#2: Automated tracking of construction and materials for improved supply chain logistics and provenance – Scoping study

FINAL REPORT – FOR PUBLIC

The University of Melbourne
Monash University
QUT
Australian Government
Department of Industry, Science, Energy and Resources
AusIndustry
Cooperative Research Centres Program

CONTENTS

CONFIDENTIAL:	☐ Yes ✓ No
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Date of this report:	15/04/2022
Project completion date:	31/01/2022
Program Leader reviewer:	Duncan Maxwell
Project Title:	Automated tracking of construction materials for improved supply chain logistics and provenance – Scoping Study
Project Duration:	6 Months
Partners:	• BlueScope Steel Limited • Holmesglen Institute • Lendlease Digital Australia Pty Limited • Monash University • Queensland University of Technology • Salesforce.com, Inc. • Sumitomo Forestry Australia Pty Ltd • The Master Builders Association of Victoria • The University of Melbourne • Victorian Building Authority • Ynomia Pty Ltd
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Acknowledgments:

The research team gratefully acknowledges the support from Building 4.0 CRC and industrial partners. This research has been assisted and guided by Michelle Gissel, Sprios Dallas, Luis Goncalves, Ryotaro Kaburagi, Hiroyuki Ueda, Karl Heinz Weiss, Steven Huang, Shobini Mahendra, Roni Parlindungan, Philip Alviano, Henry Pook, Ross Digby, Matthew Lickwar, Matthew Barbuto, Gregory Kirkendall, and Jon Kaehne.

EXECUTIVE SUMMARY

The construction supply chain is a critical enabler for the construction industry but also poses challenges and risks. This is mainly due to the typical make-to-order nature of the construction supply chain, which is often unstable, highly fragmented and geographically dispersed. The ability to track and trace, called traceability, is becoming increasingly important as it contributes to building compliance, project efficiency, safety, sustainability and performance. This scoping study aims to understand state-of-the-art traceability in the construction industry and key stakeholders' perspectives and recommend future research. The longer-term objective is to demonstrate how sensor networks can be used to provide live streamed data to improve project management and validate building compliance through measures used to guarantee the provenance of the supply chain. Systems to be developed will have the further capability of integration with the building digital twin.

This project assembled a multidisciplinary research team from the University of Melbourne, Monash University and the Queensland University of Technology, along with close collaboration and engagement with industrial partners. We used a mixture of research methods (e.g., interviews, literature review and case studies) to assess existing and emerging tracking technologies (e.g., sensors, visual tracking, information systems, data collection) for sectoral and issue appropriateness. The project comprised 8 tasks, and the key research findings are summarised below.

Traceability lessons learnt from the food industry

Traceability in the food industry is largely driven by safety and quality, which is the primary concern of any food business today. We have seen other benefits of developing traceability capability, such as optimising process efficiency, improving sustainability performance, and increasing consumer confidence. Comprehensive legislation, regulations and international standards mandating traceability exist in the food industry. Although the legislative requirements demand only minimal information and can be fulfilled even with a paper-pencil approach, some sectors (e.g., red meat) take an extra step and rely on full digitalisation and a centralised database. GS1 plays a pivotal role in traceability, providing standards for identifying, capturing, sharing and using information related to a product. The GS1 12 Identification Keys contains information describing the critical tracking events, including the who, what, where, when and why. Those ID keys can be carried with mature technologies like barcodes, RFID and QR codes. Advanced digital technologies (e.g., IoT and Blockchain) are still under development for traceability applications, with cost being the main barrier to adoption. Further, the slow adoption of digital traceability is also attributed to technological, operational and cultural obstacles.

Supply chains in building design, construction, and operation

Chapter 3 identifies several areas where supply chains in building projects differ from other industries. These are: (i) the complexity and inter-related nature of construction projects and their legal context, normally undertaken by a temporary consortium of firms; (ii) unique activities such as excavation, where the 'supply activity' is a removal activity; (iii) the active role of the demand chain participants in checking and approving the results of supply chain activities; (iv) the heavy use of a flexible mix of 'supply only', 'service only' and 'supply and service' subcontracts; and (v) the role of the lead contractor (construction systems integrator) in creating and managing a production facility which can change dramatically throughout the single contract. The discussion follows the RIBA Plan of Work 2020, using a simple example of an aluminium door assembly to relate the content to a simple example. Comments on the impact of demand chain and supply chain concepts on the development of BIM (Building Information Modelling) are presented, along with comments on the value of BIM in improving supply chain practice. It is worth noting that BIM can act as a 'repository' for storing some results of demand chain management. The ISO 19650 series of standards cover the current requirements for integrating BIM into building projects. However, many things are not captured in BIM, such as regulatory requirements and temporary works, so BIM is likely to remain a useful adjunct to demand chain and supply chain management for the foreseeable future.

State-of-the-art in sensor technology for product identification and tracking

Current sensors and associated technologies have advanced over the years. The suite of sensor technologies can enable traceability in most scenarios. However, some specific challenges are highlighted in the next section. Generally, we can integrate technologies with common standards into an integrated suite for material tracking and construction processes. Although most technologies have some standards, a few proprietary technologies may need integration with mainstream technologies for easy integration and interoperability of data flow and tracking. The available technologies are relatively advanced, and the commercial solutions would easily cater to most construction processes. In addition, the commercial solutions are flexible and can be integrated into existing technology platforms as needed. Some advanced barcoding and RFID technologies for extreme conditions (labels available for temperatures up to 1370°C, resistant to chemicals) are primarily suitable for manufacturing and tracking materials. However, cost and associated factors may limit organisations from adopting such technologies. Most of these labels are produced using specialised printers and can be purchased for long-term benefits. We can have real-time tracking information available on smartphones and dashboards by combining multiple sensors (such as GPS, cellular communications, barcode, RFID and other specific sensors). Figure 1 compares various sensor technology solutions for traceability 1.

State-of-the-art in logistics and construction onsite tracking

The uniqueness of onsite material tracking warrants a comprehensive review of the literature. Chapter 5 uses a hybrid literature review method to investigate the state-of-the-art of onsite material tracking. This task first summarises application of tracking technologies on the construction site with a bibliometric analysis, providing the audience with contextual information on the technologies and tracked objects. A critical review of onsite material tracking follows, with details of data capture and integration. We developed 3 tracking strategies, which describe the flow of tracked materials from different perspectives by tracking materials, the material handling equipment, and installed building elements. In addition to technological details, this task also scrutinises the linkage between sensors and construction management tasks and the evolution from sensor-captured data to operational insights on productivity, safety and quality.

	QR Code	Barcode	Active RFID	Passive RFID	NFC	BLE	GPS
Cost-Effective	$	$	$$$	$	$$$	$$$	$$$
Real-time tracking	⊘	⊘	⊘	⊘	⊘	✔	✔
Power Consumption	⊘	⊘	✔	⊘	✔	⊘	✔
Scanning Range	High	High	High	Low	Low	Low	Unlimited
Storage capacity	3 KB	> 100 bytes	2 KB	4-8 KB	48 Bytes – 8 KB	NA	Unlimited
Continuous scanning	✔	✔	✔	✔	✔	At regular intervals	Real-time data
Two-way Communication	⊘	⊘	⊘	⊘	✔	✔	✔
Labour Intensive	✓	✓	✓	×	✓	✓	✓
Popularity	Very high	Very high	High	High	Moderate	Moderate	Moderate

Figure 1: Comparison of sensor technology solutions

Despite the prominence evidenced by technology advancements, automated, sensor-based onsite material tracking still faces various challenges, which can be categorised into (1) technological challenges (e.g., many technologies require tedious setup, frequent sensor repositioning for unblocked line-of-sights), and (2) implementation challenges (e.g., design models, schedules and site layout plans are essential information for material tracking onsite but often not available in an integrated information platform).

State-of-the-art in information management systems and blockchain technology for traceability

Chapter 6 addresses the following research questions:

1. What are the weaknesses in existing information systems?
2. What are the challenges for blockchain technologies in the supply chain?
3. How does blockchain technology change the construction supply chain, and in which aspect or dimension?
4. Apart from the present use cases, what more uses and research streams are possible for blockchains in the construction supply chain?

BIM and Enterprise Resource Planning (ERP) systems are the most relevant information platforms for collecting, reporting and sharing product traceability information. However, one-to-many, many-to-one, and many-to-many object correlations apply across the supply chain processes, further compounding the meaning, perspective and scope of traceability. The supply chain suffers from multiple issues, such as late payments, low transparency in locating materials and data interoperability. While blockchain technology is still under development, permissioned blockchians are potentially applicable for time-sensitive applications in the construction supply chain for traceability, transparency, decentralisation, immutability, smartness and privacy. Three types of blockchain applications are most promising for traceability: 1) tracking, 2) contracting, and 3) transferring.

Stakeholder's perspectives: drivers and barriers

This study aimed to identify the drivers/benefits and barriers/challenges of digitalising construction supply chain traceability. Based on data collected through semi-structured interviews with experts (academics, practitioners and stakeholders), we consolidated 79 elements – 44 drivers/benefits and 35 barriers/challenges. Out of those, 22 elements (13 drivers/benefits and 9 barriers/challenges) were assessed as highly critical to successfully digitalise the traceability systems. Figure 2 summarises the linkages between drivers/benefits and barriers/challenges. Experts deem the drivers/benefits that promote real advantages to current traceability practices and systems more prominently. When considering the barriers/challenges, the degree to which the digital traceability's results are visible to the adopters seems to be an important issue, being able to impair the digitalisation of the construction supply chain. Some highly critical drivers/benefits (e.g., enhanced supply chain collaboration and greater supply chain transparency) may only be fully achieved if the entire construction supply chain engages in traceability digitalisation. At the same time, some barriers/challenges (e.g., short-term relationships and unbalanced risk across the supply chain) may be inherent to how the construction supply chain is designed and, hence, more difficult to overcome.

Further, companies already moving towards digitalising construction supply chain traceability (early adopters) may be able to understand and visualise the drivers/benefits and barriers/challenges more than others that have not started yet (late adopters). This suggests that the more companies advance in traceability digitalisation, the more aware they will become regarding its drivers/benefits and barriers/challenges. Nevertheless, both early and late adopters perceived some highly critical drivers/benefits and barriers/challenges equally, which may indicate their greater relevance for such digitalisation.

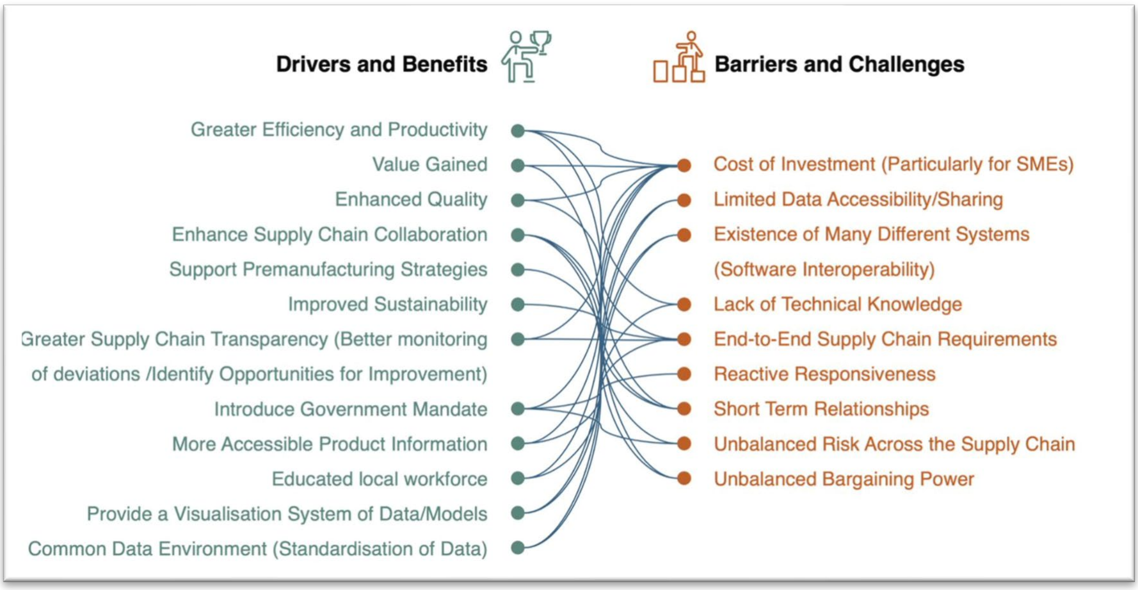

Figure 2: Drivers and barriers of adopting digitalisation in the construction industry

Case studies

Traceability technology potentially offers the opportunity for building companies to semi-automate select processes that have been traditionally manual and improve access to real-time information (of improved quality) to inform project decision making.

The project explored opportunities and barriers to digitalising traceability for several industry partners. The results of these case studies were shared with industry partners. However, this information is commercial-in-confidence, so is not included in this report.

Future research plans

This scoping study aided in the understanding of the state-of-the-art of traceability technology solutions and their current usage, development and challenges in the construction industry. However, further study is essential to transform the construction supply chain by introducing automation and digitisation for tracking and tracing construction materials and activities. Suggestions and ideas for further research are broadly categorised into 4 directions shown below:

- Roadmap for sector-wide transformation
- Digitalisation traceability solution development
- Pilot study and living lab
- Education and training.

PROJECT OVERVIEW

1.1 The background

The construction business is one of the most significant industries globally, with an annual value of $10 trillion, accounting for roughly 13% of global GDP.[1] Reflecting permanent inward immigration and acceleration of infrastructural investment, Australia is ranked 5th for construction growth among both emerging and developed economies[1]. The construction supply chain is a critical enabler for this booming industry but also poses challenges and risks. This is mainly due to the typical make-to-order nature of the construction supply chain, which is often unstable, highly fragmented and geographically dispersed.[2] The ability to track and trace, called traceability, is becoming increasingly important as all materials converge to the construction site from a global supply chain and serve a long lifetime.

A lack of real-time and reliable data causes inefficient supply chain logistics and limits how just-in-time and Lean Construction techniques can be applied in building projects. To address compliance issues, such as those raised in the Shergold-Weir Building Confidence Report[3] that have led to a lack of confidence in the industry, there is a need for secure data that identifies the origin of materials, products and assemblies. This data can register compliance with specifications, track materials/assemblies through shipping, customs and delivery to the site, and then track the progressive incorporation of these materials into the overall structure. Ongoing building element performance and compliance issues have led to recent highly publicised building failures, presenting further problems for the industry with an inability to trace back projects and supply data for non-conforming building elements, especially when problems emerge post-construction.

1.2 The objectives

Building 4.0 CRC's longer-term objective in this area is to demonstrate how sensor networks can provide live streamed data to improve project management and validate building compliance through measures to guarantee the supply chain's provenance. Systems to be developed will be capable of integration with a building's digital twin.

In the first stage, the objectives of this scoping study are:

- Map stakeholder (customer) perspectives via interviews, workshops and surveys.
- Analyse stakeholder perspectives and recommend options to develop user-friendly tracking systems, identify key risks and pain points for traceability, and develop a common understanding of the future role and potential of sensor tracking systems in the building industry.
- Report on state-of-the-art in this field with an emphasis on examples of indoor and outdoor IoT sensors and tracking systems (including RFID tags, GPS, Bluetooth, Ultra-Wideband Beacons) for real-time tracking of construction materials used in supply chains and blockchain technology, providing pathways to achieve material provenance tracking that is suited to the construction industry, appropriate for use with future smart contracts and accepted by regulators.

[1] *Oxford Economics (2021) Future of Construction: A global forecast for construction to 2030. https://www.oxfordeconomics.com/resource/Future-of-Construction/*

[2] *Vrijhoef, R., & Koskela, L. (2000). The four roles of supply chain management in construction. European journal of purchasing & supply management, 6(3-4), 169-178.*

[3] *Shergold, P., & Weir, B. (2018). Building Confidence: Improving the effectiveness of compliance and enforcement systems for the building and construction industry across Australia.*

- Use case studies (from internal partner groups and external industries) to identify and assess the main benefits (e.g., supply chain efficiency, trust, sustainability) that can result from deploying sensor networks to track materials.
- Explore sensors used for material tracking on Australian work sites to ensure appropriateness for construction, improve productivity and safety, and improve worker and customer experience.
- Identify potential tracking and monitoring challenges faced by the building industry and the barriers to uptake. Challenges will be prioritised from stakeholders' perspectives with recommendations for successful implementation.
- Verify whether and how introducing material and component supply chain tracking in building projects converges with design systems to inform and advance Lean Construction techniques.

1.3 The approach

This project has assembled a multidisciplinary research team among the University of Melbourne, Monash University and Queensland University of Technology. With close collaboration and engagement with industrial partners, we used a mix of research methods (e.g., interviews, literature review and case studies) to assess existing and emerging tracking technologies (e.g., sensors, visual tracking, information systems, data collection) for sectoral and issue appropriateness.

Reflecting the research objectives, this scoping study comprised 8 sub-tasks:

- **Task 1 Multi-stakeholder interview**: to understand stakeholder's perspectives through semi-structured interviews led by Dr Tortorella (UoM)
- **Task 2 Specification, compliance, risk review:** to report on regulatory obligations and risk analysis related to material tracking, led by Prof. Drogemuller (QUT)
- **Task 3 Sensor technology review:** to report on the state-of-the-art in sensor technologies for product identification and tracking, led by Dr Rao (UoM)
- **Task 4 Information system review:** to report on the state-of-the-art in information systems and smart contracts by using blockchain technology, led by A/Prof. Liu (Monash)
- **Task 5 Onsite tracking review:** to report on the state-of-the-art material tracking technologies on the worksite, led by Dr Fang (Monash)
- **Task 6 Case studies:** to analyse potential benefits and challenges with 3 project industrial partners, led by A/Prof. Rose (QuT), A/Prof. Liu (Monash), and Dr Li (UoM)
- **Task 7 Design integration review:** to verify how to integrate traceability and design systems towards Lean Construction, led by Dr Omrani (QUT)
- **Task 8 Industry benchmarking:** to benchmark construction with other industries for traceability (e.g., food), led by Dr. Li (UoM).

1.4 Report structure

This report presents information about tasks 1, 2, 3, 4, 5, 7 and 8 as follows:

- **Chapter 2** provides an overview of traceability in the food industry and summaries the lessons to be shared with the construction industry (task 8).
- **Chapter 3** sets the scene for the construction supply chain and reviews the associated compliance and risk issues from design to occupancy (tasks 2 and 7).
- **Chapters 4, 5 and 6** present respectively the state-of-the-art of sensor technologies (task 3), onsite tracking (task 5), and information systems and blockchain technology (task 4).
- **Chapter 7** summarises the results of the semi-structured interviews with 26 experts (task 1).

This report does not present information about task 6, which contained details that are commercial-in-confidence.

PROJECT FINDINGS AND OUTCOMES

Chapter 2 The State-of-the-art of traceability

Author: Wen Li

2.1 What is traceability?

In recent years, traceability has become increasingly important and relevant across multiple industry sectors. Unfortunately, it is often mentioned along with disastrous incidents like food recalls in the fast-moving consumer goods (FMCG) industry, modern slavery in the mining and textile industry, and cladding fire risks in the construction industry. Despite the growing frequency of 'traceability' used in academic literature and public media, its definition is evolving and sometimes conflicting.[4]

ISO8402 defines traceability as "*The ability to trace the history, application or location of an entity by means of recorded identifications*". Olsen and Borit commented, "*This definition clearly states what should be traced and also how the tracing should be done*"[3], but "*it was withdrawn by ISO and superseded by ISO9000*". The newer version deleted the phrase "*by means of recorded identification*", so it is not explicit on how to trace.

