	http://www.coreconstruction.com/news/	NO	association webpage
47	Digital Construction News	http://digitalconstructionnews.com/	YES	online news
48	Building.co.uk	http://www.building.co.uk/	YES	online news
49	Lean Construction Blog	http://leanconstructionblog.com/	YES	blog
50	Builder	http://www.builderonline.com/	YES	online news

A.2 Coordination enablers

For the review on the topic of construction supply chain coordination, the initial search returned 692 journal articles. This number was reduced by filtering to specific fields and manual check to 69 journal articles were selected for in-depth review. The selection process for the relevant publications is summarized in Figure A.1. Figure A.2 illustrates the distribution of the 69 publications by year, and Figure A.3 shows the distribution of the 69 publications by journal sources.

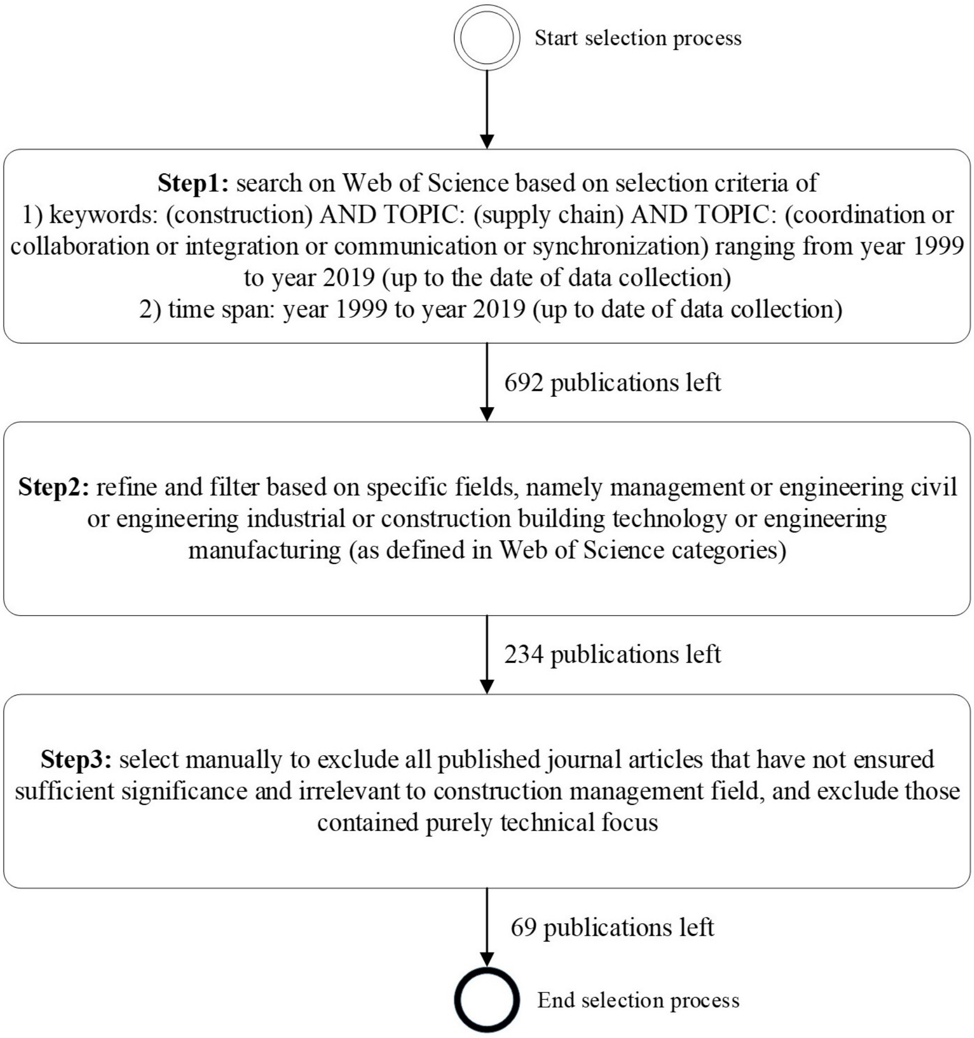


Figure A.1: The selection process for the relevant publications

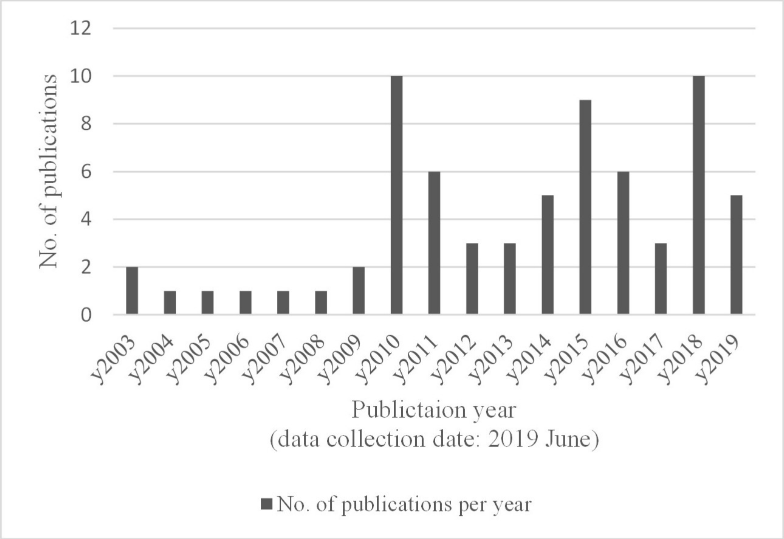


Figure A.2: The distribution of 69 publications by each year

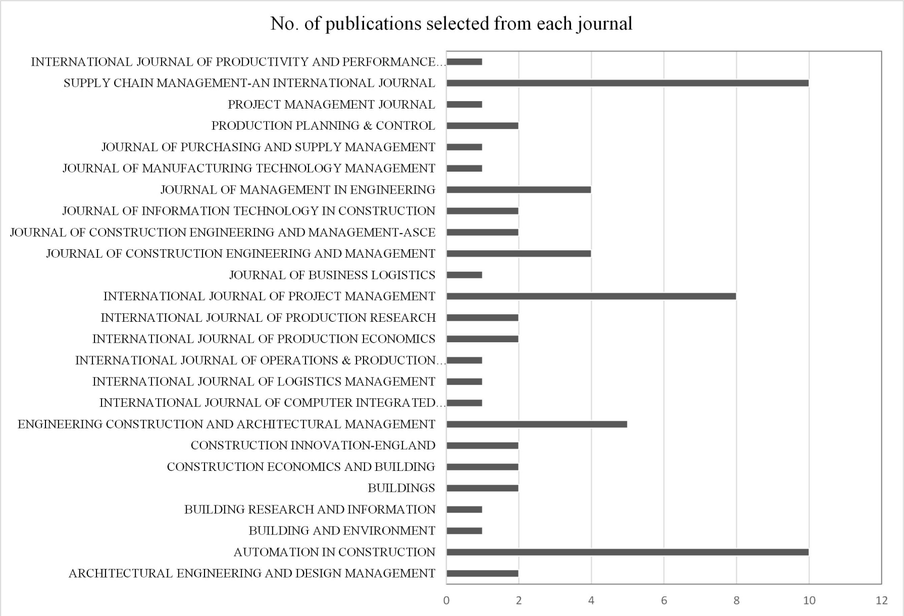