The most referred definition is by Moe, saying, "*traceability is the ability to track a product batch and its history through the whole, or part, of a production chain from harvest through transport, storage, processing, distribution and sales*."[5] Whether traceability should be necessarily or sufficiently achieved at the product batch level is still questionable. The most extensive dictionary definition of "traceability" is found in Webster's Online Dictionary, which adds, "*1) Traceability refers to the completeness of the information about every step in a process chain; 2) Traceability is the ability to chronologically interrelate the uniquely identifiable entities in a way that matters; Traceability is the ability to verify the history, location, or application of an item by means of recorded identification*".

Olsen and Borit also suggested their definition as "*The ability to access any or all information relating to that which is under consideration, throughout its entire life cycle, by means of recorded identifications.*"[3] Depending on the flow of direction, traceability can be a) back traceability, or supplier's traceability, or upstream traceability (tracing); b) internal traceability or process traceability; c) forward traceability, or client traceability or downstream traceability (tracking).[6]

The first evidence of traceability can be dated back to Historia Anglicana in 1275, which could trace back an epizootic's origin in Europe.[7] It is not surprising that the agrifood sector has the most extended history and development of traceability. Thus,

[4] *Olsen, P., & Borit, M. (2013). How to define traceability. Trends in food science & technology, 29(2), 142-150.*
[5] *Moe, T. (1998). Perspectives on traceability in food manufacture. Trends in Food Science & Technology, 9(5), 211-214.*
[6] *Perez-Aloe, R., Valverde, J. M., Lara, A., Carrillo, J. M., Roa, I., & Gonzalez, J. (2007, September). Application of RFID tags for the overall traceability of products in cheese industries. In 2007 1st Annual RFID Eurasia (pp. 1-5). IEEE.*
[7] *Montet, D., & Ray, R. C. (Eds.). (2017). Food traceability and authenticity: Analytical techniques. CRC Press.*

it is worthwhile first to explore the food industry's current traceability practice and landscape and learn from its lessons.

2.2 Traceability overview in food industry

A literature survey on the traceability landscape in the food supply chain collected over 120 literature samples from the Scopus® database using the keywords: 'Traceability' and 'Food Supply Chain'. The literature pool is limited to articles published from 2014 to 2021 and cited more than 5 times. The survey focuses on 4 aspects: 1) Drivers and benefits; 2) Regulations and compliances; 3) Identification technologies; and 4) Challenges.

2.2.1 Drivers and benefits

According to Aung and Yang, "*firms have 3 primary objectives in using traceability systems: improve supply management; facilitate traceback for food safety and quality; and differentiate and market foods with subtle or undetectable quality attributes.*"[8] Olsen and Borit suggested the potential benefits of developing traceability include a) "*Reduced cost and labour related to better information logistics and less re-punching of data internally*"; b) "*Reduced cost and labour related to exchange of information between business partners through better integration of electronic systems*"; c) "*Access to more accurate and more timely information needed to make better decisions about how and what to produce*"; and d) "*Competitive advantage through the ability to document desirable product characteristics, in particular relating to sustainability, ethics and low environmental impact.*"[9]

Through the literature sample, we have further identified 7 common drivers and benefits, which were mentioned at least 10 times:

- **Safety:** Consumer safety is the most widely cited driver for establishing traceability in food supply chains. It is a primary concern where products directly relate to the safety of consumers, and firms are severely damaged if their products cause safety issues.

- **Quality:** The quality of products is of a deep concern that strongly correlates with the product's safety. Traceability processes can potentially remove low-quality products from the supply chain to reduce hazards before a recall.

- **Sustainability:** Traceability may be required to meet regulations and gain certification to demonstrate responsible sourcing and address environmental concerns. For example, the seafood supply chain raises ethical and ecological concerns regarding where and how fish are caught. Sustainability verifications and decorations can also place value on the products.

- **Process optimisation**: Traceability systems can enhance process optimisation by providing individual information about a product, its origin and history. Being able to trace a product or material back can improve decision making by providing real-time information. This can improve the efficiency of production/project planning, reduce waste and logistics, and increase the output rate.

- **Verification:** Traceability systems can assure the origin of materials from potential areas of conflict. There has been significant research interest in halal traceability in the meat supply chain, a major consideration for Muslim consumers.

[8] *Aung, M. M., & Chang, Y. S. (2014). Traceability in a food supply chain: Safety and quality perspectives. Food control, 39, 172-184.*
[9] *Olsen, P., & Borit, M. (2013). How to define traceability. Trends in food science & technology, 29(2), 142-150.*

- **Product recall:** Traceability systems do not reduce the probability of recall but will impact its size and costs. It is closely associated with product safety and quality.

- **Improve consumer confidence:** Traceability systems that share product origin and certification with consumers in the food industry are generally described as *Farm-to-Fork* systems. However, consumer engagement with such systems appears low. Those purchasing the product are satisfied with knowing that a system has been put in place to trace and confirm the important characteristics of the product, but they have little interest in doing any tracing themselves. So, the presence of a traceability system appears to improve consumer confidence.

2.2.2 Regulations and compliances

The legislation and compliance landscape for the Australian food industry can generally be categorised into 4 areas: a) federal requirements; b) state and local council requirements; c) sector-specific standards; and d) ISO standards.

Federal requirements

Food Standards Australia New Zealand (FSANZ) is the overarching standard for food safety in Australia, which is responsible for regulating the Australia New Zealand Food Standards Code. It consists of 4 sections: introduction and standards that apply to all food, food safety standards, primary production standards, and food standards code governance. For traceability, Standard 3.2.2 – Food Safety Practices and General Requirements in chapter 3 of the Code covers the "**one step back and one step forward**" elements of traceability under Clause 5 (2) Food receipt and Clause 12 Food recall.

- **Food receipt**: A food business must not receive food unless it can identify the name of the food and the name of the supplier.

- **Food recall**: A system set out in a written document to ensure it can recall unsafe food, which records: production records, what products are manufactured or supplied, volume or quantity of products manufactured or supplied, batch or lot identification (or other markings), where products are distributed, and any other relevant production records.

- **Food labelling**: The labelling information should at least cover the name of the food, lot identification (mostly the best by date), and the name and address of the supplier.

The FSANZ food safety standard also follows the international food standards developed by Codex Alimentarius Commission (CAC). The CAC's mission is to protect the health of consumers, ensure fair international food trade, and develop standards based on sound scientific principles. In 1993, CAC recommended the Hazard Analysis and Critical Control Points (HACCP), a set of principles to guide practice such as traceability. It was recently renewed in 2020. CAC has input from 188 member countries; Codex Australia coordinates Australian input.

State and local council requirements

In Australia, the Food Standards Code is governed by state and territory. In Victoria, this is the Department of Health and Human Services, and it is controlled by the *Food Act 1984* (Vic), requiring that all food sold and produced in Victoria is safe for human consumption and meets all standards set out in the Food Standards Code.

Local councils are usually responsible for registering food businesses, monitoring compliance, providing education and advice, and taking enforcement action when needed. State and federal requirements are enforced at a local level through local health inspectors employed by local councils.

Sector-specific requirements

There are also sector-specific standards and systems for food traceability. For example, the National Livestock Identification System (NILS) is Australia's mandatory system for identifying and tracing cattle, sheep, and goats.[10] The NLIS defines 3 elements for lifetime traceability: 1) All livestock are identified by a visual or electronic eartag/device; 2) All physical locations are identified using a Property Identification Code (PIC); 3) All livestock location data and movements are recorded in a central database.

ISO standard

Many Australian food producers use and get certified with the ISO 9000 series for Quality Management Systems. ISO 22000 (2005) specified requirements for a food safety management system where an organisation in the food chain needs to demonstrate its ability to control food safety hazards to ensure food is safe at the time of human consumption. This standard includes analysing methods of food hazards from HACCP and the approach of the management system from ISO 9001. Further, ISO 22005 (2007) defined traceability principles and objectives and specified the basic requirements for designing and implementing a feed and food traceability system. It can be applied by an organisation operating at any step in the feed and food chain.[11]

2.2.3 Identification technology

Traceability can be successfully achieved only if it is built on global standards that enable interoperability between traceability systems across the whole supply chain. The GS1 global traceability standard is a voluntary business process standard describing the traceability process independently from the choice of enabling technologies. It meets the core legislative and business need to cost-effectively trace back and track forward at any point along the whole supply chain. Because it can provide globally unique identification of trade items, assets, logistic units, parties, and locations, the GS1 system is particularly well suited for traceability purposes.[11]

As the core contribution to traceability, GS1 provides 12 ID keys to enable companies to access information about items in their supply chains and share this information with trading partners (See Table 2.1 and Figure 2.1). GS1 ID keys are globally unique, and the organisation must become a member of GS1 and obtain a GS1 company prefix forming the basis of the ID keys.

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[10] *https://www.nlis.com.au/*

[11] *Aung, M. M., & Chang, Y. S. (2014). Traceability in a food supply chain: Safety and quality perspectives. Food control, 39, 172-184.*

Table 2.1: GS1 12 ID Keys [12]

ID key	Used to identify	Example
Global Trade Item Number (GTIN)	Products and services	Can of soup, chocolate bar
Global Location Number (GLN)	Parties and location	Companies, warehouses, factories, stores
Serial Shipping Container Code (SSCC)	Logistics units	Unit loads on pallets, roll cages, parcels
Global Returnable Asset Identifier (GRAI)	Returnable assets	Pallet cases, crates, totes
Global Individual Asset Identifier (GIAI)	Assets	Medical, manufacturing, transport, and IT equipment
Global Service Relation Number (GSRN)	Service provider and recipient relationships	Loyalty scheme members, doctors at a hospital, library members
Global Document Type Identifier (GDTI)	Documents	Tax demands, shipment forms, driving licences
Global Identification Number for Consignment (GINC)	Consignments	Logistics units transported together in a shipping container
Global Shipment Identification Number (GSIN)	Shipments	Logistics units delivered to a customer together
Global Coupon Number (GCN)	Coupons	Digital coupons
Global Model Number (GMN)	Product model	Medical devices

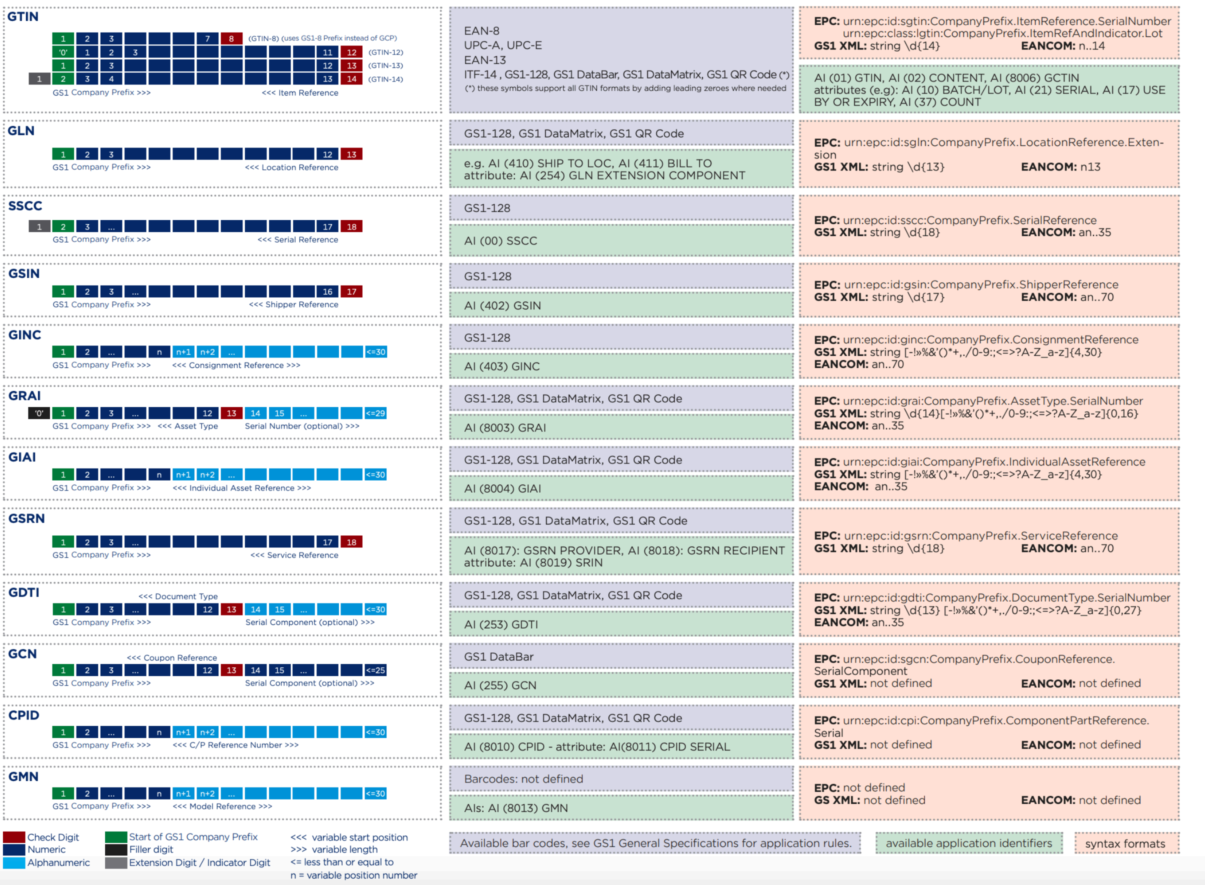

Figure 2.1: Example of GS1 12 ID Keys [13]

[12] *https://www.gs1au.org/what-we-do/standards/traceability*
[13] *https://www.gs1au.org/what-we-do/standards/traceability*

Figure 2.2 shows an example of how GS1 ID keys are used to describe critical tracking events. GS1 provides scannable solutions for items, whether individual or in a bunch. A Serialised GTIN (SGTIN) can be applied in addition to a GTIN to identify each unit of the same product. GS1 scannable solutions include GS1 DataMatrix Barcodes and GS1 EPC/RFID tags, as shown in Figure 2.3.

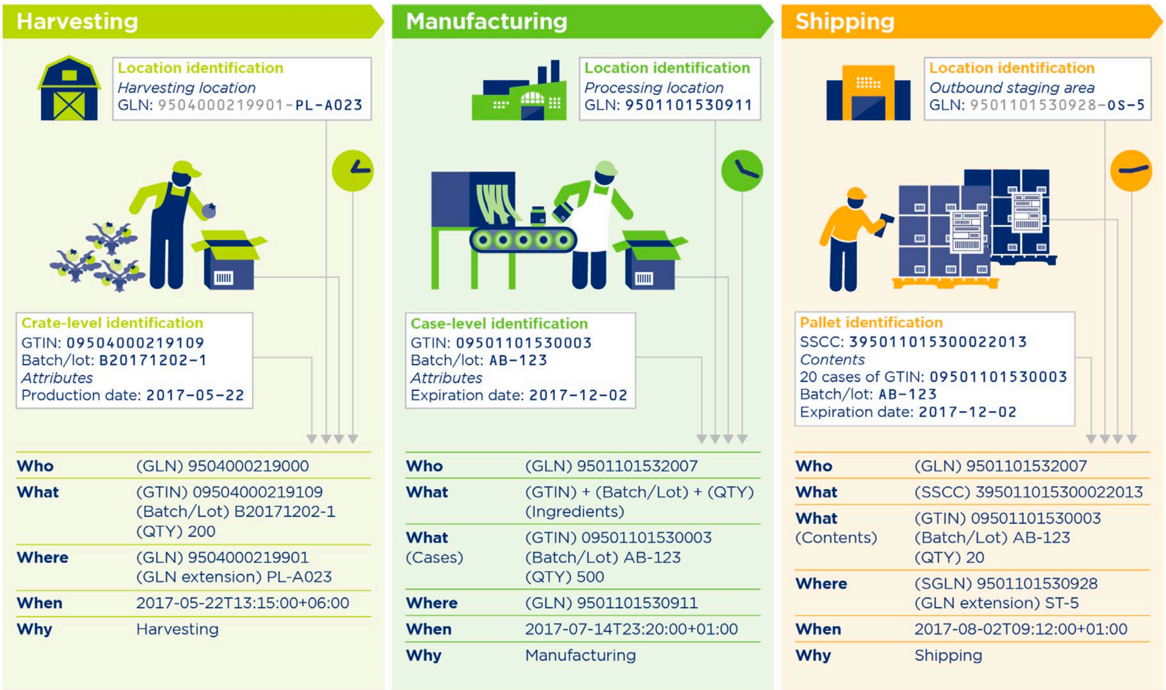

Figure 2.2: Example of GS1 ID keys application [14]

[14] *https://www.gs1au.org/what-we-do/standards/traceability*

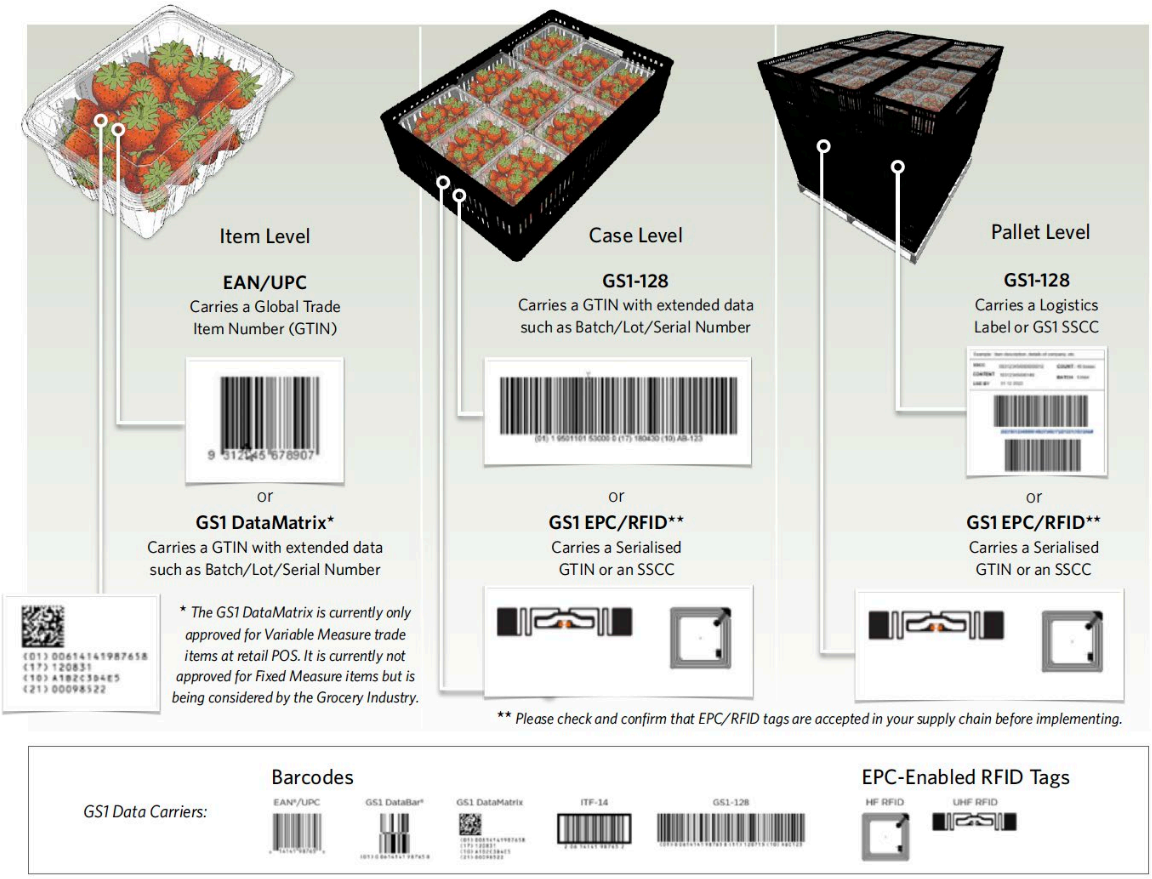

Figure 2.3: Example of GS1 Identification Technology[14]

Barcodes remain the centrepiece of identification technology used in the food industry. Meanwhile, DataMatrix (QR code) and RFID are gaining popularity for specific food products (e.g., beef). The cost of RFID is still high for low-margin industries, like agrifood and food which limits adoption for only high-value products. Further, there is an increasing body of knowledge for using Internet of Things (IoT) and blockchain technology for food supply chain traceability. Although some criticise the buzzword status of those emerging technologies, IoT-based real-time monitoring systems have effectively managed perishable or temperature-sensitive food products (e.g., cold chain logistic management) [15] According to Saberi et al., blockchain may improve traceability by reducing the need for trust between partners, but it suffers from high cost and technological immaturity. [16]

2.2.4 Challenges

Based on the literature survey, we have grouped the barriers into 4 aspects: economic, technological, operational and cultural.

Economic barriers

[15] *Tsang, Y. P., Choy, K. L., Wu, C. H., Ho, G. T., Lam, C. H., & Koo, P. S. (2018). An Internet of Things (IoT)-based risk monitoring system for managing cold supply chain risks. Industrial Management & Data Systems.*

[16] *Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. International Journal of Production Research, 57(7), 2117-2135.*

- **High cost:** Many case studies identified high cost as a potential barrier to implementing a traceability system. The costs can be due to new technology infrastructure, new employees, opportunity costs and process improvements.

- **Lack of clear benefits and value:** The understanding of a traceability system's benefits is limited throughout the literature. The quantifiable value of a traceability system will help overcome doubts that may arise due to the cost of implementation.

Operational barriers

- **Lack of global standards:** This is the most noted operational barrier despite solutions such as GS1 standards being available for traceability. The adoption of such standards is low because organisations are often hesitant to customise standards to their operations.

- **Complexity and uncertainty in supply chain:** The supply path for a product is often unknown, leading to complexity in identifying suppliers and sub-suppliers. Each organisation will have to decide what information is produced and how they can share it with other organisations.

- **Reliance on paper-based systems**: Supply chain traceability is not a new concept, with routines being established on paper.

Technical barriers

- **Verification of claims and data:** This is the most common technical barrier, because a traceability system will be redundant if the initial data is inaccurate. Technology such as blockchain may assist in protecting data, but verifying the input data will remain a challenge.

- **Data interoperability:** Data is stored inconsistently across different databases, because enforcing one traceability system is not possible in most supply chains. Standards may improve interoperability, but their use remains low.

- **Confidence and security:** Concerns over the security of a traceability system mean organisations are hesitant to share information with other members of the supply chain, an issue that could be resolved using blockchain or other encryption methods.

- **Batch level identification:** Identifying a large batch poses greater technical challenges than identifying individual items when these batches are to be later separated.

Cultural barriers

- **Gaps between developed and developing nations:** Supply chains often originated in more developing nations to deliver products and materials to more developed nations. Cultural differences can lead to varying attitudes towards the information shared and a lower investment into traceability systems due to unequal wealth distribution.

- **Lack of motivation:** This cultural barrier is tied to the costs and lack of clear benefits of a traceability system. There is a lower level of motivation in small-to-medium-sized organisations because the benefits of a traceability system are not as evident.

- **Lack of technical expertise:** A wide range of technology can be used to enable supply chain traceability. Still, the knowledge of implementing these systems across nations is not well developed.

- **Organisational changes required:** Organisational change is required to implement traceability systems, but this can be a slow process that fosters conflict.

2.3 Summary

This chapter reviewed the definition of traceability and its state-of-the-art in the food industry. We can learn a few valuable lessons when analysing and developing traceability in the construction industry:

- Traceability in the food industry is largely driven by safety and quality, which is the primary concern of any food business today. Other benefits of developing traceability capability include optimising process efficiency, improving sustainability performance, and increasing consumer confidence.

- Comprehensive legislation, regulations and international standards mandate traceability in the food industry. Although the legislative requirements demand only minimal information and can be fulfilled even with a paper-pencil approach, some sectors (e.g., red meat) take an extra step and rely on full digitalisation and a centralised database.

- GS1 plays a pivotal role in traceability, providing standards for identifying, capturing, sharing and using information related to a product. The GS1 12 identification keys contains information describing the critical tracking events, including the who, what, where, when and why. Those ID keys can be carried with mature technologies like barcodes, RFID and QR codes.

- Advanced digital technologies (e.g., IoT and blockchain) are still under development for traceability applications where the cost is the main barrier to adoption. Further, the slow adoption of digital traceability is also attributed to technological, operational and cultural obstacles.

Chapter 3 Supply chains in building design, construction and operation

Authors: Robin Drogemuller, Sara Omrani and Negar Adebi

3.1 Introduction

This chapter encapsulates the results of Task 2 – Specification, Compliance, Risk Review and Task 7 – Design Integration Review from this project. These task results are combined due to the high level of interdependence between the subjects. As is described below, the design process produces a ‘demand chain’, which is the basis for developing the ‘supply chain’, with interactions between these at various points.

We used selecting and specifying an aluminium framed door system as the basis for a grounded discussion on the design, construction and operational aspects of supply chains.

While some aspects of supply chain management as applied to the construction industry are shared with other industries, other aspects need to receive much more attention in the construction industry than in other industries. One aspect of difference is the range of types of components involved on a construction site:

- bulk materials, i.e. sand, ready mixed concrete
- discrete components that need to be assembled on-site, i.e. brickwork, using bricks and cement mortar
- entire prefabricated panels or service pods, delivered to site and then lifted into position
- air, excavation works that are required to form the foundations of the building and possibly basements (see Figure 3.1). This may be unique to construction industry supply chains.

This range of component types means some processes are handled onsite, while others can be performed in off-site environments.

Figure 3.1: Excavation required before commencing the physical building

Another aspect is the complexity and size of construction projects, with heavy inter-dependencies between systems, requiring careful planning of installation activities with significant temporary storage (buffers) to ensure inter-dependent components are available within tight time frames. Thus, the use of space for installation activities needs to be carefully controlled to ensure components can be installed in the appropriate sequence. This important aspect led to the addition of the 'Last Planner' approach when applying lean production methods to the construction industry.

The wide range of legal requirements on construction projects is also important. Building codes in each country specify requirements for various types of buildings, either directly or by calling up separate standards and codes, such as the Australian National Building Code.[17] Standards and industry standard specifications, such as NATSPEC, capture normal industry practice and change with time as approaches to specification, installation and operation adapt.

The chapter takes a 'whole-of-project' perspective to support the explicit project goal of identifying opportunities for future research activity. This means the considerations are not just restricted to identifying products and how they are ordered and delivered, but also how the need for a product is identified, specified, ordered, checked for conformance, delivered, stored, installed and then certified as being appropriately installed. It should also be recognised that the entire construction project process is a supply chain, consisting of design, documentation, management, construction and operation services that deliver the completed project as a physical product.

The 'whole-of-project' approach also raises an interesting question that does not appear to be addressed in the literature: "Is the construction industry unique in that its demand chain is also a significant supply chain?" This question reflects the range of disciplines, complexity of documentation and interrelated approvals processes involved in planning a building.

This report considers both 'grey' literature and standard academic literature. Grey literature is often much more up-to-date than academic literature and provides more details, but it also needs to be treated with more care.

3.2 Differences between construction and manufacturing

It is difficult to draw an exact boundary between the construction industry and manufacturing, because most products are manufactured before being brought on to the construction site.[18] The current promotion of modern methods of construction tends to blur the distinction even further.

The Construction Industry Institute (CII), in their report RS191-1,[19] identified the differences between the construction and manufacturing industries as:

Customer focus

- Project managers/contractors do not control all of the supply chain.
- The largest contractors control only a small proportion of the market. In manufacturing the largest manufacturers control significant proportions of the market.

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[17] *Australian Building Code Board (2019), National Construction Code, Volume 1.*
[18] *Segerstedt, A., & Olofsson, T. (2010). Supply chains in the construction industry. Supply Chain Management: An International Journal, 15(5), 347-353. https://doi.org/10.1108/13598541011068260*
[19] *CII (2022) Lean Principles in Construction, RT-191 Topic Summary, https://www.construction-institute.org/resources/knowledgebase/knowledge-areas/construction-execution/topics/rt-191*

Culture/people

- High turnover of personnel in construction reduces the incentives and return on investment in training.
- Construction workers are craft skilled. Workers in manufacturing specialise in processes.

Workplace standardisation

- At the project level, construction projects have a fluid organisation.
- The production environment configuration changes constantly, making it more difficult to apply visual management systems.

Elimination of waste

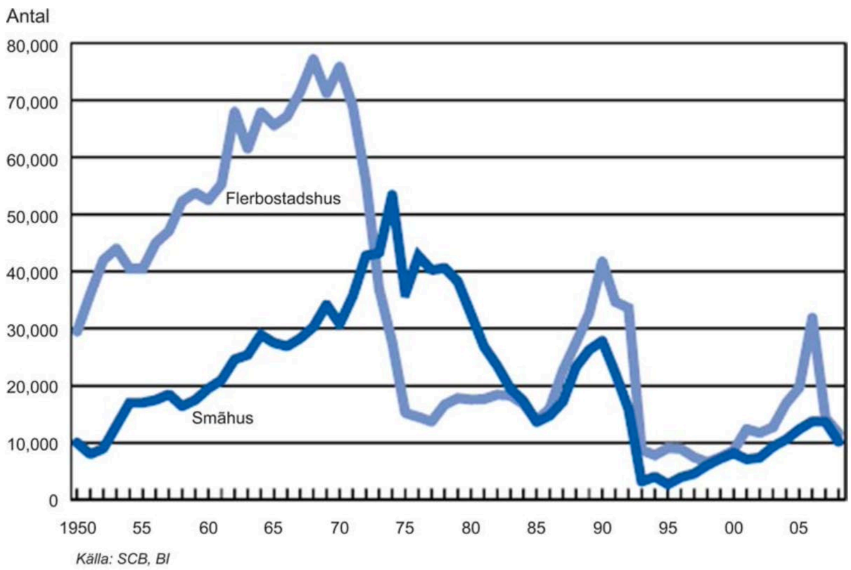
- The production sequence is largely discretionary under subcontracts.
- Material flow is not uniform. Supply lines vary at different locations within the project.

Continuous improvement/built-in quality

- High staff turnover means there is less opportunity for training.
- Development of a quality-tracking system is difficult.

The primary issue from the above factors is the greater degree of discretionary behaviour and increased uncertainty in construction projects. In manufacturing, production systems are defined and controlled by the configuration of the production line. In construction projects, the production system is defined by project managers and individual workers.

Another factor that distinguishes the construction industry from other industries is the high degree of variability of work. Figure 3.2 describes the Swedish industry, where there is and has been a higher level of design for manufacturing (DfM) and prefabrication than in Australia. The reasons for this variability are 2-fold: (i) economic factors external to the construction industry and (ii) governments using the construction industry as an economic regulator by pumping money into construction to boost the overall economy and reducing government expenditure on construction to slow the economy. The construction industry is an ideal economic regulator due to its significance in the economy (~10% GDP), its geographically distributed nature, and the low cost of entry and ease of exit as the economy fluctuates. This use as an economic regulator increases the risk in off-site and prefabricated manufacturing facilities because larger-scale facilities need even demand to function effectively.

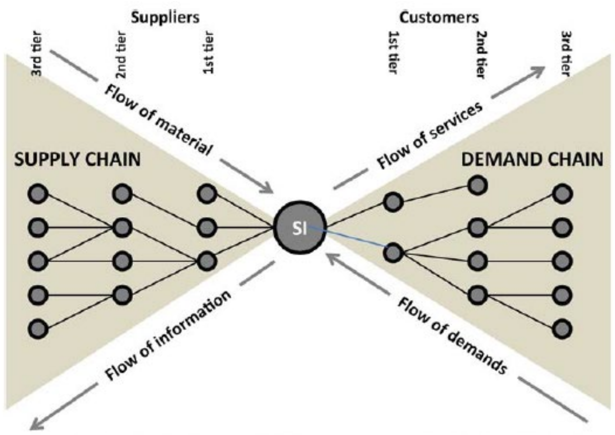


Source: Statistics Sweden and the Swedish Construction Federation

Figure 3.2: Swedish apartment block starts from 1950–2008[20]

3.3 Relationship between demand and supply chains

While this project focuses on supply chains, supply chains are built around meeting the needs identified in the demand chain. The system integrator sits at the centre of the supply and demand chains. [20] However, under traditional methods of construction such as design–tender–construct, the system integrator during the design stage is the architect, while once the construction contract is let, the head contractor then becomes the system integrator. Under more integrated forms of contract, such as design–construct and integrated project delivery, the system integrator role can be much more stable.



Source: Adapted after Lambert *et al.* (1998), London and Kenley (2000) and Vrijhof and deRidder (2005)

Figure 3.3: Supply chains and demand chains

Figure 3.3 illustrates that the requirements of the ‘customers’ – the flow of demands – are used by the system integrator to produce the requirements for a building component or system, which is then broken down in the supply chain to identify the parts that, when put together in the appropriate configuration, will meet the

[20] *Segerstedt, A., & Olofsson, T. (2010). Supply chains in the construction industry. Supply Chain Management: An International Journal, 15(5), 347-353. https://doi.org/10.1108/13598541011068260*

requirements and provide the services required. This is explained in more detail below, using a case study.

3.4 RIBA plan of work

The RIBA Plan of Work 2020[21] defines widely recognised stages in the construction project lifecycle and consists of 8 stages:

- Stage 0: Strategic definition
- Stage 1: Preparation and briefing
- Stage 2: Concept design
- Stage 3: Spatial coordination
- Stage 4: Technical design
- Stage 5: Manufacturing and construction
- Stage 6: Handover
- Stage 7: Use.

This workflow will be the basis for the case study, with the addition of the first section on industry context that is necessary to identify constraints on innovation that are brought out in more detail in subsequent sections. This is a supply chain of services that produces the design.

The 'services' provided throughout the project are:[21]

- conservation strategy
- cost strategy
- fire safety strategy
- health and safety strategy
- inclusive design strategy
- planning strategy
- plan for use strategy
- procurement strategy
- sustainability strategy.

3.5 Industry context

The architecture, engineering and construction (AEC) industry produces some of the largest, most complex artifacts that human beings are capable of. The Burj Khalifa (Figure 3.4) is currently the world's tallest building and was built using a concrete frame. Concrete is a technology that dates back to the Roman empire, first being used over 2,000 years ago. The addition of steel reinforcing in the late 1800s and early 1900s to produce reinforced concrete allowed concrete to be used in ways beyond anything the Romans could have envisaged.

[21] *RIBA (2020) RIBA Plan of Work 2020,* https://www.architecture.com/knowledge-and-resources/resources-landing-page/riba-plan-of-work

Figure 3.4: Burj Khalifa [22]

With tall structures such as the Burj Khalifa, structural engineers still need to consider the traditional factors – resisting applied forces, with seismic and wind loads becoming dominant – but they also need to understand differential axial shortening, where the deflection of the structural frame increases with the addition of each new storey. If the constructors on the Burj Khalifa had initially built each storey as per the finished dimensions there would have been over a metre of difference in height between the central structural core and the perimeter beams and columns at the top of the building (personal communication with Evelyn Storey from AURECON). Obviously, a floor with a slope of 1 m will not meet the design constraints.

In other words, in building construction, the result is much more than the sum of its parts. There needs to be a system integrator for each major subsystem, liaising with the overall system integrator.

Even our simple case study needs integration between the door fabricator (ability to install the security cabling once the door assembly arrives onsite) and the door hardware supplier, and security supplier and the installers to ensure the swipe card system is compatible with the door handle hardware.

3.6 Regulatory obligations

The AEC industry is subject to significant regulatory control. The modern development of building codes can be dated back to the Great Fire of London in 1666, as a response to the significant loss of life and property in that event. Modern building codes control health, safety and amenity.

The National Construction Code (NCC) is enabled in Queensland, in a similar manner to the other Australian states and territories. The hierarchy is shown schematically in Figure 3.5.

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[22] https://www.architectmagazine.com/project-gallery/burj-khalifa

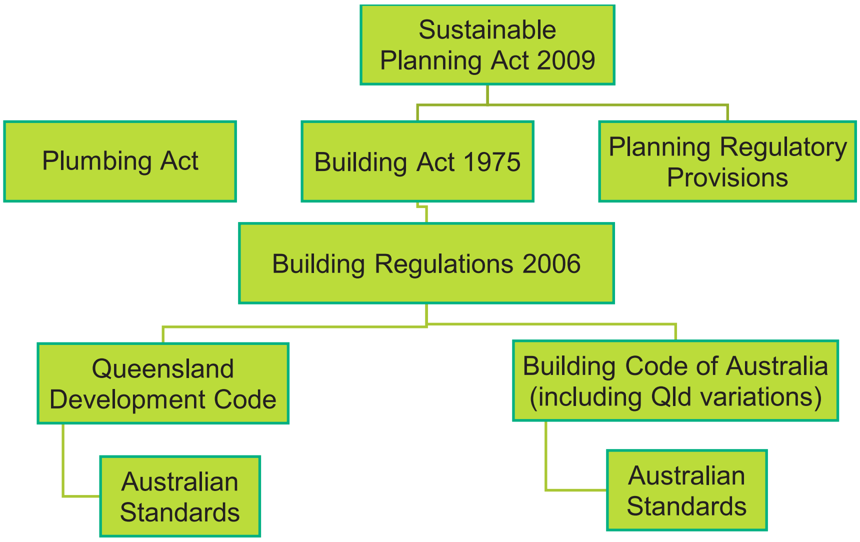

Figure3.5: Building related legislation in Queensland (Melissa Chandler, Lendlease)

The NCC defines the minimum requirements that buildings must achieve to be certified for occupancy. Most buildings need to comply with around 4,000 individual codes and standards. Appropriate use of these standards sets the requirements for the products and processes within the building.

The Building Code of Australia (BCA) volumes within the NCC are performance-based codes. The provisions can be divided into performance requirements and compliance solutions as illustrated in Figure 3.6. This is analogous to the demand chain/supply chain relationship discussed later in this chapter. The performance requirements state what level(s) of performance are required (demand) and the compliance solutions identify those solutions that meet the requirements (supply) either by already being assessed as complying, or by a range of certification methods, as explained more fully within the BCA section A2.