Figure A.3: The distribution of the 69 publications by journals (Most of the relevant publications originated from the journal of Automation in Construction, Engineering Construction and Architectural Management, International Journal of Project Management, and Supply Chain Management-An International Journal)

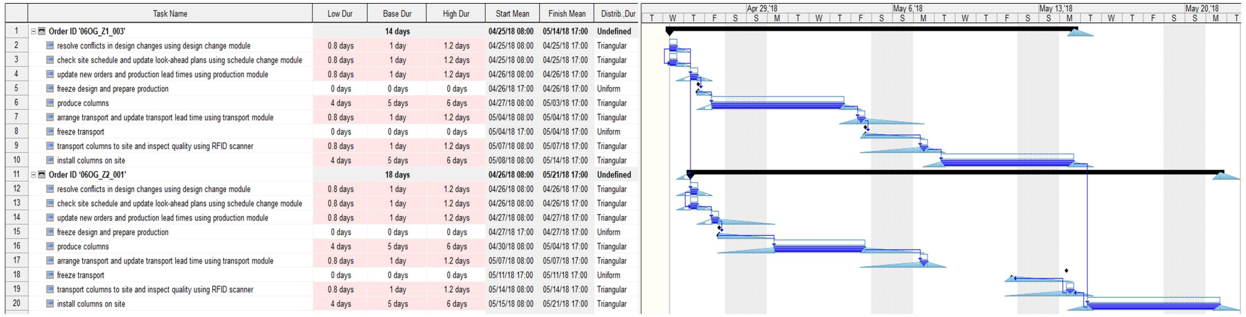
Appendix B

Appendix: Process simulations

The durations of the sub-processes for BIM-RFID-TRA and BIM-RFID-LAP workflows are provided in Table B.1. The discrete event simulations for both workflows were conducted in a java programming environment that allows the simulations repeat 1000 times to create the process simulation results in a stochastic framework.

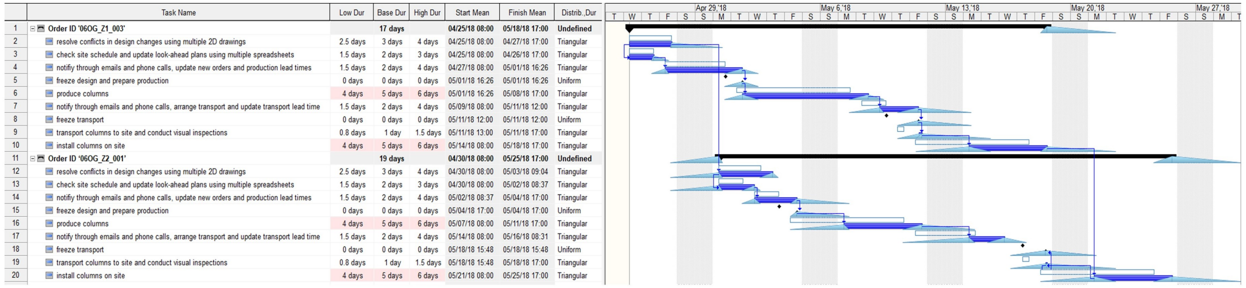
Table B.1: The durations of each sub-process during the estimation phase, procurement phase, transportation phase, inspection and storage phase, and material use phase (Note: TRIA(a, c, b) means a triangular distribution with lower limit value a, upper limit value b and mode value c, $N(\mu, \sigma^2)$ means a normal distribution with mean value μ and variance σ^2, $U(d, e)$ means a uniform distribution with minimum value d and maximum value e.)