A completed building must conform to the NCC, as conformance must be certified before a Certificate of Occupancy is provided. A building cannot be handed over to the client and occupied before the Certificate of Occupancy has been given. Hence, the project is not complete and final payments cannot be made.

Major problems arise when the prescribed products and processes are not adhered to. It is emerging that the recent Grenfell Tower disaster in the UK was a result of inappropriate fire testing and certification of materials, poor design decisions and non-conforming installation of the products. This resulted in the deaths of 71 people.

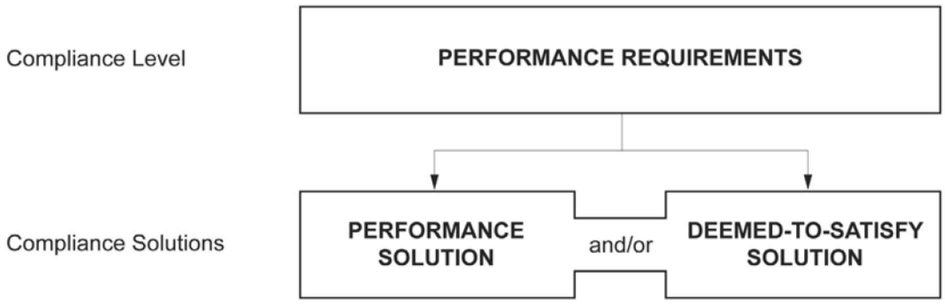

Figure 3.6: Structure of BCA

3.7 Australian Standards

Standards Australia manages the process of creating and maintaining standards. Standards are produced by industry committees who come together to create standards that meet the need for consistency in the specifications that products and services in Australia should live up to. They cover issues such as performance (star rating of windows for energy performance), safety (fire resistance) and analytical methods (structural design).

Unlike the NCC, standards have no legal standing on their own. Standards may be called up either from the NCC, in which case they have legal status, or in the project specification(s), in which case they have contractual status.

When considering supply chains, often a range of standards must be considered at different levels in the demand/supply. For example, tracing the supply chain of materials involved in in-situ concrete in buildings through referring to the standards called up in NATSPEC is shown in Figure 3.7.

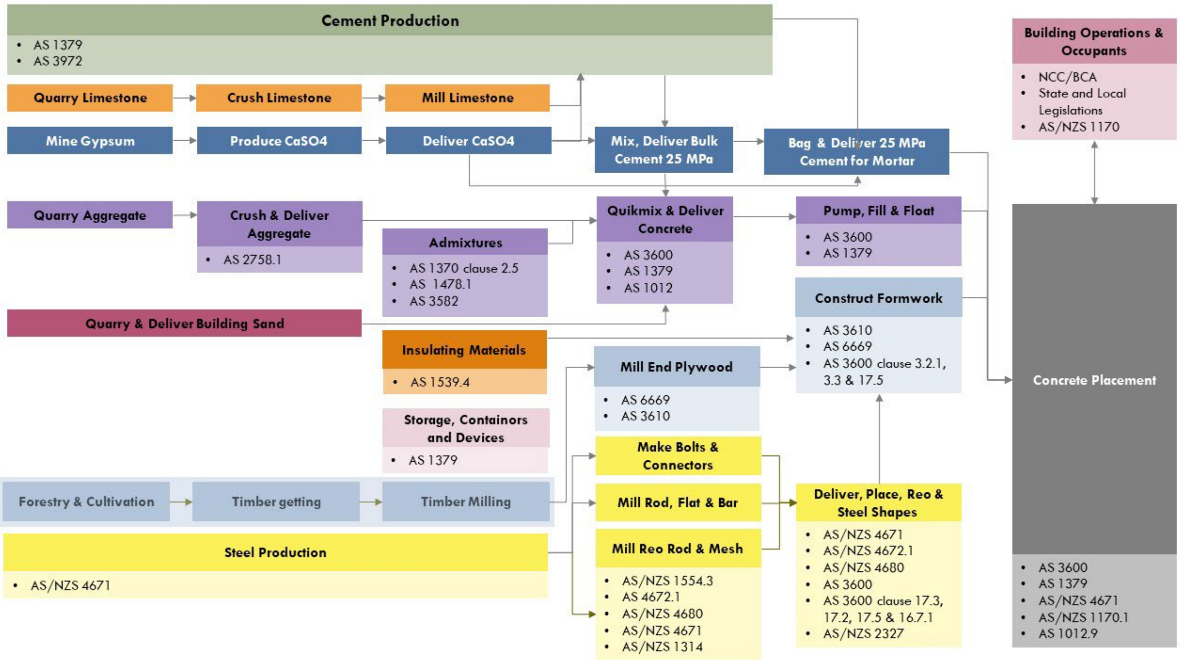

Figure 3.7: References to Australian Standards for in-situ concrete in NATSPEC

3.8 Contract documents

AEC contacts normally consist of 3 separate documents:

- The formal contract document which specifies the legal relationships between the various parties to the contract. Common Australian standard forms of contract include ABIC, AS 2124, AS 4000, AS 4905 and AS 4902.
- The contract drawings, which show the location, extent and relationships between building components.
- The specification, which is a textual document that defines the quality and workmanship required under the contract.

Different contract documents are often used for lower levels in the tier of contracts and subcontracts that apply to building contracts.

There also different types of contractual relationships. In design–tender–construct contracts, the architect is normally the systems integrator during the design phase (demand chain realisation), with the major systems integrator role switching to the head contractor during construction (supply chain realisation). Under design–construction contracts, such as AS 4902, a project manager may retain the role of systems integrator through the entire procurement process.

3.9 Specifications

NATSPEC, the Australian national building specification,[23] provides a basis for preparing construction specifications based on Australian codes, standards and practices. It encapsulates and provides guidance on the material in over 4,000 Australian Standards that apply to buildings.

NATSPEC Building Professional consists of 186 work sections (at March 2022) each of which covers a specific aspect of a trade or work package. There are also general work sections that cover aspects relevant to all work sections:

1. Tendering
2. Preliminaries
3. Quality
4. Commissioning
5. General requirements
6. Environmental management.

A NATSPEC specification is normally produced by using the SPECbuilder software, which guides the user through the process by assisting with structuring the document, providing hints and advice, and also indicating where the document may need to be customised for a particular project.

3.10 A case study

A simple example that illustrates the necessary concepts is the design, selection, manufacture, installation and maintenance of an aluminium framed door. An example is shown in Figure 3.8, from both the outside and the inside. The relevant considerations to note are:

- The door is part of a framing system which is embedded within the structure of the building.
- The door has an access control system (swipe card) to the right of the outside face.
- There are 3 evenly spaced stainless steel hinges visible on the outside.
- The green light above the interior face of the door indicates that this is a required exit for egress in the case of fire.
- There is a door closer fixed to the top of the interior face of the door.
- There are lever handles on both sides of the door, which will be connected to the box containing the access control.
- There is a white strip applied to the glass at mid-height to improve visibility.
- There is a security camera aimed at the door, together with the warning sign above the door on the outside face.

[23] *https://www.natspec.com.au/*

Figure 3.8: Exterior (a) and Interior (b) of front door to an apartment building

A detail of the major component parts is shown in Figure 3.9:

- door Frame, made up of the head jamb and the side jambs
- hinge securing the door to the frame, which also requires screws.

The door consisting of:

- aluminium top and bottom rails and the two stiles (sides)
- glass panel
- neoprene strips to hold the glazing in place
- screws to secure the components of the door and frame
- plastic blocks to take the ends of some screws.

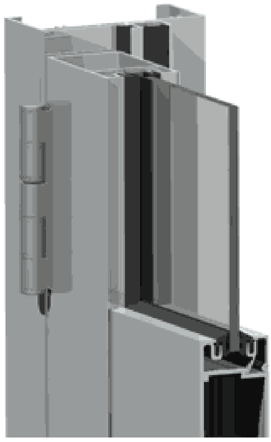

Figure 3.9: Section through door base, hinged side (https://professional.gjames.com/data/assets/image/0010/23968/475-3d-door-sill.png)

This case study is mapped onto the RIBA Plan of Work in the following sections. The Plan of Work is a supply chain specification for the design, construction and facility management services for a building project.

Strategic definition

This stage examines the most appropriate way of meeting the client's needs, such as deciding whether to build a new facility or lease an existing one. The case study is of slight significance at this stage. The need for secure access would be identified in the client's requirements (demand chain) and would either be added to the client's brief if building works were going to be undertaken, or used as one of the factors in deciding whether existing premises were suitable for either purchase or leasing.

Preparation and briefing

This stage involves preparing the brief – a detailed description of the client's requirements. This would include recording that the door requires both camera security and swipe card access.

There would also be a decision on whether the contract documents were going to be prescriptive (fully detailing the selected building components and how they are installed) or descriptive (giving performance requirements that the supplier then uses to choose which building components they will supply and how they will be installed). This would include deciding on whether the security to the building, and our door, will be installed and managed by the client, or by an external provider.

Concept design

This stage develops the architectural concept within the context of the client brief. The location of the door would be identified in the architectural concept, with liaison with the engineers designing the building services.

The door location and width would be determined by fire safety provisions from the NCC, including the distance from other required exits. It would also need to be housed in a structurally sound location that provided secure fixing, electrical supply and communication cabling.

Since this door is a main entrance door to the building, the timing of installation of services to the door and the installation of the door assembly will affect when 'lock up' occurs – when the building is secure from casual entry and reasonably weatherproof. This allows many of the work packages providing expensive or fragile components to start.

Spatial coordination

This stage is about ensuring the initial architectural design concepts are sound. It includes detailed simulations across a range of engineering services. In a large project, the door could play a role in pedestrian flow, thermal and fire evacuation simulations. It would also be assessed against detailed NCC provisions. Location and width are determined by NCC egress (escape) provisions. Access by people with disabilities is defined in AS 1428: Design for access and mobility. Both considerations have wider impacts because the door must be easily accessible by the public from the street and from inside the building, and have clear passage for wheelchairs (no steps) and tactile markers to the door for the visually impaired.

Technical design

The technical design stage involves preparing all information required to manufacture and construct a building. Realistically, no significant building project is ever 'fully described'. It would be more accurate to say it involves preparaing all the information required by the next lower layer in the demand or supply chain (in the ideal situation).

For our case study, this is where most of the detail about the door is generated. On the demand side, the size of the opening that the door assembly will fill is given, as well as the required door width. This information is then used as input by the designers to provide an initial design for the door assembly.

Aluminium door and window fabricators provide guidance to designers and specifiers on using their products. Figure 3.10 shows a portion of the table provided by G James. This provides the key information necessary to select between 2 of G James' major systems.

	472 Series Hinged	475 Series Hinged
Recommended Application	Housing	Low rise apartment, commercial & retail applications
Perimeter Frame Options	• 101mm (Inwards or outwards opening) • 125mm (inward opening doors / outward opening screen)	101mm & 152mm
AS 1428 (DA) Compliant Sill / Threshold	No	• 101mm - 475-008 • 152mm - 675-005 or 675-036
Screening	Fly, barrier & Crimsafe screens to 125mm frame only	Fly & Crimsafe outwards opening screens in retro-fit frame
Max. Water Penetration	• 150 Pa. - Standard sill • 450 Pa. - Outward opening configuration with sub-sill	200 Pa. using 475-021 threshold with sub-sill [1]
Glazing	• Single glazed - up to 6.38mm • Double glazed (IGU) - 20mm	• Up to 11.52mm - 475-200 Series • Up to 15mm - 475-300 Series • Up to 30.52mm - 476-200 Series
Max. Size.	• Single Door - 2400mm (h) x 950mm (w) [2] • Double Door - 2400mm (h) x 1810mm (w) [2]	2700mm (h) x 1000mm (w) [3]
Energy Ratings Available	Yes	Yes
Max. Acoustic Rating [4]	Rw 31	Rw 35
Bushfire Attack Level	Tested and certified to BAL-40 [4]	No
Handle/ Lock Options	Lever handle with optional multi-point locking	Dependent on application, consult your G.James representative

Figure 3.10: Selection table for G James aluminium door systems [24]

The geometrical configuration of the door assembly would be provided as a drawing similar to Figure 3.11. Other details – such as the type and colour of the anodised finish, the type and number of hinges, the door handle and the door closer – are normally written up in the specification.

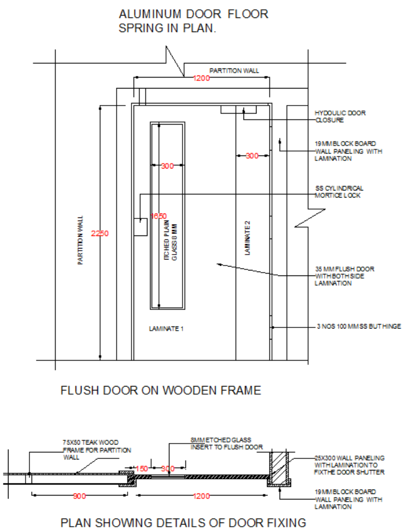

Figure 3.11: Elevation of door assembly

Industry experience must be applied here, because the door closer at the top of the door applies a significant torque to the door on the vertical axis and the hinges when

[24] *https://gjames.com/doors/hinged-doors*

the door is opened and closed. There can be significant maintenance issues if the hinges are not specified adequately. Figure 3.12 shows the addition of an extra hinge on each door to decrease the likelihood of the upper door hinges failing due to this torque.

Figure 3.12: Door assembly with extra hinge [25]

The energy performance of glass doors and windows must be assessed against the NCC Volume 1 Section J and Volume 2 Part 3.12. The data needed to assess some products from G James is shown in Figure 3.13.

Series	Glass	Uw	SHGCw	VTw	Glazing
475	**25mm Series Aluminium Fixed Window** 6.38mm Solect Pewter 129 Laminate Low-e #4	4.20	0.45	0.35	Single
475	**25mm Series Aluminium Fixed Window** 6.38mm Solect Green 819 Laminate Low-e #4	4.20	0.45	0.64	Single
475	**25mm Series Aluminium Fixed Window** 6.38mm Solect Clear 119 Laminate Low-e #4	4.20	0.62	0.73	Single
475	**Aluminium Fixed Window** 10.76mm Solect 719 Laminate Low-e #4	4.30	0.34	0.52	Single
475	**Aluminium Fixed Window** 10.76mm Solect 819 Laminate Green Low-e #4	4.30	0.35	0.52	Single
475	**Aluminium Fixed Window** 10.76mm Solect 319 Laminate Low-e #4	4.30	0.37	0.31	Single

Figure 3.13: WERS Ratings for some of G James windows [26]

[25] https://knoxaluminium.com.au/hinge-door/
[26] https://professional.gjames.com/windows/475-series/wers

Manufacturing and construction

Things get very complicated at this stage for 2 significant reasons. First, the ‘as wished for’ technical design must be converted into a ‘realisable’ technical design. Second, an internal supply/transportation system must be defined to move the components and resources around the project, as the project is realised.

Assumptions are made during the detailed design process about whether building components are manufactured off site or on site. The system integrators, at the various levels within this stage, need to analyse these assumptions and then decide whether there is an alternative approach to realising the desired result. The form of contract will determine whether approval is required to make changes in achieving the end result or not.

During this stage, a wide range of things need to be supplied:

1. physical components required for the completed building:
   a. discrete components that are fully or partially assembled, i.e. windows
   b. bulk components that need to be formed on site, i.e. in-situ concrete, excavation
2. physical components required for temporary works required during construction:
   a. discrete components such as scaffolding, prefabricated formwork
   b. bulk components such as the timber and sheets required to build traditional formwork
3. personnel required to transport and/or install the physical components
4. an internal transportation system that adapts through the construction process:
   a. cranes, personnel hoists, boom pumps
   b. laydown and storage areas
   c. loading bays on multistorey projects
5. services, such as inspections and certifications by external bodies.

Figure 3.14 shows a laydown and materials storage area, where materials, components and equipment are delivered and may be temporarily stored. An adjacent site or area may be used on sites where the total site area is covered by the building. It is common for the laydown and storage areas to change position through the project as areas are needed for other uses.

Figure 3.14: Laydown area for delivery and storage of materials, formwork and scaffolding

Figure 3.15 shows a tower crane, personnel hoist and loading bays used on high rise construction.

Figure 3.15: Tower crane and personnel hoist for vertical transportation on multistorey building

A series of cranes may need to be used to provide horizontal movement on projects which have a large, continuous built area (Figure 3.16).

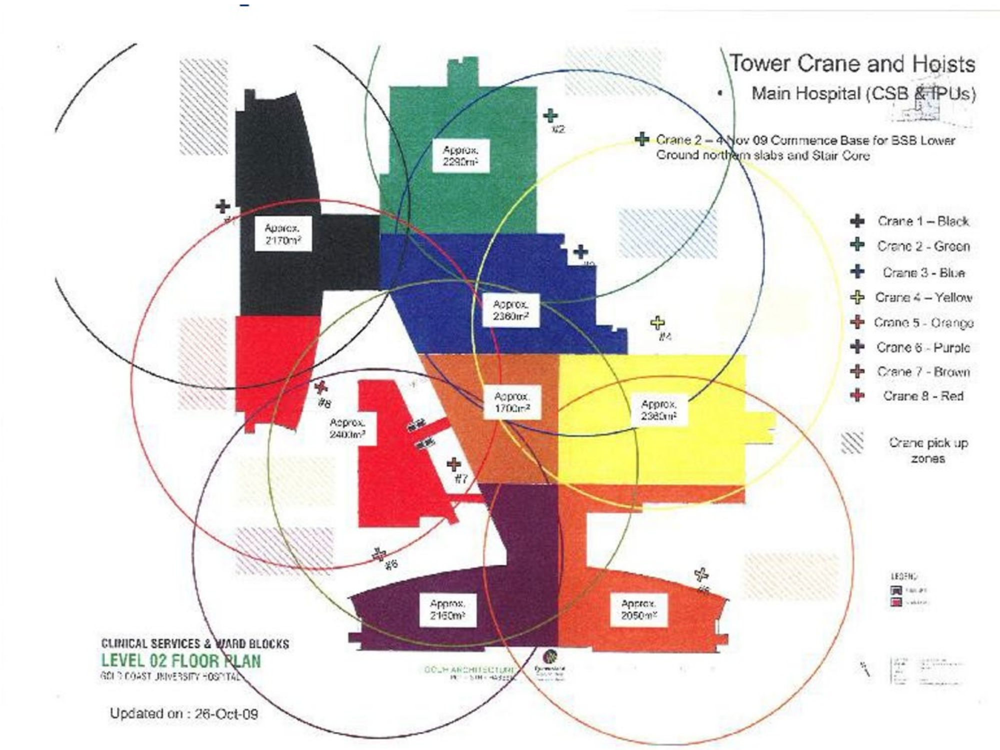

Figure 3.16: Crane layout to provide horizontal movement on Sunshine Coast Hospital (Lendlease)

The most significant temporary works on high rise construction are shown in Figure 3.17. The cost of these has to be spread across the project activities. The size, capacity and leasing time of each depend on the work packages for which they are needed, and the maximum size, weight and reach required.