Sub-processes in the BIM-RFID-LAP workflow				**Sub-processes in the BIM-RFID-TRA workflow**			
Sub-process ID	**Time (hr)**	**Sub-process ID**	**Time (hr)**	**Sub-process ID**	**Time (hr)**	**Sub-process ID**	**Time (hr)**
MRP01	N(20,1)	PRO19	N(4,0.1)	MRP01	N(20,1)	TRA04	N(2,0.1)
MRP02	N(20,1)	PRO20	U(1.6,8)	MRP02	N(20,1)	TRA05	N(2,0.1)
MRP03	N(8,0.5)	PRO21	N(4,0.1)	MRP03	TRIA (40,80,160)	TRA06	U(4,8)
MRP04	N(16,0.5)	PRO22	N(4,0.1)	MRP04	TRIA (30,60,120)	INS01	N(3,0.1)
MRP05	TRIA (20,40,80)	PRO23	N(0.25,0.1)	MRP05	TRIA (15,30,60)	INS02	N(0.4,0.1)
MRP06	TRIA (40,80,160)	PRO24	U(2,10)	MRP06	TRIA (60,120,240)	INS03	N(0.4,0.1)
MRP07	TRIA (30,60,120)	PRO25	N(2,0.1)	MRP07	TRIA (10,20,40)	INS04	N(0.4,0.1)
MRP08	TRIA (15,30,60)	PRO26	N(1,0.1)	MRP08	TRIA (10,20,40)	INS05	N(1,0.1)
MRP09	TRIA (60,120,240)	PRO27	U(0.4,2.5)	MRP09	N(6,0.5)	INS06	N(1,0.1)
MRP10	TRIA (10,20,40)	PRO28	N(1,0.1)	MRP10	N(6,0.5)	INS07	N(2,0.1)
MRP11	TRIA (10,20,40)	PRO29	N(1,0.1)	MRP11	N(1,0.1)	STO01	TRIA (8,12,16)
MRP12	N(8,0.5)	PRO30	N(0.2,0.1)	PRO01	U(8,24)	USE01	N(1,0.1)
MRP13	N(6,0.5)	PRO31	175	PRO02	U(8,24)	USE02	N(1,0.1)
MRP14	N(6,0.5)	PRO32	16	PRO03	N(8,0.5)	USE03	U(8,40)
MRP15	N(1,0.1)	PRO33	8	PRO04	N(2,0.5)	USE04	16
MRP16	N(1,0.1)	TRA01	N(0.25,0.1)	PRO05	TRIA (8,12,16)	USE05	8
PRO01	TRIA (4,8,16)	TRA02	U(8,24)	PRO06	N(8,0.5)	USE06	U(0,4)
PRO02	N(8,0.5)	TRA03	N(1,0.1)	PRO07	N(1,0.1)	USE07	N(0.25,0.1)
PRO03	N(2,0.5)	TRA04	N(0.4,0.1)	PRO08	N(1,0.1)	USE08	N(8,0.5)
PRO04	TRIA (8,12,16)	TRA05	N(3,0.1)	PRO09	N(1,0.1)	USE09	N(4,0.1)
PRO05	N(8,0.5)	TRA06	N(2,0.1)	PRO10	TRIA (15,30,60)	USE10	U(1.6,8)
PRO06	N(1,0.1)	TRA07	N(2,0.1)	PRO11	TRIA (60,120,240)	USE11	N(1,0.1)
PRO07	N(1,0.1)	TRA08	U(4,8)	PRO12	N(2,0.5)	USE12	N(1,0.1)
PRO08	N(1,0.1)	INS01	N(3,0.1)	PRO13	N(1,0.1)	USE13	N(0.25,0.1)
PRO09	TRIA (15,30,60)	INS02	N(0.4,0.1)	PRO14	U(8,40)	USE14	U(2,10)
PRO10	TRIA (60,120,240)	INS03	N(0.4,0.1)	PRO15	TRIA (60,120,240)	USE15	N(2,0.1)
PRO11	N(1,0.1)	INS04	N(0.4,0.1)	PRO16	TRIA (60,120,240)	USE16	N(1,0.1)
PRO12	N(0.25,0.1)	INS05	N(1,0.1)	PRO17	N(1,0.1)	USE17	U(0.4,2.5)
PRO13	N(0.25,0.1)	INS06	N(1,0.1)	PRO18	175	USE18	N(4,0.1)
PRO14	N(2,0.1)	INS07	N(2,0.1)	PRO19	16	USE19	N(4,0.1)
PRO15	N(1,0.1)	USE01	N(0.25,0.1)	TRA01	N(1,0.1)	USE20	N(0.25,0.1)
PRO16	N(1,0.1)	USE02	3	TRA02	N(0.4,0.1)	USE21	3
PRO17	U(8,40)	USE03	N(20,1)	TRA03	N(3,0.1)	USE22	N(20,1)
PRO18	N(8,0.5)						



	Task Name	Low Dur	Base Dur	High Dur	Start Mean	Finish Mean	Distrib.,Dur
1	**Order ID '06OG_Z1_003'**		**14 days**		**04/25/18 08:00**	**05/14/18 17:00**	**Undefined**
2	resolve conflicts in design changes using design change module	0.8 days	1 day	1.2 days	04/25/18 08:00	04/25/18 17:00	Triangular
3	check site schedule and update look-ahead plans using schedule change module	0.8 days	1 day	1.2 days	04/25/18 08:00	04/25/18 17:00	Triangular
4	update new orders and production lead times using production module	0.8 days	1 day	1.2 days	04/26/18 08:00	04/26/18 17:00	Triangular
5	freeze design and prepare production	0 days	0 days	0 days	04/26/18 17:00	04/26/18 17:00	Uniform
6	produce columns	4 days	5 days	6 days	04/27/18 08:00	05/03/18 17:00	Triangular
7	arrange transport and update transport lead time using transport module	0.8 days	1 day	1.2 days	05/04/18 08:00	05/04/18 17:00	Triangular
8	freeze transport	0 days	0 days	0 days	05/04/18 17:00	05/04/18 17:00	Uniform
9	transport columns to site and inspect quality using RFID scanner	0.8 days	1 day	1.2 days	05/07/18 08:00	05/07/18 17:00	Triangular
10	install columns on site	4 days	5 days	6 days	05/08/18 08:00	05/14/18 17:00	Triangular
11	**Order ID '06OG_Z2_001'**		**18 days**		**04/26/18 08:00**	**05/21/18 17:00**	**Undefined**
12	resolve conflicts in design changes using design change module	0.8 days	1 day	1.2 days	04/26/18 08:00	04/26/18 17:00	Triangular
13	check site schedule and update look-ahead plans using schedule change module	0.8 days	1 day	1.2 days	04/26/18 08:00	04/26/18 17:00	Triangular
14	update new orders and production lead times using production module	0.8 days	1 day	1.2 days	04/27/18 08:00	04/27/18 17:00	Triangular
15	freeze design and prepare production	0 days	0 days	0 days	04/27/18 17:00	04/27/18 17:00	Uniform
16	produce columns	4 days	5 days	6 days	04/30/18 08:00	05/04/18 17:00	Triangular
17	arrange transport and update transport lead time using transport module	0.8 days	1 day	1.2 days	05/07/18 08:00	05/07/18 17:00	Triangular
18	freeze transport	0 days	0 days	0 days	05/11/18 17:00	05/11/18 17:00	Uniform
19	transport columns to site and inspect quality using RFID scanner	0.8 days	1 day	1.2 days	05/14/18 08:00	05/14/18 17:00	Triangular
20	install columns on site	4 days	5 days	6 days	05/15/18 08:00	05/21/18 17:00	Triangular

(a)