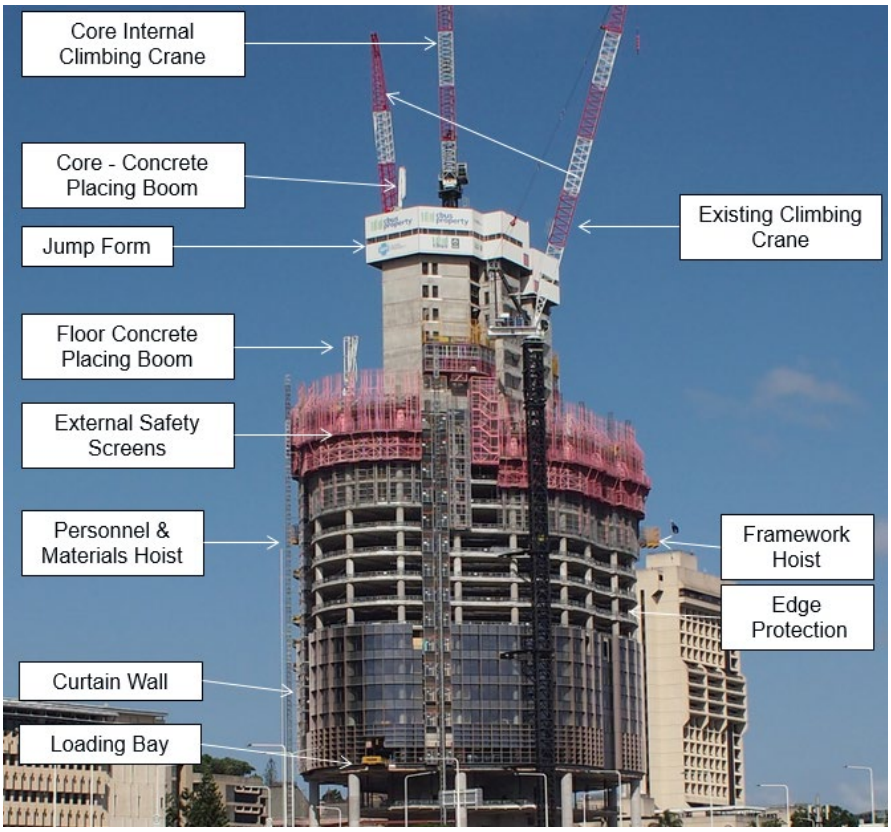

Figure 3.17: Temporary works on high rise construction (Nick Barker - Robert Bird Group)

The subcontractual relationships between parties during construction can be of various types. There can be a single subcontract for supply, delivery and installation of a component. Internal finishes are a good example of this simple relationship. There can also be contracts for supply only, where components or materials are supplied to site and then installed by a separate subcontractor.

Another supply relationship is with the building certifier, who inspects the construction works at key times and then certifies the works comply with the NCC. The Certificate of Occupancy is a key deliverable signed off by the building certifier, which is necessary before the building can be handed over to the client and occupied by users.

For the door assembly example, the entire door assembly will normally be manufactured off site. If suitable lifting equipment is available, it may be brought on site as a single assembly, lifted into place and then fixed. If appropriate lifting equipment is not available, then it may be brought on to site as separate assemblies and then put together and fixed.

The subcontractors for aluminium framed windows, doors and curtain walls can be ‘fabrication only’, buying the finished aluminium extrusions, and then cutting and assembling them. Other large suppliers, such as G James, have their own plant that can produce customised extrusion profiles (Figure 3.18)

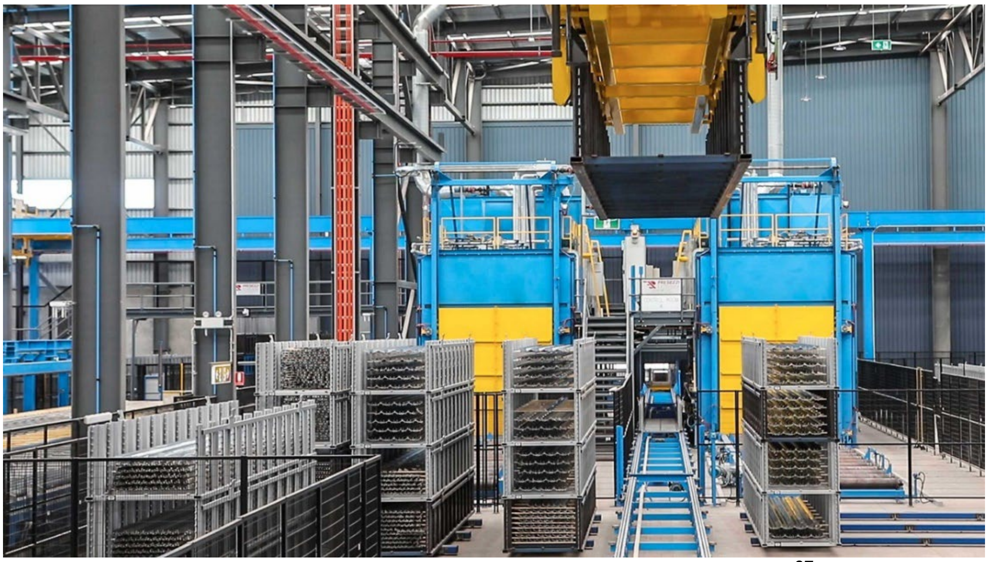

Figure 3.18: G James aluminium extrusion plant [27]

Returning to the aluminium door frame example, when building components are delivered to site, they need to be placed in their final position, often passing through laydown and storage areas. The methods of transporting the components need to be considered carefully in the context of OH&S issues, such as ensuring loads do not exceed the carrying capacity of the people and equipment necessary to transport, place and secure the components. In the case of the door assembly, the surrounding frame and the door leaf itself could be delivered separately if the weight of each component was less than the weight that can be carried by 2 people.

[27] https://gjames.com/sites/default/files/2018-12/aluminium-overview-capabilities.jpg

Figure 3.19 shows window frames and the glazing that will be placed into the frames being delivered as separate components to an apartment building complex, presumably to keep the weight of each part within allowable limits.

Figure 3.19: Window frames and glazing being delivered to site

Handover

At handover, the contractor normally provides:

- as built documentation
- legally required certificates
- maintenance data – warranties, spare/replacement parts, preventative maintenance tasks, resources
- operations data – startup/shutdown procedures, trouble shooting procedures
- asset information – schedules of spaces, space capabilities, lists of fixed and moveable property.

Most of this information must be gathered and collated from the various subcontractors and suppliers. The US Army Corps of Engineers initiated a standard to support gathering all of this data, known as COBie. [28]

Use

The records provided at handover must enable continued servicing and maintenance of the building. A useful concept when considering the lifecycle of buildings is 'shearing layers', a concept coined by architect Frank Duffy and further developed by Brand. [29] This describes the lifecycle of the various components of buildings as illustrated in Figure 3.20. Basically, for a typical office building, the site is eternal, the structure can last 50–100 years, the skin (façade) for 25–50 years, services for 15 years, space plan for 5–10 years and stuff (loose furniture and partitions) for 5 years.

These different lifecycles means that design for disassembly should be applied to ensure minimal interruption and wastage during building refurbishments.

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[28] *https://www.thenbs.com/knowledge/what-is-cobie*
[29] *Brand, S. (1995). How buildings learn: What happens after they're built. Penguin.*

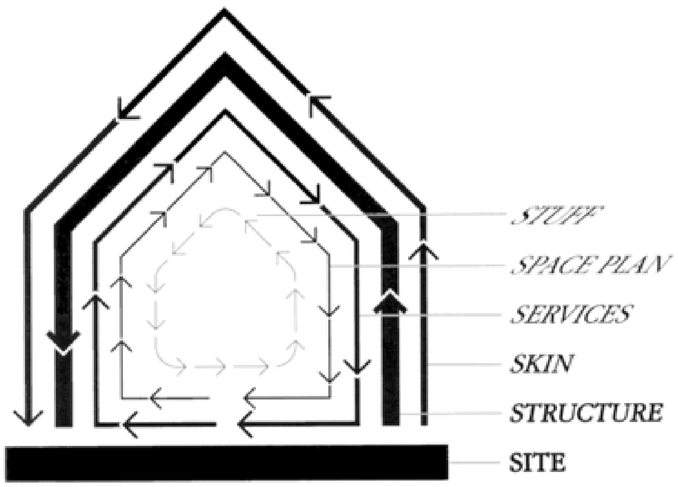


Figure 3.20: Shearing layers[29]

3.11 Lean Construction

A definition of Lean Construction is "the continuous process of eliminating waste, meeting or exceeding all customer requirements, focusing on the entire value stream, and pursuing perfection in the execution of a constructed project".[19] This definition fits well with the goals of efficient demand chain management and supply chain management.

The 5 principles of Lean are:

1. Value – specify value of the service or product, understand the customer and add the value they need
2. Value stream – identify and define the value stream – the steps to achieve value
3. Flow – eliminate waste, improve information and production flow
4. Pull – respond to the pull (requirements) of the customer
5. Perfection – continuous improvement of product and process.

The steps in implementing lean can be broken down into:

1. Reducing motion – placing components, people and plant where they are needed without wasted movement
2. Minimising waiting – bringing components, people and plant together when needed
3. Optimising transport – reducing transportation to the site and within the site. Often the focus is on crane and lift scheduling
4. Reducing defects – ensuring things meet requirements before being brought on site or installed
5. Avoiding overprocessing – meeting specifications, not exceeding them, i.e. higher standard of concrete finish than required
6. Avoiding overproduction – not producing more than is required
7. Maintaining inventory – ensuring enough resources are available, without being excessive
8. Maintaining talent – having appropriately qualified and skilled staff who aim for continuous improvement.

The above concepts impact on supply chain management by ensuring the appropriate products, resources and personnel are available at the right location on site at the appropriate time for smooth commencement and completion of the processes required to deliver the result and at the required level of quality. The Last Planner concept was introduced specifically for the construction industry due to the complex inter-relationships between demand chains (meeting the needs of the customer) and supply chains (ensuring all relevant resources are at the right location at the right time).

3.12 Risk analysis and material tracking

Risk analysis involves the following steps:[30]

1. identification
2. assessment, including likelihood and severity
3. analysis, identifying the effects on project tasks and organisation
4. control, where remedial actions are taken
5. monitoring and feedback.

The greatest risk for a building project is not achieving the Certificate of Occupancy. This prevents the building being occupied, leading to non-completion of the contract, missing final payments and legal repercussions.

There can be 2 fundamental reasons for this failure. First, the supply process does not meet the demand chain requirements because deliver key configurations fail. Second, the building may perfectly meet the requirements of the demand chain, but errors in interpreting the demand chain requirements mean they do not meet all of the external legal requirements. Considering Figure 3.3 (p 26), these 2 types of failure can occur at any point in the demand chain and supply chain. Consequently, risk mitigation must consider both the demand and supply results at each node in Figure 3.3.

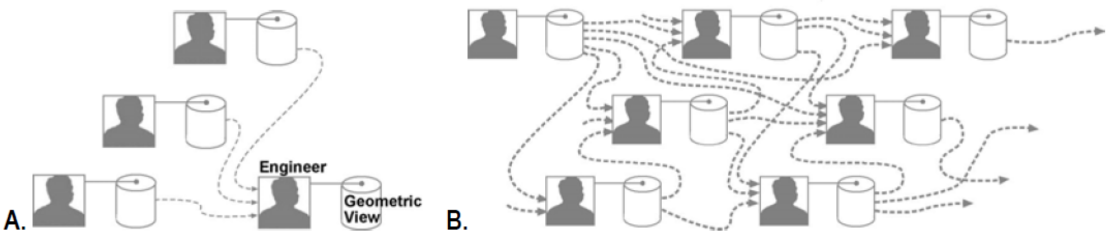
A further complication is that the deliverables from one supply chain for a work package within the contract must be compatible with those from other work packages. To give a simple example from a high school project, the exposed external columns were off form, in-situ concrete. They were to be painted with a tough, low build, 2-part epoxy paint that was extremely graffiti resistant. Unfortunately, the specification called for only a Class C finish to the concrete and the paint was a very thin layer. Hence, any imperfections and honeycombing were obvious and difficult to paint. A variation costing $400,000 was required to render the imperfections in the concrete columns. This outcome could have been avoided if the specifier followed the Lean Construction approach of checking the inputs to the painting process of the concrete columns against the requirements of the process. This activity also maps onto the demand chain/supply chain approach, illustrating the complementarity of the 2 approaches.

3.13 BIM/digital twins

The development of BIM (Building Information Modelling) forced the construction industry to take a deeper look at how information is generated and used. Haymaker

[30] *Tah, J. H. M., & Carr, V. (2000). Information modelling for a construction project risk management system. Engineering, Construction and Architectural Management, 7(2), 107-119.* https://doi.org/10.1108/eb021136

(2003) developed the concept of Perspectors (Figure 3.21), based on the idea of re-usable knowledge modules in building design[31, 32].



A. Engineers construct and integrate views from other views. B. The process in A occurs iteratively: A project model emerges as a graph of directed dependencies between views. The dependencies are drawn as dashed lines because these dependencies are mostly implicit on AEC projects today.

Figure 3.21: Dependencies between Perspectors[31]

Straightening this concept into a tree shows obvious similarities to the demand chain side of Figure 3.3. While Haymaker's work is relatively old, knowledge/decision dependencies in computer aided building design are still an active area of research.[33]

We do not explain how BIM can be integrated in demand chain and supply chain management, other than to note BIM can act as a 'repository' for storing some results of demand chain management and as a source of information for supply chain management. The current requirements for integrating BIM into building projects is covered by the ISO 19650 series of standards. However, many things are not captured in BIM, such as regulatory requirements and temporary works. So, BIM is likely to remain a useful adjunct to demand chain and supply chain management for the foreseeable future.

[31] *Haymaker, J., Kunz, J., Suter, B. A., & Fischer, M. A. (2003). Perspectors: Composable, Reusable Reasoning Modules to Automatically Construct a Geometric Engineering View from Other Geometric Engineering Views.*

[32] *Haymaker, J., Suter, B. A., Fischer, M. A., & Kunz, J. (2003). The Perspective Approach: Enabling Engineers to Construct and Integrate Geometric Views to Generate an Evolving Project Model (CIFE Working Paper, Issue.*

[33] *Rasmussen, M. H., Lefrançois, M., Pauwels, P., Hviid, C. A., & Karlshøj, J. (2019). Managing interrelated project information in AEC Knowledge Graphs. Automation in Construction, 108, 102956.* https://doi.org/https://doi.org/10.1016/j.autcon.2019.102956

Chapter 4 State-of-the-art in sensor technology for product identification and tracking

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4.1 Introduction

Thanks to improvements in sensor technology and the Internet of Things (IoT), many construction tasks can now be monitored automatically and in real time. Multiple stakeholders' systems and subsystems (contractors, suppliers, logistics providers and others) can smoothly connect via mobile tablets and smartphone apps to provide a complete picture of diverse building processes.[34] Digital twins have revolutionised the construction industry and are more significant with the long lifecycle of built assets. Product identification is an essential aspect to consider when developing the digital twin to take full advantage of the data collected and stored in the project. This task (Task 3) focuses on identifying different sensing and communication technologies available for product identification and tracking materials, as shown in Figure 4.1.

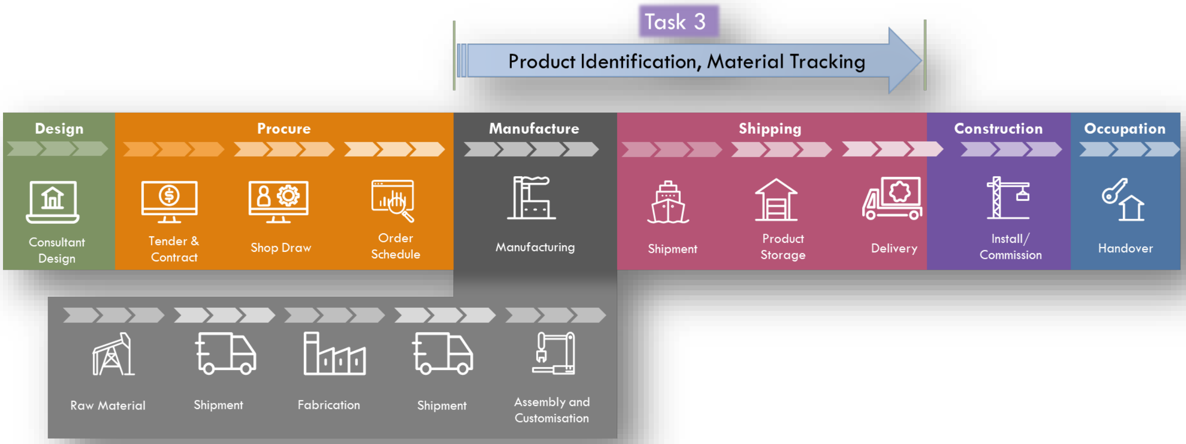

Figure 4.1: Task 3 focus – primarily on product identification and tracking materials

Future construction will have sensors for tracking and monitoring materials, equipment, vehicles and people in real time. Figure 4.2 depicts a future construction site.[35] The digital skin extends beyond the building site's physical location to the very beginning of the supply chain (raw materials). With real-time information retrieval and distribution, structured and efficient communication, and embedded intelligence, the currently fragmented and highly dynamic construction industry supply chain will become more robust and productive in the future.

RFID tags will be attached to tools and components on the building site, including prefabricated units and linked to corresponding work routines to increase productivity. Once the worker scans the tool's barcode, the workers' smart glasses will display a

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[34] *Rao AS, Randovic M, Liu Y, Hu S, Fang Y, Khoshelham K, Palaniswami M, Ngo T. Real-time Monitoring of Construction Sites: Sensors, Methods, and Applications. Automation in Construction.*

[35] *Edirisinghe R. Digital skin of the construction site: Smart sensor technologies towards the future smart construction site. Engineering, Construction and Architectural Management.*

movie. Materials will be labelled to be tracked from production to distribution to transportation and finally to the job site. Visual representations of context characteristics associated with staff on site will help monitor resources. Onsite material tracking (including raw material utilisation via sensors, as shown in Figure 4.1) will also be non-invasive. Scanning technologies deployed through a smart device app or proximity or RFID sensor technology will enable workers to track the amounts of onsite material.

For better project schedule control, site scheduling visualised on BIM will be integrated with material consumption and auto updated in the system for progress monitoring (planned vs actual material consumption). Innovative technology, smartphones or even drones will aid in digitising the 'as-built' model. The BIM model will enable lifecycle tracking of installed components (such as the heating, ventilation and air conditioning or HVAC system shown in Figure 4.2).

***Figure 4.2: Future construction procurement*[36]**

4.2 Sensors

The advent of sensor systems and IoT spurred a new research direction in the construction industry. In recent times, sensor networks are widely applied in various automation applications. This section reviews the potential sensor technologies and the specific issues and challenges associated with deploying sensors for improved

[36] *https://www.emerald.com/insight/content/doi/10.1108/ECAM-04-2017-0066/full/html*

construction monitoring. We explore the existing solutions proposed in the literature in various construction categories according to their design and implementation-related parameters. We surveyed the sensor deployments for various construction applications in Australia and global scenarios, and analysed the devices, sensors, and communication techniques associated with IoT applications We highlighted the prospects and problems of these solutions while identifying the factors for improvement and future directions of work. Onsite positioning and tracking technologies involve sensors for measurement, location tracking, communication and mapping to help engineers and managers retrieve important construction activity information, which will be discussed in Chapter 5.