	Task Name	Low Dur	Base Dur	High Dur	Start Mean	Finish Mean	Distrib.,Dur
1	**Order ID '06OG_Z1_003'**		**17 days**		**04/25/18 08:00**	**05/18/18 17:00**	**Undefined**
2	resolve conflicts in design changes using multiple 2D drawings	2.5 days	3 days	4 days	04/25/18 08:00	04/27/18 17:00	Triangular
3	check site schedule and update look-ahead plans using multiple spreadsheets	1.5 days	2 days	3 days	04/25/18 08:00	04/26/18 17:00	Triangular
4	notifiy through emails and phone calls, update new orders and production lead times	1.5 days	2 days	4 days	04/27/18 08:00	05/01/18 16:26	Triangular
5	freeze design and prepare production	0 days	0 days	0 days	05/01/18 16:26	05/01/18 16:26	Uniform
6	produce columns	4 days	5 days	6 days	05/01/18 16:26	05/08/18 17:00	Triangular
7	notify through emails and phone calls, arrange transport and update transport lead time	1.5 days	2 days	4 days	05/09/18 08:00	05/11/18 12:00	Triangular
8	freeze transport	0 days	0 days	0 days	05/11/18 12:00	05/11/18 12:00	Uniform
9	transport columns to site and conduct visual inspections	0.8 days	1 day	1.5 days	05/11/18 13:00	05/11/18 17:00	Triangular
10	install columns on site	4 days	5 days	6 days	05/14/18 08:00	05/18/18 17:00	Triangular
11	**Order ID '06OG_Z2_001'**		**19 days**		**04/30/18 08:00**	**05/25/18 17:00**	**Undefined**
12	resolve conflicts in design changes using multiple 2D drawings	2.5 days	3 days	4 days	04/30/18 08:00	05/03/18 09:04	Triangular
13	check site schedule and update look-ahead plans using multiple spreadsheets	1.5 days	2 days	3 days	04/30/18 08:00	05/02/18 08:37	Triangular
14	notifiy through emails and phone calls, update new orders and production lead times	1.5 days	2 days	4 days	05/02/18 08:37	05/04/18 17:00	Triangular
15	freeze design and prepare production	0 days	0 days	0 days	05/04/18 17:00	05/04/18 17:00	Uniform
16	produce columns	4 days	5 days	6 days	05/07/18 08:00	05/11/18 17:00	Triangular
17	notify through emails and phone calls, arrange transport and update transport lead time	1.5 days	2 days	4 days	05/14/18 08:00	05/16/18 08:31	Triangular
18	freeze transport	0 days	0 days	0 days	05/18/18 15:48	05/18/18 15:48	Uniform
19	transport columns to site and conduct visual inspections	0.8 days	1 day	1.5 days	05/18/18 15:48	05/18/18 17:00	Triangular
20	install columns on site	4 days	5 days	6 days	05/21/18 08:00	05/25/18 17:00	Triangular

(b)

Figure B.1: The data and the scheduling charts for the Monte Carlo simulations (the colors indicate irrelevant information to this research). Upper chart: The data and the scheduling charts for the material flow processes using the integrated management framework; Lower chart:(a) The data and the scheduling charts for the material flow processes using the traditional management framework (e.g., multiple spreadsheets, numerous phone calls and emails)

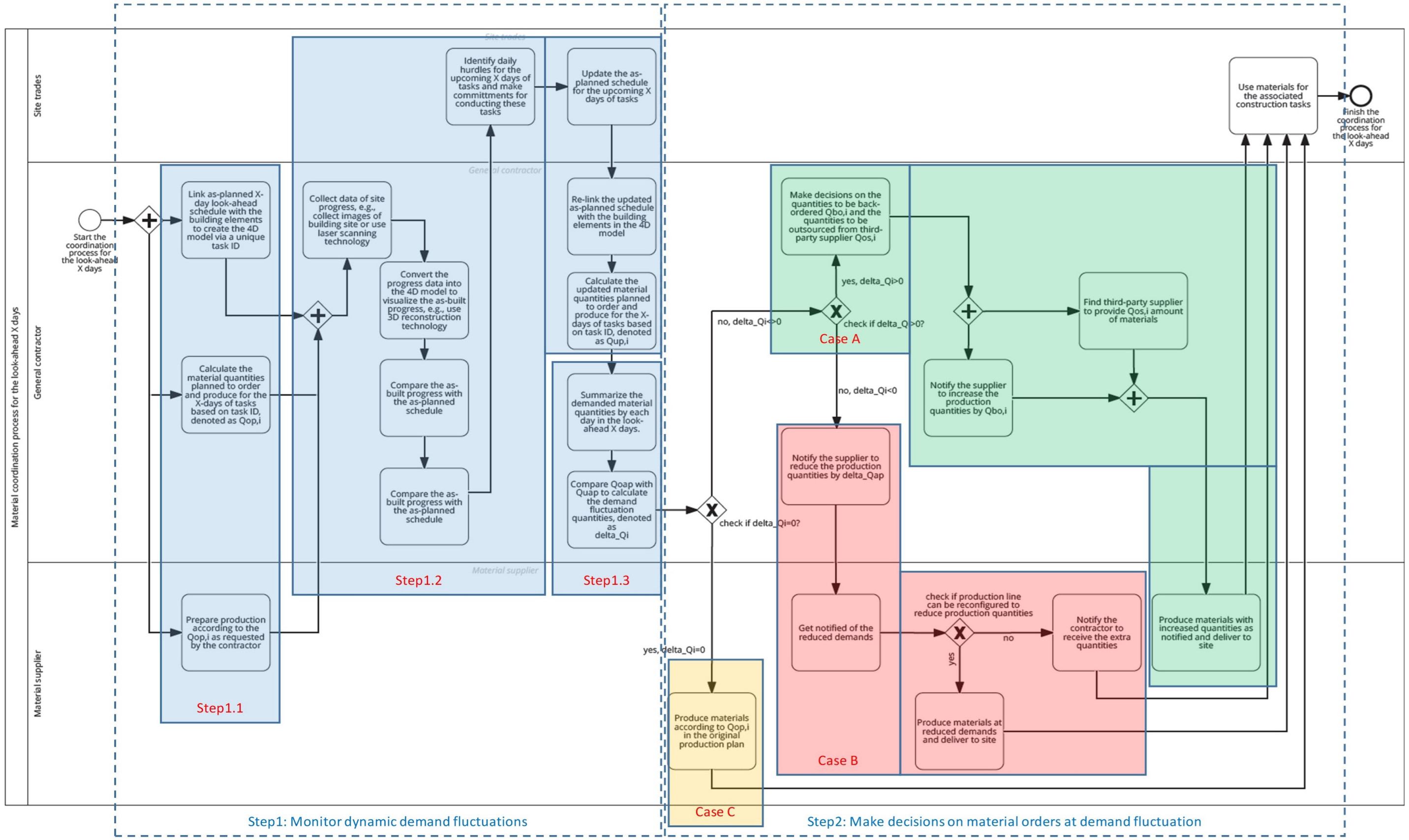


Figure B.2: The detailed processes of implementing the supplier-contractor coordination approach