4.3 Sensor specification

Table 4.1 provides an overview of sensors and sensing technologies available and commonly used in the building and construction industry for identifying and tracking materials, vehicles, equipment and people.

Table 4.1: Overview of sensing technologies in identifying materials, vehicles, equipment and people

Technology	Frequency	Type	Data rate	Range	Applications
RFID	LF: 30-300 kHz			10 cm	Animal tracking, access control
	HF: 13.56 MHz			10 cm – 1 m	Near Field Communication (NFC); payment, waste management, automation, health and medical, and manufacturing, garment tracking
	UHF: 868-930 MHz SHF: 2.45GHz	Passive/ Active		15 m 100 m	Asset management, container tracking, baggage tracking, work in progress tracking
Barcode		1D barcode		1m – 5m	Material control, warehouse inventory, tool and consumable material issue, timekeeping, purchasing, accounting, scheduling, document control and office operations
QR Code		2D barcode			
GPS	L1 (1,575.42 MHz) L2 (1,227.60 MHz)			<5 m accuracy	Locate and track equipment or material, positioning information for the design and as-built reference points, geofencing
Bluetooth (BLE)	2.4 –2.4835GHz		125 kbit/s 500 kbit/s 1 Mbit/s 2 Mbit/s	15 m	Smart homes, wearables, automotive, PCs, proximity, fitness, Industrial (construction)
ZigBee	2.45 GHz		250 Kbps	10m – 100m	Production control, building control, home automation, building automation
4G	850MHz 900MHz 2100MHz		5-15 Mbps	3 km – 15 km	Construction cabin connections, video surveillance, Augmented and virtual reality
Wi-Fi	2.4 GHz 5 GHz		20-100 Mbps	50 m – 100 m	Wireless internet access, positioning, and tracking

Technology	Frequency	Type	Data rate	Range	Applications
Ultra-wideband (UWB)	3.1 GHz-10.6 GHz		100 Mbps	1 m – 200 m 1m accuracy	Asset tracking, tracking position
LoRaWAN	915MHz - 928 MHz		27 Kbps	5 km – 10 km	Location tracking of assets, materials and workers; monitoring the temperature and supply of materials; safety zones for assets and workers; utilisation of construction vehicles
SigFox	920 MHz		600 bps	10 km – 40 km	

4.4 Automated identification and tracking in construction industry

We can broadly categorise the sensors and technologies into the following 4 categories:

- **Location-based sensors**: Barcode, RFID, GPS, WLAN, UWB, Ultrasound
- **Communication technologies**: Bluetooth, Wi-Fi, Cellular (2G-5G), ZigBee, LoRa, SigFox
- **Vision-based sensors**: Visible camera, thermal camera, smart camera
- **Wireless network sensors**: temperature, pressure, displacement, light and optical fibre sensors.

Figure 4.3 shows the overview of these categories of sensors and communication technologies. We focus on using a combination of sensors and technologies to track materials from source to on-site.

4.4.1 Location-based sensors

Barcode

Barcoding[34] is one of the oldest and most widely used information technologies owing to its low cost, high reliability and ease of production. With a series of parallel and adjacent bars that employees can record using a hand-held optical scanner or bar code reader, the barcode systems are used in materials, construction progress and labour tracking. Further, the high data content and type capacity enable storing encrypted alphanumeric characters with sensitive details associated with the product besides inventory and lifecycle management. While actual construction work remains very physical, construction companies are beginning to see the financial and organisational benefits of implementing barcodes into their work.

RFID

Radio-frequency identification (RFID)[34] technology exchanges information via electromagnetic signals. RFID implementation consists of tags, readers and antennas to communicate through radio signals for identifying the target measurement. This enables the identification system to read and write the data without any mechanical or optical contact. RFID systems are composed of a transponder and transceiver (reader) that gather and transmit information wirelessly to an RFID tag, often without the need for a direct line-of-sight to the tags.

Based on the required level of automation, the technology implementation may include active (battery-powered), semi-passive (battery-assisted) or passive (without battery) tags. Because of its ability to identify and track objects, RFID has been one of the most extended and promising wireless non-contact systems used for diverse applications: aviation, construction, facility management, health, retailing, logistics and security, among others. In construction, this automatic identification technology has been extensively used to store and retrieve essential data from identified items using small tags due to its wide reading range, the ability to operate without line-of-sight, and its durability in construction environments under different weather conditions. RFID technology is widely adopted in all 4 main stages of the lifecycle of a facility: planning and design, construction and commission, operation and maintenance.

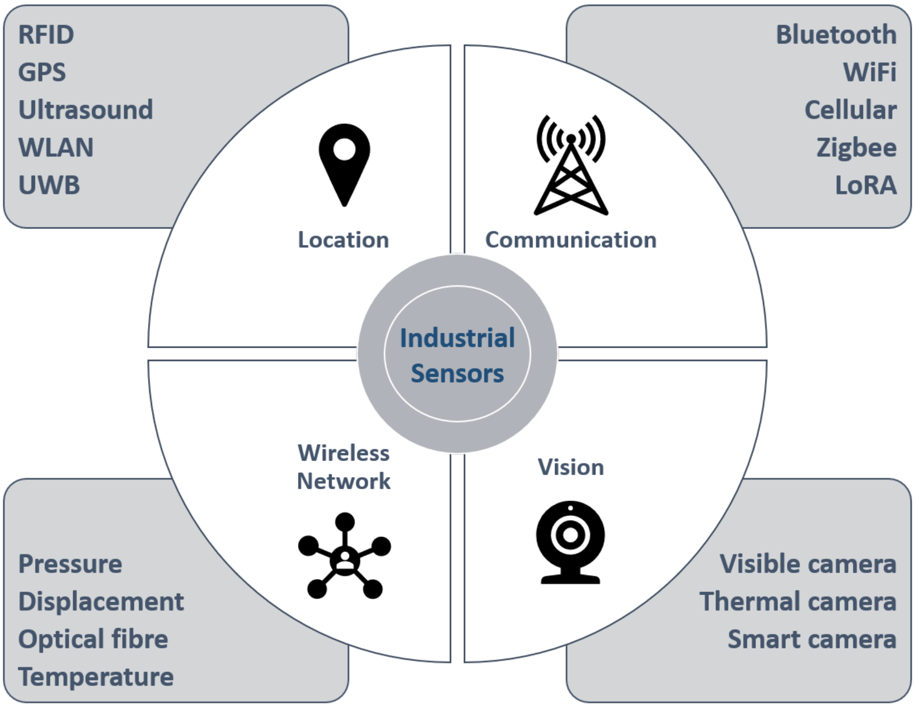

Figure 4.3: Overview of different sensor and communication technologies

GPS

The Global Positioning System (GPS)[34] consists of satellites, ground control stations and user receivers. It uses GPS tracking devices that communicate with a satellite system in orbit to track the GPS tag's location. Besides its uses in engineering surveys and monitoring the deformation in buildings or building components, GPS has been developed for monitoring safety in building construction, including machinery equipment and construction materials. While GPS is widely used for tracking in outdoor environments, its accuracy is compromised indoors with obstacles such as basements, tunnels and culverts. GPS has also been significantly promoted in construction safety management in the past few decades. The accuracy and efficiency decrease once the signals are blocked in such conditions.

GIS

The Geographical Information System (GIS)[34] integrates data from various sources into valuable, project-specific spatial and non-spatial information. The database management capabilities of GIS are adopted for building the construction resource database to facilitate project planning, procurement, preconstruction management and construction monitoring.

WLAN

Wireless Local Area Network (WLAN) uses radio technology for data transmission within the coverage area of wireless signals. The WLAN cannot work in dynamic and complex construction sites due to its limited signal coverage area and requirement for wireless construction transmitters. Khoury and Kamat[37] measured the accuracy of WLAN in laboratory environments and reported an error of 2 m. Taneja[38] has further reported the WLAN positioning error as being in the range of 1.52-4.57 m for static and 7.62 m for dynamic scenarios. Wi-Fi is the most widely used WLAN standard for information exchange or connecting to the Internet wirelessly based on the IEEE 802.11 standards family (IEEE 802.11, 802.11a/b/g/n). Wireless technology is found in smartphones and tablets to desktops and laptops. Wi-Fi provides a decent communication range in the order of 20 m (indoor) to 100 m (outdoor) with a data transmission rate of 2–54 mbps at the 2.4 GHz frequency of the Industrial, Scientific and Medical (ISM) band.

UWB

Ultra-wideband[34] is a wireless radio short-range communication technology adopted in complex environments and known for its precision, transmission speed, reliability and low energy consumption. This fast and secure positioning technology can provide 3-dimensional (3D) location estimation with superior accuracy unmatched by other wireless technology. Compared with traditional narrowband systems, UWB sensors transmit low-power, short-duration electromagnetic pulses of large bandwidth (equal to or greater than 500 MHz). These compact devices provide reliable low-latency location data in a read range of up to 200 m. In outdoor sites, longer read ranges close to 1,000 m can also be acquired beyond what laser scanning or vision-based detection

[37] *Khoury HM, Kamat VR. Evaluation of position tracking technologies for user localisation in indoor construction environments. Automation in construction. 2009 Jul 1;18(4):444-57.*

[38] *Taneja S, Akcamete A, Akinci B, Garrett Jr JH, Soibelman L, East EW. Analysis of three indoor localisation technologies for supporting operations and maintenance field tasks. Journal of Computing in Civil Engineering. 2012 Nov 1;26(6):708-19.*

systems offer. There has been great interest in UWB implementation in diverse applications as an innovative long-distance wireless positioning technology.

4.4.2 Communication technologies

ZigBee

ZigBee[34] is a 2-way wireless communication technique with the characteristics of short distance, low complexity, low energy consumption, low transition speed and low costs. This technology defines the network and application layer protocols based on IEEE 802.15.4 standard for data transition using low power radio-enabled electronic devices. Being energy-efficient, low cost and reliable, ZigBee is a preferred technology for construction applications. ZigBee also supports short-distance (10–20 m) data communication over multi-tier, decentralised, ad-hoc and mesh networks. However, ZigBee applications yield low data rates of only 20–40 kbps and 250 kbps at 868/915 MHz and 2.4 GHz frequencies of the ISM band, respectively. Various studies have been done to explore its application potential by combining it with other positioning techniques such as RFID and wireless sensor network (WSN) rather than using ZigBee alone in AP and AFS. Meng et al.[39] reported an average error of 0.76 m when acquiring personnel position data in coal mines. Shen et al.[40] designed an automated tunnel-boring-machine positioning system based on ZigBee and tested its performance. The test was conducted by the designed system and a specialist surveyor independently. The differences between the 2 surveys were less than 2 mm, verifying the accuracy of the designed system. ZigBee is flexible and expandable technology that favours sending small data such as location information.[41]

Cellular communications (1G to 5G)

The Global System for Mobile Communications (GSM)[34] is a cellular telecommunication standard developed by the European Telecommunications Standards Institute (ETSI). The GSM specified second-generation (2G) digital cellular networks, popularly used by smartphones and tablets. The first-generation (1G) cellular networks used analogue communication, and 2G development replaced 1G. After that, the 3rd Generation Partnership Project (3GPP) developed the third-generation (3G) Universal Mobile Telecommunications System (UMTS) standards based on the GSM standard. The 3GPP also developed the fourth generation (4G) LTE Advanced and the fifth-generation (5G) standards. Cellular technology uses the construction industry to enhance real-time progress tracking, safety and spatial inspection even beyond communication. The cellular data communication networks have several base stations located in different areas to provide worldwide voice and data services. While low-band cellular ranges (600 MHz, 800 MHz, 900 MHz) allow for more excellent geographic coverage and are not affected by obstacles, mid-band cellular ranges (2.5 GHz, 3.5 GHz, 3.7–4.2 GHz) provide faster speeds and greater capacity. Mid-band connectivity helped with real-time safety and progress monitoring. Low-band connectivity provides long-distance tracking to monitor impaired driving, transmit digital forms, and track valuable assets. As a result, digital cellular networks

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[39] *Xiangrui M, Xuezhan X, Guangming Z. True threedimensional coal mine personnel positioning system based on 3D visualisation and ZigBee technology. JournalofChinaCoalSoci-ety. 2014;39(S1):603-8.*
[40] *Shen X, Lu M, Fernando S, AbouRizk SM. Tunnel boring machine positioning automation in tunnel construction. In ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction 2012 (Vol. 29, p. 1). IAARC Publications.*
[41] *Rodas J, Barral V, Escudero CJ. Architecture for multi-technology real-time location systems. Sensors. 2013 Feb;13(2):2220-53.*

are helpful for both indoor and outdoor positioning. [42, 43] For example, a cellular network combined with GPS tracked vehicle movements [44, 45] and employees' safety based on smartphones using a 3G/4G/5G network.

Bluetooth

Bluetooth[34] is a low power, low-cost wireless technology based on the IEEE 802.15.1 standard, used for communication between portable devices and desktops over a short-range (8–10 m). The Bluetooth standard defines a personal area network (PAN) communication using the licence-free, globally available 2.4 GHz frequency of the ISM band. The data rate achieved in various versions of the Bluetooth ranges from 1 to 24 mbps. While Bluetooth technology was initially designed as a short-range wireless connectivity solution for personal, portable and hand-held electronic devices, it is extended to various fields due to its ubiquitous nature. [46] The ultra-low-power, low-cost version of this standard is named Bluetooth Low Energy (BLE) was initially introduced by Nokia in 2006 as Wibree. [47] However, in 2010, BLE was merged with the main Bluetooth standard, version 4.0. BLE also uses the 2.4 GHz ISM frequency band with adaptive frequency hopping to reduce interference. BLE topology supports one-to-one as well as one-to-many connections between devices. Despite the abovementioned technological advantages, the cost of Bluetooth is a significant constraint of its wide use. Figure 4.4 shows an overview of wireless communication technologies regarding range and data rates, which allows industry practitioners to choose the solution needed for their industrial application.

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[42] *Otsason V, Varshavsky A, LaMarca A, De Lara E. Accurate GSM indoor localisation. In International conference on ubiquitous computing 2005 Sep 11 (pp. 141-158). Springer, Berlin, Heidelberg.*

[43] *Varshavsky A, De Lara E, Hightower J, LaMarca A, Otsason V. GSM indoor localisation. Pervasive and mobile computing. 2007 Dec 1;3(6):698-720.*

[44] *Rao AS, Izadi D, Tellis RF, Ekanayake SW, Pathirana PN. Data monitoring sensor network for BigNet research testbed. In 2009 International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP) 2009 Dec 7 (pp. 169-173). IEEE.*

[45] *Lee S, Tewolde G, Kwon J. Design and implementation of vehicle tracking system using GPS/GSM/GPRS technology and smartphone application. In2014 IEEE world forum on Internet of things (WF-IoT) 2014 Mar 6 (pp. 353-358). IEEE.*

[46] *Bluetooth Technology < https://www.bluetooth.com/learn-about-bluetooth/>*

[47] *Bluetooth Low Energy, Wikepedia < https://en.wikipedia.org/wiki/Bluetooth_Low_Energy>*

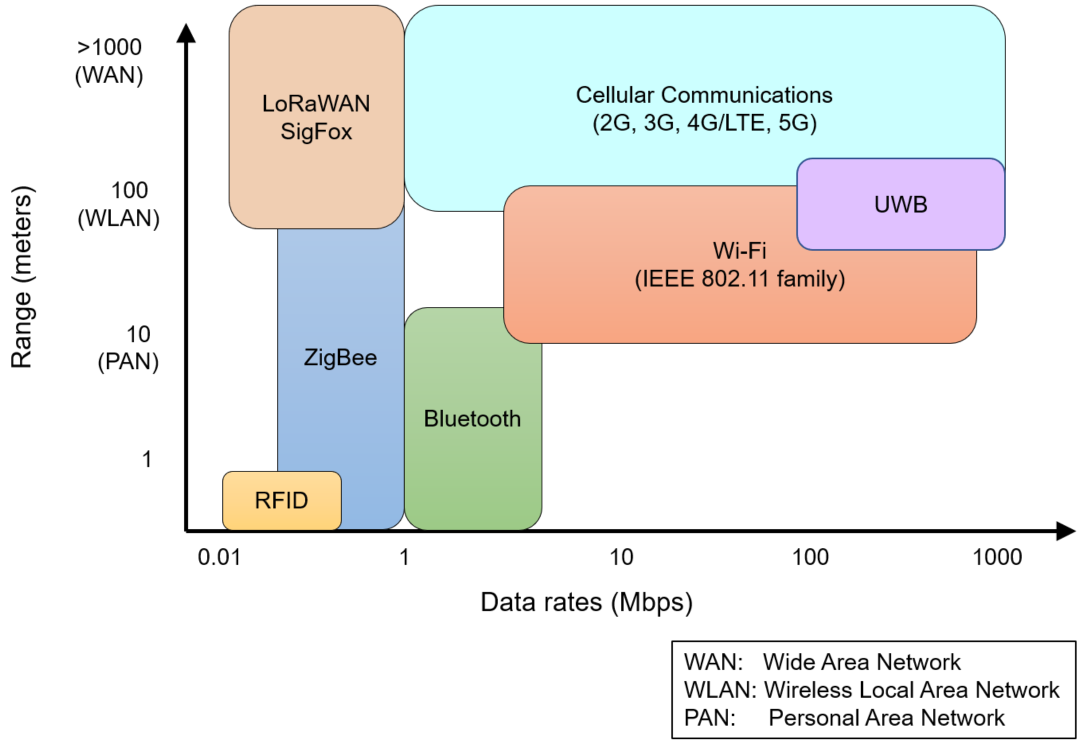

Figure 4.4: Overview of wireless communication for tracking and monitoring materials, vehicles, equipment, and people, both off-site and on-site[34]

4.4.3 Vision sensors

Camera

Camera technology[34] uses image sensors to collect photos or videos for vision-based sensing. Cameras can facilitate automated data collection means for sophisticated, data-driven analytical techniques. Various image processing and automation algorithms are used to acquire information from the surrounding environment. Researchers in the construction field have been investigating novel solutions that rely on image processing and computer vision techniques to accurately retrieve the workforce and equipment information from the daily construction job site videos. However, vision-based sensing is vulnerable to the impact of the surrounding environment, such as lighting conditions and background colour.[48] Since there is a tremendous amount of information in images or videos neglected by humans but that can be read and understood by algorithms, it provides a foundation for applying vision-based sensing in construction management. Vision-based sensing is limited to the elementary level with a human in the loop; more intelligent solutions with automated human interpretation are desirable to replace manual supervision.

[48] *Gu Y, Lo A, Niemegeers I. A survey of indoor positioning systems for wireless personal networks. IEEE Communications surveys & tutorials. 2009 Mar 4;11(1):13-32.*

Table 4.2: Comparison of different product identification and tracking technologies [49]

	QR code	Barcode	RFID		NFC	BLE	GPS
			Active	Passive			
Cost-effective	✓	✓	✗	✓	✗	✗	✗
Real-time tracking	✗	✗	✗	✗	✗	✓	✓
Power consumption	✗	✗	✓	✗	✓	✗	✓
Scanning range	High	High	High	Low	Low	Low	Unlimited
Storage capacity	3 KB	> 100 bytes	2 KB	4-8 KB	48 Bytes – 8 KB	NA	Unlimited*
Continuous scanning	✓	✓	✓	✓	✓	At regular intervals	Real-time data
Two-way communication	✗	✗	✗	✗	✓	✓	✓
Labour Intensive	✓	✓	✓	✗	✓	✓	✓
Popularity	Very high	Very high	High	High	Moderate	Moderate	Moderate

** can hold a large amount of data*

Table 4.3: Comparison of tracking technologies in the construction industry

Technology	Materials	Bulk consumables	Tools	Assets	Vehicles	People	PPE
Barcode	x	x	x	x			x
QR Code	x	x	x				
RFID	x		x	x	x	x	x
GPS				x	x		
Cellular				x	x	x	
Bluetooth						x	x
Wi-Fi					x	x	

[49] *https://www.assetinfinity.com/blog/asset-tracking-technologies*

4.5 Literature review

This section reviews the available academic literature of tracking materials, workers, equipment/vehicles and construction progress.

4.5.1 Tracking materials

Demand for real-time monitoring technologies for efficient material control is growing, to optimise project costs in the construction industry. Location sensing and tracking methods enhance production management by arranging for materials to arrive in the correct quantity and quality at the right time for their immediate inclusion in the construction process while minimising the work-in-process inventory on site. This section elaborates on various works reported in the literature in the construction domain about tracking materials with accurate onsite location-aware information.

Signal measurements from indoor location sensing technologies are used to derive spatial information for location identification and material tracking. Many researchers have extensively investigated various enabling technologies, such as embedded barcodes, RFID, GPS, video and audio technologies, Laser Detection and Ranging (LiDAR) for automatically obtaining the physical information for construction site monitoring. RFID-based tracking methods have been widely used for monitoring materials and other available resources. Alternative tracking technologies like indoor GPS, WLAN, UWB and ZigBee have also proven helpful in lifecycle and productivity management.[50, 51]

Barcodes are widely implemented for tracking construction products. Chang et al. used barcode technology to identify structural steel products for progress management and quality assurance.[52] Junggon Kim et al. reports a case study of tracking steel for real production progress using barcode information systems.[53]

RFID is one of the most promising wireless non-contact systems with great potential to monitor construction processes. Most indoor positioning methods with limited communication range are based on RFID. Several RFID tags are placed on site for tracking materials in different stages of the building construction lifecycle. RFID is well known for its ability to scan multiple items at once. While the passive tags need to be retrieved by a worker with a mobile RFID reader on site at a short range of less than 15 m, the active tags send information automatically long distances (up to 100 m) at extra cost. RFID technology can potentially allow dynamic identification and modification of the attributes of target objects and tracking without direct contact. However, special considerations should be made when applying the tags on metal surfaces (e.g., reinforcement mesh, steel scaffold, shoring, shutter, metal door or hoarding) or if electromagnetic sources are working under a frequency similar to that of the system. The material to which the tag adheres could significantly interfere with RFID tag operation; it is essential to evaluate the material – RFID tag combination before industrial practice. Jaselskis and El-Misalami stated passive tags need to be mounted at 1 cm surface distance to prevent collision and electromagnetic

[50] *Li, Heng, et al. "Real-time locating systems applications in construction." Automation in Construction 63 (2016): 37-47.*
[51] *Skibniewski MJ, Jang WS. Simulation of accuracy performance for wireless sensor-based construction asset tracking. Computer-Aided Civil and Infrastructure Engineering. 2009 Jul;24(5):335-45.*
[52] *Montaser A, Moselhi O. RFID indoor location identification for construction projects. Automation in Construction. 2014 Apr 1;39:167-79.*
[53] *Kim, Junggon, et al. Management system for structural steel products using barcodes between construction job site and steel fabrication shop (2012)*

interferences.[54] Mo and Zhang performed a detailed study about the interferences of metal surfaces on passive tags. They concluded the ideal location for the tag is one-fourth the transmission wavelength of the antenna to receive good signal strength.[55]

Song et al. presented the advantage of using RFID technology in the automated tracking of pipe spools: fast identification and location of pipe spools, accurate and real-time location information during shipment, and reliable pipe-fitting schedule.[56, 57] Li and Becerick concluded RFID to be the most suitable indoor localisation sensing method by analysing several metrics like accuracy, affordability, line of sight, wireless communications, context identification, onboard data storage, power supply and wide applications in the industry.[58] Ali and Osama studied 3 different methods to locate an object using RFID technology – triangulation, proximity, and scene analysis – at a construction facility in Montreal and a lab environment.[59] Song et al.[56] and Gu et al.[48] reported the average error of 2D positioning with RFID to be 3.7 m. Razavi and Moselhi [60] showed the average positioning error was about 1.3 m in indoor environments. While RFID can locate single or multiple targets precisely in a static or dynamic indoor environment, the researchers are investigating different locating methods or advanced methods to improve the accuracy of RFID.

WLAN and ZigBee have been the real-time choice of owners and supervisors for tracking a wide range of activities with an accuracy of 1–3 m for a communication range of 100 m. This ZigBee-based WSN technology is preferred to the traditional RFID approach in indoor, enclosed or partially covered indoor settings where line of sight communication is unavailable. Along with intelligent networking and continuous tracking capabilities, the ZigBee-based WSN system also enables real-time, two-way wireless data communication between any sensor nodes in the network. Shen et al. highlighted the high reliability and security of ZigBee wireless data communication for complicated construction scenarios with signal blockage, distortion or deteriorations.[61] They also proposed a WSN application framework for indoor construction resource tracking with a group of stationary and mobile sensor nodes that can communicate. Song et al. proposed a material tracker system to identify location and logistics flow using ZigBee and RFID.

GPS is a satellite-based technology widely used to track the most valuable and high-risk construction equipment where the position and navigation of construction activities are considered. Song et al.[62] used GPS to track steel structural materials throughout the construction process, from manufacturing to construction, from inventory until installation, and even for long-term maintenance. When there is a need to attach a GPS receiver to each site object, this technology is uneconomical. It causes multipath

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[54] Jaselskis, E.J.; El-Misalami, T. Implementing Radio Frequency Identification in the Construction Process. J. Constr. Eng. Manag. 2003, 129, 680–688.
[55] Mo L, Zhang H. RFID antenna near the surface of metal. In2007 International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications 2007 Aug 16 (pp. 803-806). IEEE.
[56] Song J, Haas CT, Caldas CH. Tracking the location of materials on construction job sites. Journal of construction engineering and management. 2006 Sep;132(9):911-8.
[57] Song J, Haas CT, Caldas C, Ergen E, Akinci B. Automating the task of tracking the delivery and receipt of fabricated pipe spools in industrial projects. Automation in construction. 2006 Mar 1;15(2):166-77.
[58] Li N, Becerik-Gerber B. Life-cycle approach for implementing RFID technology in construction: Learning from academic and industry use cases. Journal of Construction Engineering and Management. 2011 Dec 1;137(12):1089-98.
[59] Montaser A, Moselhi O. RFID indoor location identification for construction projects. Automation in Construction. 2014 Apr 1;39:167-79.
[60] Razavi SN, Moselhi O. GPS-less indoor construction location sensing. Automation in Construction. 2012 Dec 1;28: 128-36.
[61] Shen Y, Yang P, Luo Y. Development of a customised wireless sensor system for large-scale spatial structures and its applications in two cases. International Journal of Structural Stability and Dynamics. 2016 May 28;16(04):1640017.
[62] Song L, Mohammed T, Stayshich D, Eldin N. A cost effective material tracking and locating solution for material laydown yard. Procedia Engineering. 2015 Jan 1;123:538-45.

errors in congested environments where positioning can be severely degraded due to blockage, deflection and distortion of satellite signals. Lu et al.[63] pointed out the average error in tracking a concrete mixer truck in a large dense urban area in Hong Kong was less than 10 m using a combination of GPS, dead reckoning vehicle navigation and Bluetooth beacons. Pradhananga and Teizer[64] reported an average error of 1.1 m when locating equipment with GPS in an open area. However, it increased to 2.15–4.16 m in the presence of nearby obstacles. Li et al.[65] integrated GPS, GIS and WAN technologies to augment the functionality of a barcode system for real-time tracking of material and equipment to minimise material wastage. UWB and indoor GPS are alternative tracking technologies with better performance accuracy of 0.1–0.5 m and 0.01–0.02 m, respectively. However, these devices are expensive and bulky for real-time implementation in the construction industry.

Jiang et al.[66] presented the development of a real-time labour consumption measurement system based on GPS, GIS and 3G telecommunications on a dam construction site. They applied to the world's third-largest hydropower project. An alternative low-accuracy GPS technology, commonly referred to as civilian GPS technology, is available to track anywhere on the surface of the earth at an accuracy of 5–15 m. By installing a receiver at the desired location on the construction site, this technology can be easily adapted for complex sites. Several studies on accuracy improvement and dedicated correction were implemented to exploit its unlimited operational scope with improved accuracy of large construction sites.

4.5.2 Tracking workers

To prevent accidents at an early stage, research focused on identifying risks and improving workers' safety. Various factors are monitored with the sensor systems to record real-time location and information to reduce accidents. While RFID is extensively used for construction safety management, WSNs and vision-based sensing are the next preferred technologies.

Accident prevention and hazard identification systems with RFID, UWB, ZigBee and WSN have been in practice for a while. These systems unintentionally prevent workers from entering into dangerous zones, identify workers unsafe behaviour, and forewarn collision and high-altitude falling accidents.

Wu et al.[67] designed and implemented a hybrid ZigBee RFID network architecture in a construction site for autonomous information requirements. Kim et al. implemented a Wi-Fi-based real-time locating (RTL) system with wireless communication technique in a tunnel construction site to monitor labourer safety with a single tag. Jin-Sun Lim et al.[68] combined a conventional RTL system with an accelerometer with BLE and validated their system in underground construction and bridge overlay sites.

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[63] *Lu M, Chen W, Shen X, Lam HC, Liu J. Positioning and tracking construction vehicles in highly dense urban areas and building construction sites. Automation in construction. 2007 Aug 1;16(5):647-56.*
[64] *Pradhananga N, Teizer J. Automatic spatio-temporal analysis of construction site equipment operations using GPS data. Automation in Construction. 2013 Jan 1;29:107-22.*
[65] *Li H, Chen Z, Yong L, Kong SC. Application of integrated GPS and GIS technology for reducing construction waste and improving construction efficiency. Automation in Construction. 2005 Jun 1;14(3):323-31.*
[66] *Jiang S, Skibniewski MJ, Yuan Y, Sun C, Lu Y. Ultra-wide band applications in industry: a critical review. Journal of Civil Engineering and Management. 2011 Sep 1;17(3):437-44.*
[67] *Wu W, Yang H, Chew DA, Yang SH, Gibb AG, Li Q. Towards an autonomous real-time tracking system of near-miss accidents on construction sites. Automation in Construction. 2010 Mar 1;19(2):134-41.*
[68] *Lim JS, Song KI, Lee HL. Real-time location tracking of multiple construction laborers. Sensors. 2016 Nov;16(11):1869.*

Tiezer et al.[69, 70] tracked workers with UWB location technology and analysed the trajectories which laid the foundation for applications in construction safety management. Yang and Teizer[71, 72] estimated the posture of construction labourers and classified it using a real-time range camera. They also designed a system that could identify drivers' vision blind areas based on the location of their head for real-time safety assistance. Lee et al.[73] implemented mobile sensing devices by applying multiple sensors like ultrasound and infrared to alert broadcast or text messages when they come close to the pre-set areas.

Research focuses on accidental forewarning systems to prevent fall accidents and devastating consequences involving falls from a high elevation. Carbonari et al.[74] classified areas that may have accidents arising from falling objects. Montaseri et al. used RFID sensors to locate workers doing high elevation work in real time. An integrated BIM model with location-based technologies is proposed to warn of potential construction accidents.

Zhu et al.[75] acquired workers and equipment location information using multiple cameras at the construction site and performed a robust analysis to predict their following locations. Khoury et al.[76] developed a vision-based tracking system integrated with a foot-mounted inertia measurement unit to monitor labourers at construction sites.

In building construction sites, Navon and Goldschmidt[77] proposed a conceptual model based on ground-based RF stations, following the same positioning principles as GPS. Labour input for on-site activities could be determined by measuring the time-of-flight (TOF) of the radio wave between the labour resources and RF stations. However, sufficient field test data were lacking in their research, and the feasibility and accuracy of applying the RF system were not assessed.

4.5.3 Tracking resources, equipment and vehicles

Interest is growing in monitoring equipment status and resource utilisation for effective supply-demand balance. These sensors can track vehicles and equipment in real time and receive real-time notification of the movements and location data.

[69] *Teizer J, Lao D, Sofer M. Rapid automated monitoring of construction site activities using ultra-wideband. InProceedings of the 24th International Symposium on Automation and Robotics in Construction, Kochi, Kerala, India 2007 Sep 19 (pp. 19-21).*
[70] *Teizer J, Vela PA. Personnel tracking on construction sites using video cameras. Advanced Engineering Informatics. 2009 Oct 1;23(4):452-62.*
[71] *Yang J, Arif O, Vela PA, Teizer J, Shi Z. Tracking multiple workers on construction sites using video cameras. Advanced Engineering Informatics. 2010 Nov 1;24(4):428-34.*
[72] *Teizer J. Status quo and open challenges in vision-based sensing and tracking of temporary resources on infrastructure construction sites. Advanced Engineering Informatics. 2015 Apr 1;29(2):225-38.*
[73] *Lee HS, Lee KP, Park M, Baek Y, Lee S. RFID-based real-time locating system for construction safety management. Journal of Computing in Civil Engineering. 2012 May 1;26(3):366-77.*
[74] *Carbonari A, Giretti A, Naticchia B. A proactive system for real-time safety management in construction sites. Automation in construction. 2011 Oct 1;20(6):686-98.*
[75] *Zhu Z, Park MW, Koch C, Soltani M, Hammad A, Davari K. Predicting movements of on-site workers and mobile equipment for enhancing construction site safety. Automation in Construction. 2016 Aug 1;68:95-101.*
[76] *Khoury H, Chdid D, Oueis R, Elhajj I, Asmar D. Infrastructureless approach for ubiquitous user location tracking in construction environments. Automation in Construction. 2015 Aug 1;56:47-66.*
[77] *Navon R, Goldschmidt E. Monitoring labor inputs: automated-data-collection model and enabling technologies. Automation in construction. 2003 Mar 1;12(2):185-99.*

Naresh and Jahren[78, 79] conceptualised various construction vehicle tracking systems that transmit text-based signals using radio systems, acquire discrete point positions using RFID systems and locate vehicles in real time using GPS tracking systems.

Roberts et al.[80] implemented a real-time kinematics (RTK) GPS positioning system for autonomous control and guidance of construction plants (asphalt paver or bulldozer) using line-of-sight for real-time communication. It can provide precise location up to a few millimetres when a reference receiver was located at a nearby point with well-defined coordinates. However, the application setting was limited to an open-air road construction site.

Peyret et al.[81] also evaluated the precision of using RTK GPS for elevation control of the screed of an asphalt paver. They found the drift error due to the multipath effects of GPS signals rendered the raw positioning measurements not accurate enough for supporting the control systems.

Oloufa et al.[82] utilised GPS technology and wireless communications for equipment tracking and collision detection in earth-moving projects in open areas. The differential GPS provides submetre accuracy for collision detection and tracking construction vehicles in excavation operations. They also installed GPS units on vehicles to track current vehicle locations. Tracking data were relayed over a low-band FM frequency voice radio and the Internet for real-time query and display. However, evaluation of the accuracy and reliability of the GPS signals, the differential signals and the communications channels in tracking vehicles and equipment on and off construction sites was not given but recommended for future investigation.

Ming Lu et al.[83] showed the limitations of applying GPS for tracking construction vehicles in a highly dense urban area by conducting extensive field tests in Hong Kong. They presented a continuous, all-location, real-time solution for tracking and positioning construction vehicles by integrating GPS with the dead reckoning-based vehicle navigation technology. This integrated construction vehicle navigation solution was demonstrated along with its experimental results obtained from site trials. Field tests revealed the practical working range for beacons to communicate with the navigation unit in the truck reduced to only 20 m under site conditions.

4.5.4 Tracking construction progress

Various bottlenecks can delay a project and impact the economy due to several moving parts/vehicles, labour force, large equipment and tons of materials in the construction industry. Industry needs a better approach to monitoring actual engine run-time to optimise predictive maintenance schedules and improve billing accuracy. Most construction companies rely on project management construction software to

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[78] aselskis EJ, Anderson MR, Jahren CT, Rodriguez Y, Njos S. Radio-frequency identification applications in construction industry. Journal of construction engineering and management. 1995 Jun;121(2):189-96.
[79] Naresh AL, Jahren CT. Communications and tracking for construction vehicles. Journal of construction engineering and management. 1997 Sep;123(3):261-8.
[80] Roberts GW, Dodson AH, Ashkenazi V. Global Positioning System aided autonomous construction plant control and guidance. Automation in Construction. 1999 Jun 1;8(5):589-95.
[81] Peyret F, Betaille D, Hintzy G. High-precision application of GPS in the field of real-time equipment positioning. Automation in construction. 2000 May 1;9(3):299-314.
[82] Oloufa AA, Ikeda M, Oda H. Situational awareness of construction equipment using GPS, wireless and web technologies. Automation in Construction. 2003 Nov 1;12(6):737-48.
[83] Lu M, Chen W, Shen X, Lam HC, Liu J. Positioning and tracking construction vehicles in highly dense urban areas and building construction sites. Automation in construction. 2007 Aug 1;16(5):647-56.

manage productivity through the efficient schedule, client communication and change order request. While these management platforms help with information flow and scheduling, they do not monitor construction activities at a localised platform. IoT sensors enable localised and real-time monitoring that can address this challenge.

IoT-based construction tracking solutions will enable companies to increase productivity, lower maintenance costs, eliminate security concerns and improve worker safety.[84] RFID sensors have been used to measure progress in building sites accurately. In addition, this control strategy helps manage labour, safety and management. Yoon et al.[85] proposed and evaluated the component control at every stage of ordering, production, transportation, storing, installation and inspection tasks.

Ghanem et al.[86] monitored overall construction project performance using an automated RFID-based system through an aggregate performance percentage measure called earned value. By measuring cost and schedule performance against a baseline plan using earned value, the progress is monitored using metrics like productivity, efficiency, labour hours, tracking time and estimation accuracy. Keeping track of the material used on site, based on the estimated quantity permitted, users can better estimate the amount of work done on a construction site.

Machine control using GPS and positioning sensors allows for precise operation of construction equipment and real-time reporting progress, movements and status. This technology can be used to plan and coordinate construction activities, increasing productivity and reducing delays. Further, AI-powered systems with machine vision components and solutions from image sensors, cameras and acquisition boards can significantly benefit the construction industry. Deep learning solutions complement the machine vision to arrive at sophisticated vision software, intelligent vision systems and innovative vision sensors that can significantly enhance construction automation and progress.[87] Other trending methods like location-aware computing can help make faster, more accurate and more consistent decisions on construction sites by leveraging timely and accurate access to project information.

4.6 Tracking – case studies, industry examples

This section provides an overview of commonly used product identification and tracking technologies for tracking materials in the construction industry. We listed 12 materials and provided an overview for 10 of these materials in Appendix A. Table 4.4 summarises the findings and comparisons.