Appendix C

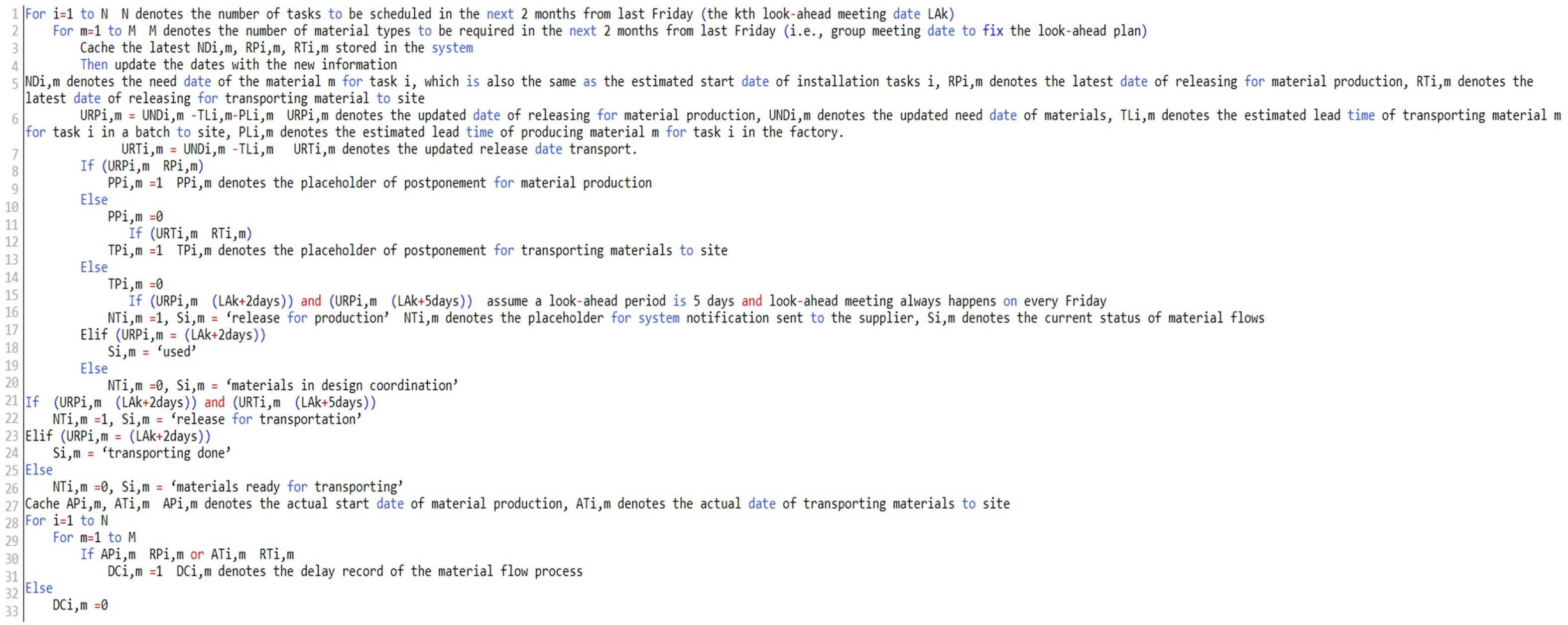
Appendix: Integrated system

When prototyping for integrated management framework for the ETO material flows, the functional modules are linked to support the feedback loops and coordination of the milestone dates. The link is realized by automatically calculating the dates when materials should be produced and transported to site. 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). The updates of milestone enabled by the calculations in functional modules are shown in Figure C.1.

In order to build the database for the prototype, three steps need be done to integrate the data from different data sources. The detailed processes for data integration into MySQL server are shown in Figure C.2. 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 are 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.

To demonstrate the functionality of the design module in the prototype, an example of using the design-change module is shown in Figure C.3, where there is a design change request regarding the column with an element ID '1774324'.

To facilitate the design data exchange processes, the MySQL database is connected to the parametric models in Autodesk Revit through the Dynamo programming interface to enable the automatic information exchange and the updates among different stakeholders. The data import and export processes through Dynamo interface are shown in Figure C.4 and C.5.



```
For i=1 to N  N denotes the number of tasks to be scheduled in the next 2 months from last Friday (the kth look-ahead meeting date LAk)
    For m=1 to M  M denotes the number of material types to be required in the next 2 months from last Friday (i.e., group meeting date to fix the look-ahead plan)
        Cache the latest NDi,m, RPi,m, RTi,m stored in the system
        Then update the dates with the new information
NDi,m denotes the need date of the material m for task i, which is also the same as the estimated start date of installation tasks i, RPi,m denotes the latest date of releasing for material production, RTi,m denotes the
latest date of releasing for transporting material to site
        URPi,m = UNDi,m -TLi,m-PLi,m  URPi,m denotes the updated date of releasing for material production, UNDi,m denotes the updated need date of materials, TLi,m denotes the estimated lead time of transporting material m
for task i in a batch to site, PLi,m denotes the estimated lead time of producing material m for task i in the factory.
              URTi,m = UNDi,m -TLi,m   URTi,m denotes the updated release date transport.
        If (URPi,m  RPi,m)
            PPi,m =1  PPi,m denotes the placeholder of postponement for material production
        Else
            PPi,m =0
               If (URTi,m  RTi,m)
            TPi,m =1  TPi,m denotes the placeholder of postponement for transporting materials to site
        Else
            TPi,m =0
               If (URPi,m  (LAk+2days)) and (URPi,m  (LAk+5days))  assume a look-ahead period is 5 days and look-ahead meeting always happens on every Friday
            NTi,m =1, Si,m = ‘release for production’  NTi,m denotes the placeholder for system notification sent to the supplier, Si,m denotes the current status of material flows
        Elif (URPi,m = (LAk+2days))
            Si,m = ‘used’
        Else
            NTi,m =0, Si,m = ‘materials in design coordination’
If  (URPi,m  (LAk+2days)) and (URTi,m  (LAk+5days))
    NTi,m =1, Si,m = ‘release for transportation’
Elif (URPi,m = (LAk+2days))
    Si,m = ‘transporting done’
Else
    NTi,m =0, Si,m = ‘materials ready for transporting’
Cache APi,m, ATi,m  APi,m denotes the actual start date of material production, ATi,m denotes the actual date of transporting materials to site
For i=1 to N
    For m=1 to M
        If APi,m  RPi,m or ATi,m  RTi,m
            DCi,m =1  DCi,m denotes the delay record of the material flow process
Else
    DCi,m =0
```

Figure C.1: The pseudocode to support the calculations of milestone dates

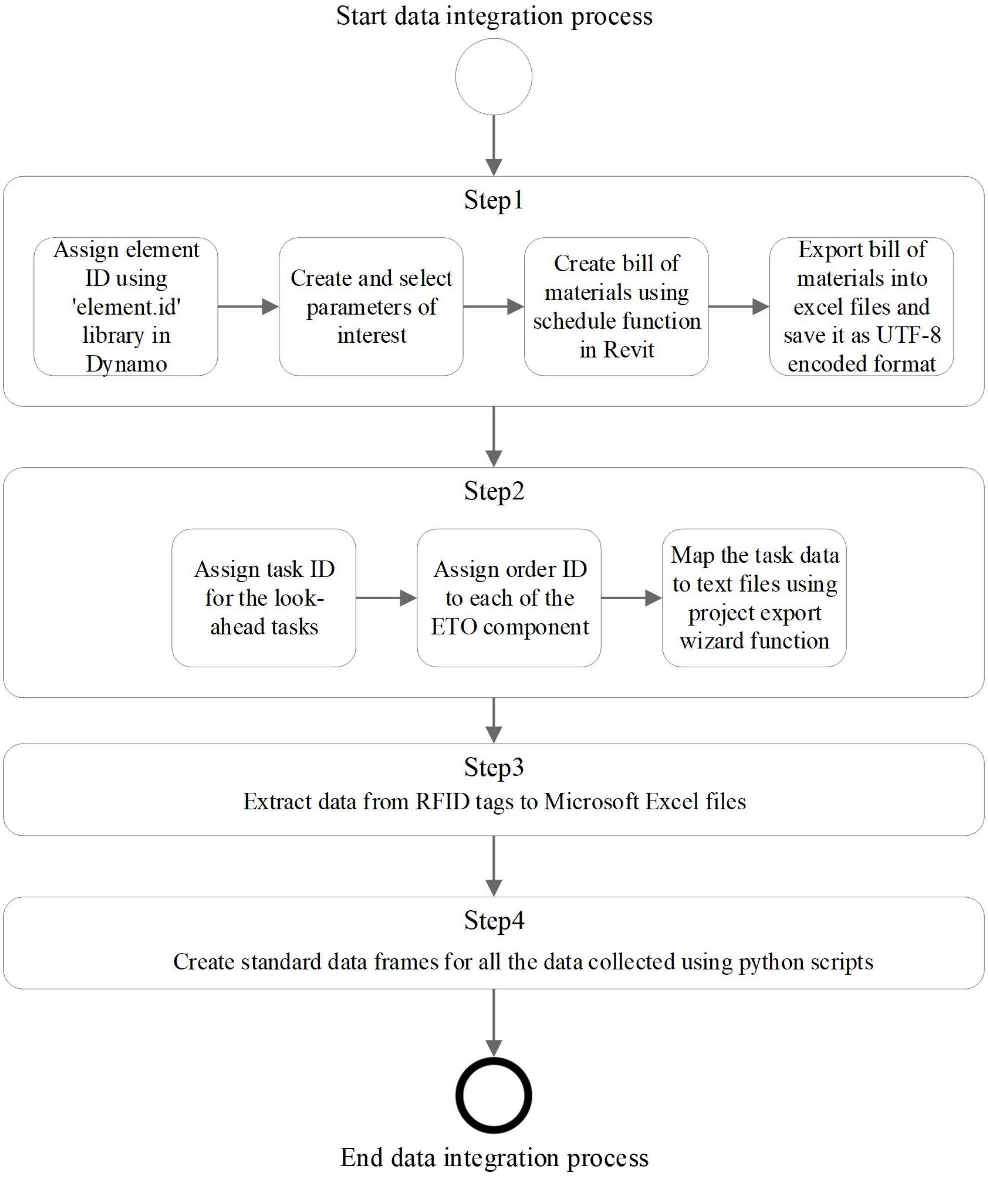
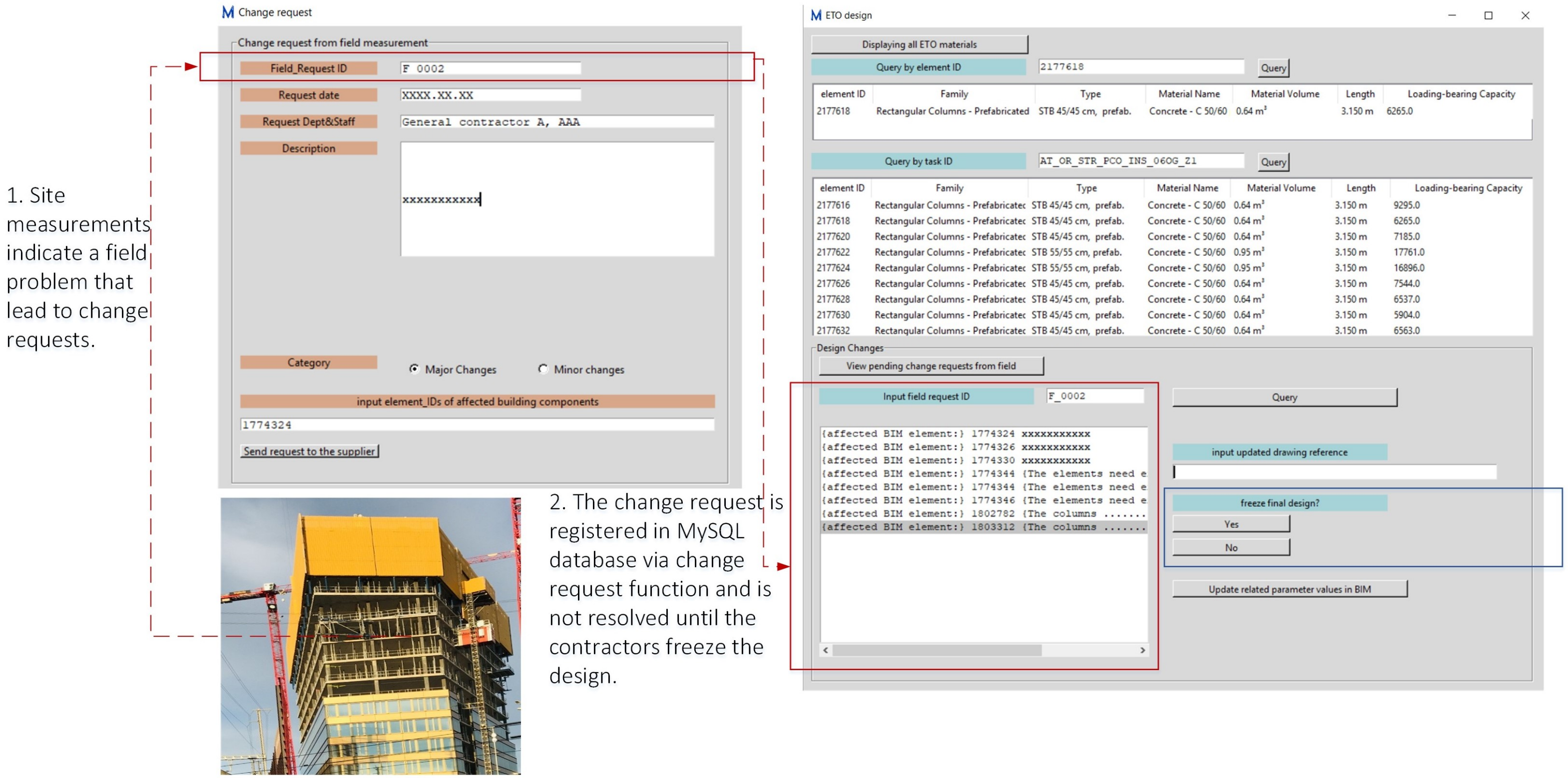


Figure C.2: The detailed processes for data integration into MySQL server



1. Site measurements indicate a field problem that lead to change requests.

2. The change request is registered in MySQL database via change request function and is not resolved until the contractors freeze the design.

Field_Request ID	F 0002
Request date	XXXX.XX.XX
Request Dept&Staff	General contractor A, AAA
Description	xxxxxxxxxxx
Category	● Major Changes ○ Minor changes
input element_IDs of affected building components	1774324

Query by element ID: 2177618

element ID	Family	Type	Material Name	Material Volume	Length	Loading-bearing Capacity
2177618	Rectangular Columns - Prefabricated	STB 45/45 cm, prefab.	Concrete - C 50/60	0.64 m³	3.150 m	6265.0

Query by task ID: AT_OR_STR_PCO_INS_06OG_Z1

element ID	Family	Type	Material Name	Material Volume	Length	Loading-bearing Capacity
2177616	Rectangular Columns - Prefabricatec	STB 45/45 cm, prefab.	Concrete - C 50/60	0.64 m³	3.150 m	9295.0
2177618	Rectangular Columns - Prefabricatec	STB 45/45 cm, prefab.	Concrete - C 50/60	0.64 m³	3.150 m	6265.0
2177620	Rectangular Columns - Prefabricatec	STB 45/45 cm, prefab.	Concrete - C 50/60	0.64 m³	3.150 m	7185.0
2177622	Rectangular Columns - Prefabricatec	STB 55/55 cm, prefab.	Concrete - C 50/60	0.95 m³	3.150 m	17761.0
2177624	Rectangular Columns - Prefabricatec	STB 55/55 cm, prefab.	Concrete - C 50/60	0.95 m³	3.150 m	16896.0
2177626	Rectangular Columns - Prefabricatec	STB 45/45 cm, prefab.	Concrete - C 50/60	0.64 m³	3.150 m	7544.0
2177628	Rectangular Columns - Prefabricatec	STB 45/45 cm, prefab.	Concrete - C 50/60	0.64 m³	3.150 m	6537.0
2177630	Rectangular Columns - Prefabricatec	STB 45/45 cm, prefab.	Concrete - C 50/60	0.64 m³	3.150 m	5904.0
2177632	Rectangular Columns - Prefabricatec	STB 45/45 cm, prefab.	Concrete - C 50/60	0.64 m³	3.150 m	6563.0

Design Changes

Input field request ID: F_0002

```
{affected BIM element:} 1774324 xxxxxxxxxxx
{affected BIM element:} 1774326 xxxxxxxxxxx
{affected BIM element:} 1774330 xxxxxxxxxxx
{affected BIM element:} 1774344 {The elements need e
{affected BIM element:} 1774344 {The elements need e
{affected BIM element:} 1774346 {The elements need e
{affected BIM element:} 1802782 {The columns .......
{affected BIM element:} 1803312 {The columns .......
```

Figure C.3: The 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)

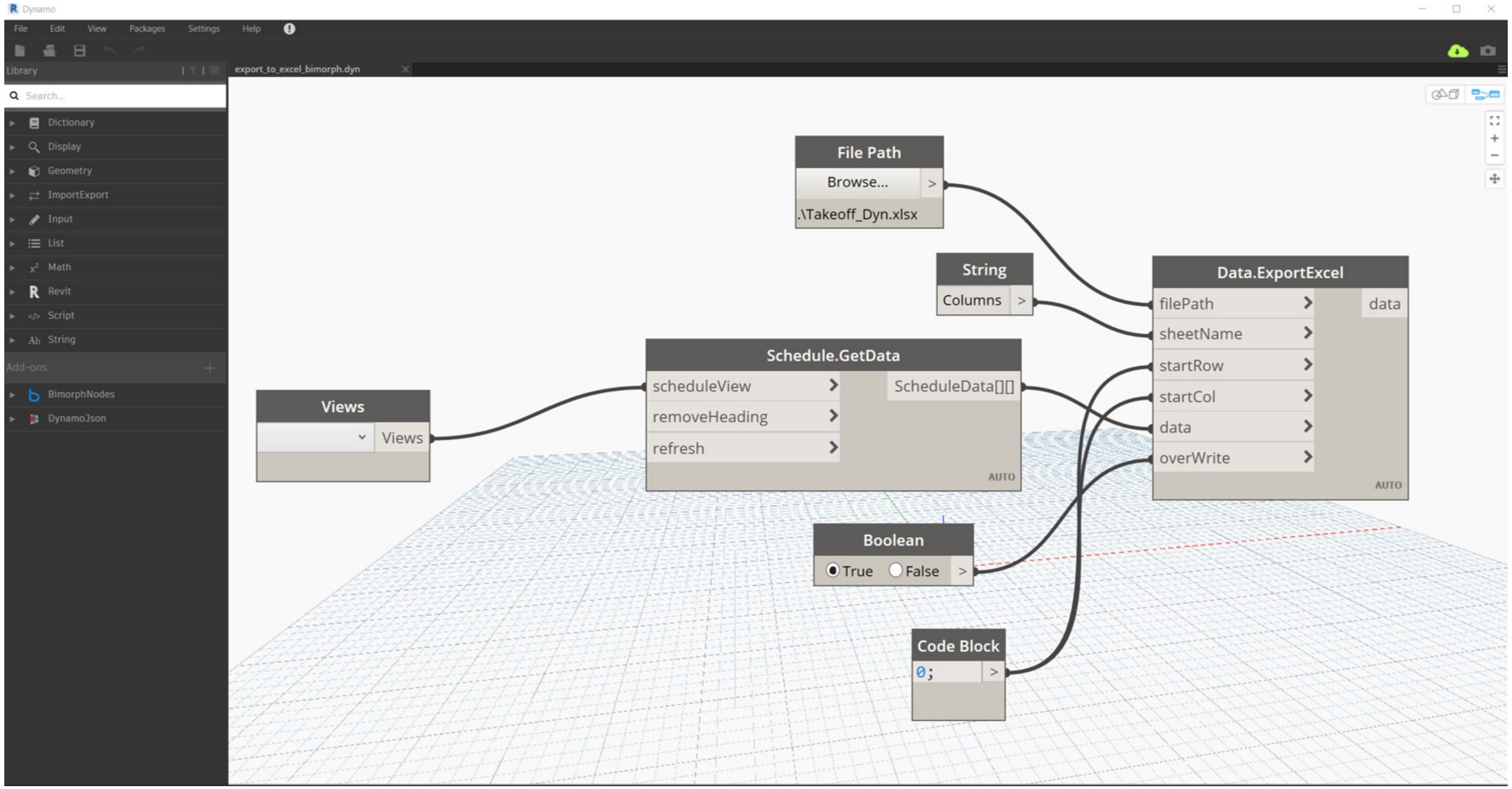


Figure C.4: BIM data export by Dynamo scripts

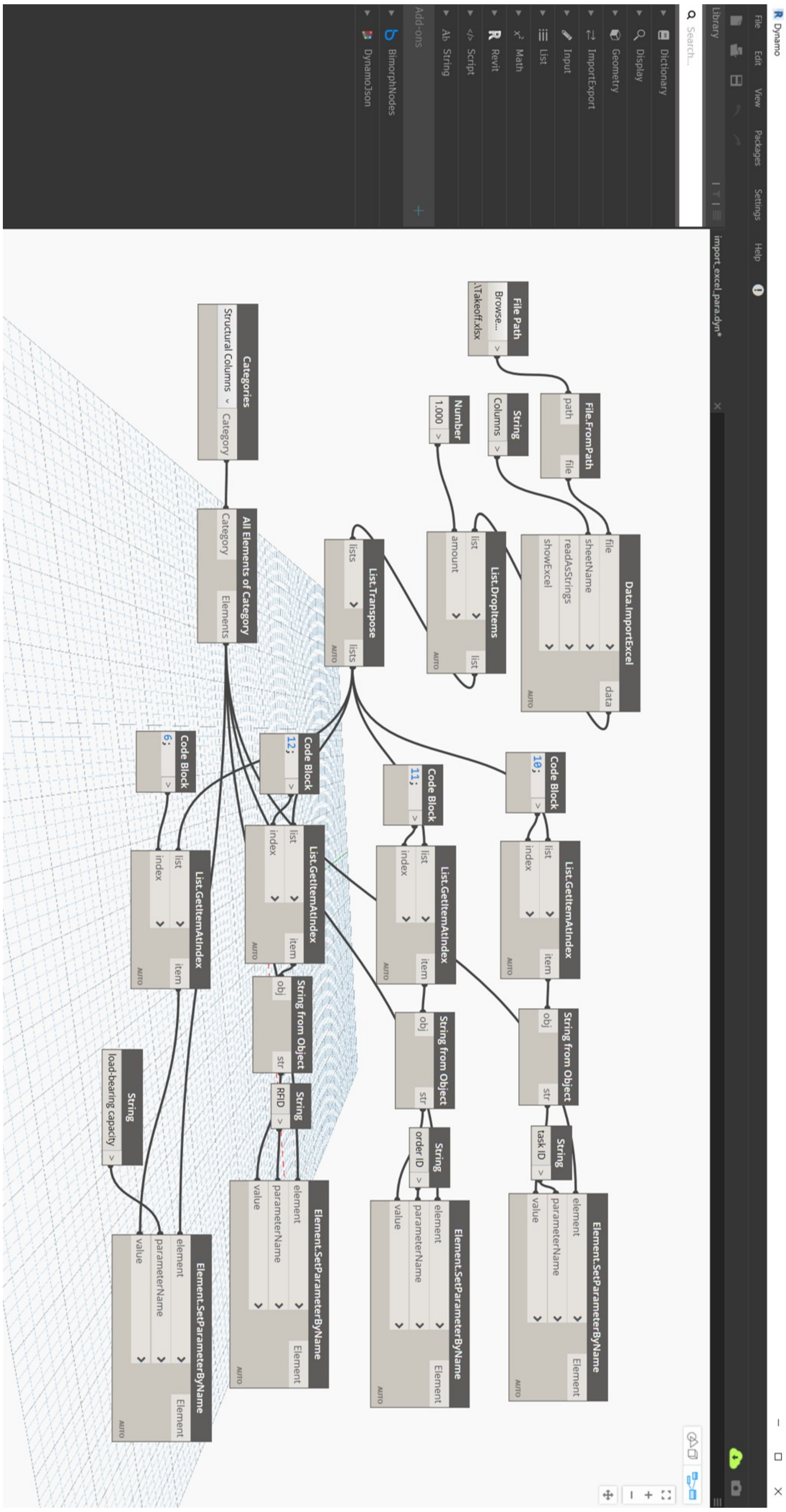


Figure C.5: BIM data import by Dynamo scripts

APPENDIX D

Terms and acronyms

- **BIM** Building Information Modelling
- **BPMN** Business Process Model and Notation
- **CC** Construction Coordination
- **CMA-ES** Covariance Matrix Adaptation Evolution Strategy
- **CSC** Construction Supply Chain
- **CSCC** Construction Supply Chain Coordination
- **DEAP** Distributed Evolutionary Algorithms in Python
- **DfMA** Design for Manufacturing and Assembly
- **ERP** Enterprise Resource Planning
- **ETO** Engineer-to-Order
- **GIS** Global Positioning System
- **GUI** Graphic User Interface
- **ICT** Information Communication Technology
- **IFC** Industry Foundation Classes
- **IFOA** Integrated Form of Agreement
- **IoT** Internet of Things
- **IPD** Integrated Project Delivery
- **JIT** Just-In-Time
- **LAP** Look-ahead Planning
- **RFID** Radio Frequency Identification
- **SCOR** Supply Chain Operations Reference