[84] Construction Equipment Tracking< https://www.iotforall.com/use-case/construction-equipment-tracking>
[85] Yoon SW, Chin S, Kim Y, Kwon S. An application model of RFID technology on progress measurement and management of construction works. In Proceedings of the 23rd International Symposium on Automation and Robotics in Construction (ISARC 2006), Tokyo, Japan 2006 Oct (Vol. 35).
[86] Ghanem AG, AbdelRazig YA. A framework for real-time construction project progress tracking. In Earth & Space 2006: Engineering, Construction, and Operations in Challenging Environment 2006 (pp. 1-8).
[87] Li Y, Liu C. Applications of multirotor drone technologies in construction management. International Journal of Construction Management. 2019 Sep 3;19(5):401-12.

Table 4.4: Comparison of identification and tracking technologies for different construction materials

	Short range			Long range		
Material	**Barcode**	**RFID**	**Bluetooth**	**LoRA**	**SigFox**	**4G**
Structural steel	X	X				
Timber	X	X				
Prefab timber	X	X				
Doors and windows	X	X				
Steel reinforcement	X	X				
Roofing		X				
Lightings		X	X			
Piping and fittings			X			
Cables		X				
Precast concrete		X				
In-situ concrete		X	X			
Soil				X	X	X

4.7 Key findings

- The current sensors and associated technologies have advanced over the years. The suite of sensor technologies can enable real-time tracking of materials in most scenarios. However, some specific challenges are highlighted in the next section.
- We can integrate technologies having common standards into an integrated suite for material tracking and construction processes, in general.
- Although most technologies have some sort of standards, there could be a few proprietary technologies that need integration with mainstream technologies for easy integration and interoperability of data flow and tracking.
- The technologies currently available are relatively advanced, and the commercial solutions available would easily cater to most construction processes. In addition, the commercial solutions are flexible and can be integrated into existing technology platforms on a needs basis.
- There are some advanced barcoding and RFID technologies for extreme conditions (labels available for temperatures up to 1,370°C, resistant to chemicals), primarily suitable for manufacturing and tracking of materials. However, cost and associated factors may limit an organisation from adopting such technologies. Most of these labels are produced using specialised printers, and they can be purchased for long-term benefits.
- We can have real-time racking information available on smartphones and dashboards by combining multiple sensors (such as GPS, cellular communications, barcode, RFID and other specific sensors).

Chapter 5 State-of-the-art in logistics and construction onsite tracking

Authors: Yihai Fang, Xin Ma

5.1 Introduction

Transporting construction materials is a critical task in construction processes, accounting for more than 15% of the total project expenditure.[88] More importantly, the impact of the material transportation is not limited to logistics costs; the productivity losses of most value-adding activities are associated with the mismatch of workforces and materials, such as workers searching and waiting for the right construction material to accomplish their work.[89] In traditional material management methods, construction materials logistics are manually tracked and updated from factories to the construction sites.[90] This manual method causes excessive procedures (e.g., counting and inspections) and extra labour costs that are avoidable with the aid of sensing technologies. Researchers and construction practitioners have investigated multiple tracking and monitoring technologies to capture and report material logistics, including LiDAR, computer vision (CV), real-time locating system (RTLS) and radio-frequency identification (RFID). As a result, the visibility of materials is enhanced in some logistics procedures (e.g., production and transportation), making it possible for data-driven decision making on material management.[91]

However, unlike other venues along the supply chain (e.g., factories, ports and distribution centres), the construction site is highly complex and dynamic in nature. Thus, applying sensing technologies on construction sites faces unique difficulties, such as the stringent requirements on data accuracy, ever-changing material-delivery demands, and complex interactions between materials, construction equipment and workers.[92] These pose various challenges to sensors, information management systems, and the data reasoning process that links raw data to construction activity information. Yet, the complexity of construction sites also enables diverse material tracking strategies. Instead of tracking materials in each onsite logistics procedure (e.g., onsite inventory-taking and installation), some alternative sensing strategies use *material handling equipment* or *as-built building models* as proxies to understand material status. As such, sufficient details of onsite material flow can be captured to meet the demands of operational management, with reduced efforts and costs of sensor deployment (e.g., tagging materials).

The uniqueness of onsite material tracking warrants a comprehensive review of the literature. This task utilises a hybrid literature review method to investigate the state-

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[88] *G. Yang, S. Wang, H. Okamura, B. Shen, Y. Ueda, T. Yasui, T. Yamada, Y. Miyazawa, S. Yoshida, Y. Inada, S. Ino, K. Okuhata, Y. Mizobuchi, Hallway exploration-inspired guidance: applications in autonomous material transportation in construction sites, Automation in Construction. 128 (2021). doi:10.1016/j.autcon.2021.103758.*

[89] *H. Bardareh, O. Moselhi, Automated Data Acquisition for Indoor Localization and Tracking of Materials Onsite, in: Proceedings of the 37th International Symposium on Automation and Robotics in Construction, ISARC 2020: From Demonstration to Practical Use - To New Stage of Construction Robot, 2020. doi:10.22260/isarc2020/0106.*

[90] *Z. Ren, C.J. Anumba, J. Tah, RFID-facilitated construction materials management (RFID-CMM) - A case study of water-supply project, Advanced Engineering Informatics. 25 (2011) 198–207. doi:10.1016/j.aei.2010.02.002.*

[91] *Y. Niu, W. Lu, D. Liu, K. Chen, C. Anumba, G.G. Huang, An SCO-Enabled Logistics and Supply Chain–Management System in Construction, Journal of Construction Engineering and Management. 143 (2017). doi:10.1061/(asce)co.1943-7862.0001232.*

[92] *K. Chen, G. Xu, F. Xue, R.Y. Zhong, D. Liu, W. Lu, A Physical Internet-enabled Building Information Modelling System for prefabricated construction, International Journal of Computer Integrated Manufacturing. 31 (2018). doi:10.1080/0951192X.2017.1379095.*

of-the-art of onsite material tracking. This task first summarises the applications of tracking technologies on construction sites with a bibliometric analysis, providing the audience with contextual information on the technologies and tracked objects. A critical review of onsite material tracking follows, with details of data capture and integration. In addition to technological details, this task also scrutinises the linkage between sensors and construction management tasks and the evolution from sensor-captured data to operational insights on productivity, safety and quality. These analyses finally lead to recommendations for tracking materials onsite.

The rest of this chapter is structured as follows: Section 5.2 presents the results of the bibliometric analysis. Section 5.3 elaborates on the critical review, which first describes onsite material flow conceptually and then explains 3 different tracking strategies that track/monitor the materials/components, material handling equipment and building elements. The strategies are then reflected in Section 5.4, discussing their benefits and challenges and identifying the trade-offs for developing and implementing the material tracking strategy for a construction project.

5.2 Applications of sensing technology on construction sites: a literature overview

In the past 2 decades, tracking onsite resources has gained increasing attention. Onsite resources (i.e., materials, workers and equipment) often interact with others in construction processes, so the real-time information of these resources (e.g., locations, status) usually contextualises each other. For example, crane movements could indicate the installation status of prefabricated structural components under certain circumstances[93] Moreover, material tracking, worker tracking and equipment tracking tasks often overlap with regard to tracking technology. Many studies have attempted to use one single sensing technology to track all types of onsite resources.[94] Based on the observation, the authors believe overviewing these applications of tracking technologies enriches the understanding of onsite material tracking. So, this section investigates the onsite resource tracking studies via a bibliometric analysis. The bibliometric analysis uses a literature database named Scopus, which is a high-quality source for book series, journals and trade journals. We identified 132 English articles by searching ‘construction site/project’ and ‘tracking’ in titles, abstracts and keywords in the engineering field since 2000. After manually screening irrelevant items, we narrowed the data set to 77 publications. We performed 2 analyses on this data set.

First, quantifying the adoption of different technologies provides hints of their maturity and availability. Figure 5.1 illustrates the proportion of each tracking technology in a pie chart (left) and presents the number of frequently adopted technologies (i.e., adopted more than twice) versus the year of publication (right). Interest in CV, GNSS and BLE technologies has increased in recent years, while UWB and RFID technologies have been studied since 2008, although the number of studies is relatively small.

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[93] *Y. Niu, W. Lu, K. Chen, G.G. Huang, C. Anumba, Smart construction objects, Journal of Computing in Civil Engineering. 30 (2016) 04015070. doi:10.1061/(ASCE)CP.1943-5487.0000550.*

[94] *J. Teizer, H. Neve, H. Li, S. Wandahl, J. König, B. Ochner, M. König, J. Lerche, Construction resource efficiency improvement by Long Range Wide Area Network tracking and monitoring, Automation in Construction. 116 (2020). doi:10.1016/j.autcon.2020.103245.*

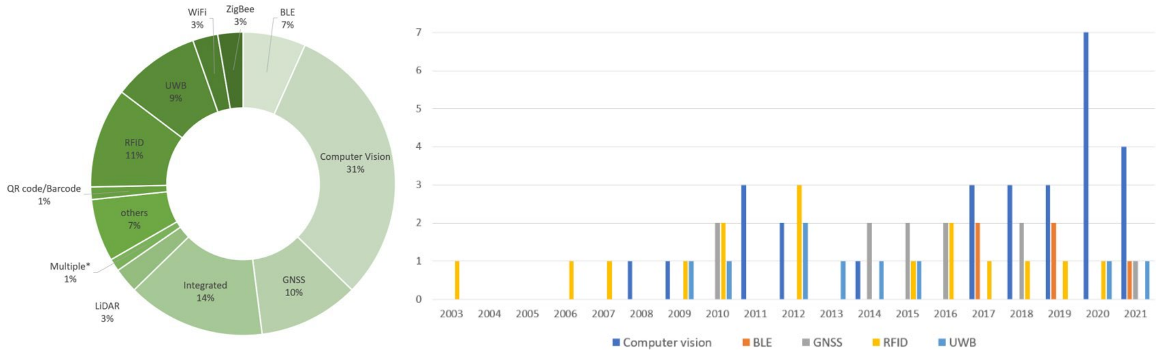


Figure 5.1: Tracking technologies adopted in the reviewed literature: the composition and trend (2000 to 2021)

Figure 5.2 further categorises the publications based on the object being tracked with a breakdown of technology used. Research on material tracking is not as popular as other objects such as workers and equipment. The insufficiency of material tracking studies necessitates the investigation of other studies, including those on material handling equipment (e.g., cranes and lifts) or comprehensive tracking systems for multiple resources. The diagram shows material tracking primarily relies on integrated sensors and RFID, which is unique compared with other tracked objects. This phenomenon suggests the diverse demands for material-related information (e.g., the identification, locations, the procurement information) and the complexity of the tracking systems, especially the information management component.

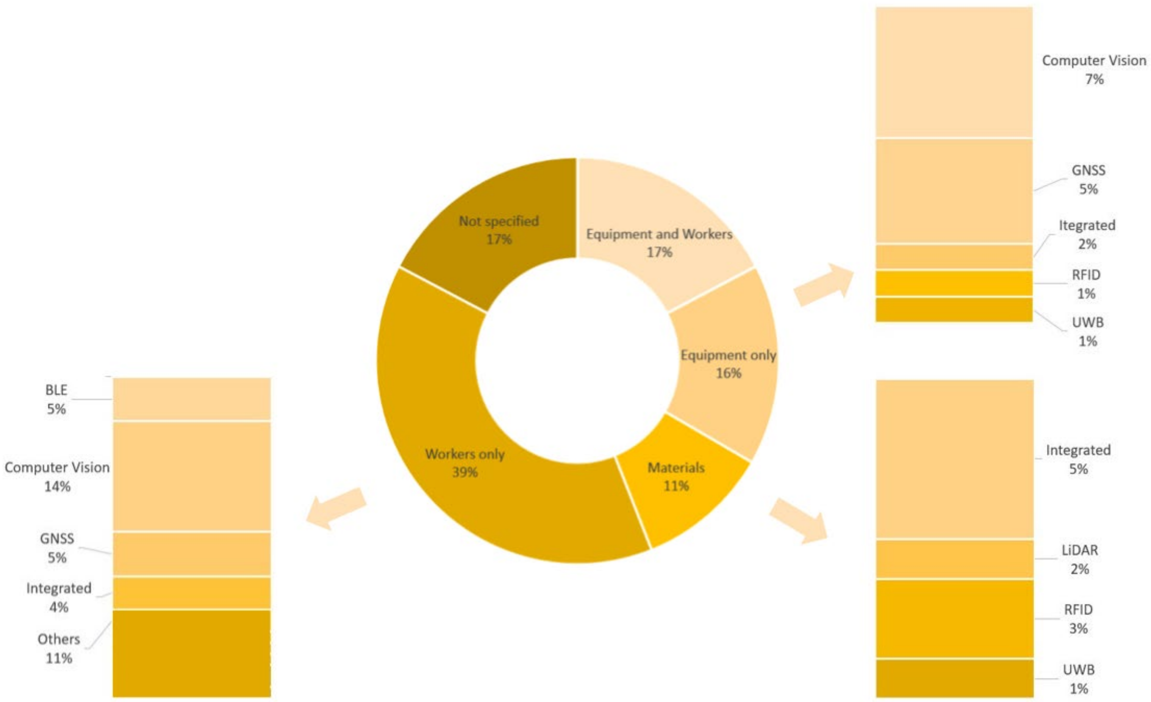


Figure 5.2: Tracked resources in the review literature: the composition with tracking technology breakdown (2000 to 2021)

5.3 Applications of sensing technology in onsite material tracking

This section presents a critical review of onsite material tracking. The following subsections first present a conceptual framework of onsite material flow, elaborating on the logistics activities, participating equipment and statuses of materials. Then, the research works are clustered according to their tracked objects in the material flow, including materials/components, material handling equipment and building elements (e.g., installed components). From a strategic perspective, these 3 strategies monitor different objects to reflect the same onsite material flow, which have unique infrastructure requirements (e.g., sensors and information systems) and provide different levels of information, respectively. Sections 5.3.2–5.3.4 summarise both hardware and software requirements of each reviewed literature, along with managerial benefits demonstrated in their case studies.

5.3.1 Onsite material flow: a conceptual framework

Material flow in a typical building project can be described as the input of construction materials together with their packaging materials and the output of construction wastes.[95] As shown in Figure 5.3, most construction materials, if not damaged, are finally installed as building elements, and their packaging materials and extracted materials (i.e., excavated soils) are discarded as construction wastes. Such material flow typically requires 5 onsite logistics activities: material receipt and inspection, material unloading, material sorting/storing, material installation and waste disposal. The first 4 activities are also known as material delivery, which is our focus. This process mobilises materials with limited types of horizontal and vertical transportation equipment (e.g., hand trucks, forklifts, cranes, and lifts), whose productivity is directly related to the efficiency of material delivery. Past research works explored 3 sensor strategies to identify, locate and retrieve information about the material flow. Sections below summarise the implementation of the 3 sensor strategies, respectively.

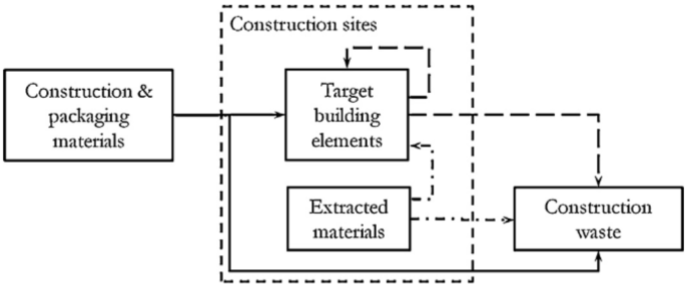


Figure 5.3: Overall material flow of a typical building construction project, adapted from[95]

5.3.2 Tracking materials directly

Tracking materials on construction sites has gained extensive research interest in the past decade. Partly, this interest is attributed to the increasing popularity of prefabrication. Prefabricated building components usually have a long supply lead time and low interchangeability. The efficiency of their transportation and installation directly influences construction progress.[96]

Prefabricated piping/HVAC components and prefabricated structural components are the 2 most widely investigated types of prefabricated materials in the literature. Piping is a costly process involving miscellaneous engineered items (e.g., spools, supports,

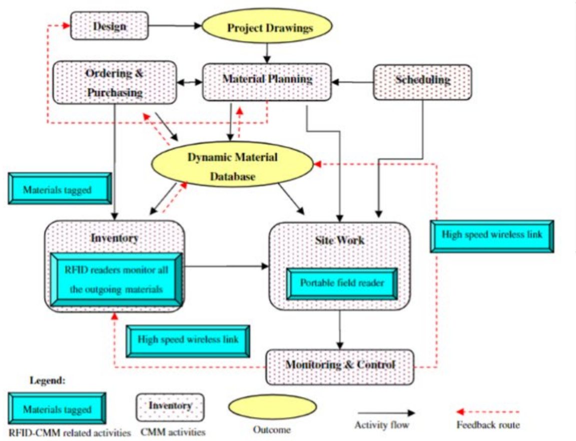
[95] *Y. Li, X. Zhang, G. Ding, Z. Feng, Developing a quantitative construction waste estimation model for building construction projects, Resources, Conservation and Recycling. 106 (2016). doi:10.1016/j.resconrec.2015.11.001.*

[96] *J. Song, C.T. Haas, C. Caldas, E. Ergen, B. Akinci, Automating the task of tracking the delivery and receipt of fabricated pipe spools in industrial projects, Automation in Construction. 15 (2006). doi:10.1016/j.autcon.2005.03.001.*

hangers, safety valves). Traditional material management methods cannot update the material flow quickly and accurately, resulting in redundant onsite inventory and a huge productivity loss in searching the right components.[97] Among many early attempts, researchers deployed RFID technologies on pipe supports and hangers to automate the inventory receiving and inspection process.[98] Manual data capturing methods (e.g., kick-and-count and fill in the forms) were replaced by a digitalised approach (e.g., scan and enter semantic information with handheld read-write terminals), resulting in up to 80% time saving and a reduced need for manpower. Soon after, the RFID technology was adopted to track pipe spools by installing fixed RFID readers at the site access and using handheld readers in the laydown yard and around the flatbed trailer.[95] Procurement information (e.g., purchase order number) and inspection results were then integrated into offline systems. The same sensor setup was adopted in a more comprehensive material management system for a water supply project, with RFID tags attached to materials, fixed readers installed at the site accesses, and handheld readers carried during site walks.[90] In this system, the sensor-collected data is uploaded to the Xara online database, which is compatible with material procurement systems for material ordering and inquiries. The RFID facilitated material database enables prompt adjustment of material planning and project scheduling. Other technologies can also be found in the inventory-taking process for pipes. In[99], for example, computer vision was adopted to automatically count the quantity of steel pipes at the construction gate.

With limited localisation precision, RFID technology can provide only a rough spatial estimation. Some studies aimed to integrate multiple sensing technologies for improved precision and granularity. For example, GPS-enabled mobile RFID readers are one of the effective combinations of multiple sensing systems.[100] The GPS-enabled RFID readers were installed on forklifts[97] or carried by workers[101] to locate pipe spools, safety valves and pipe supports in the laydown area. Maps with location marks are distributed to workers to enhance their situational awareness. In indoor environments where GPS is not applicable, UWB was used to track RFID readers,[89] and the captured location was then superimposed with the relative distance between RFID readers and tags to find tracked objects (i.e., plumbing and HVAC components).

[97] *D.G. Torrent, C.H. Caldas, Methodology for Automating the Identification and Localisation of Construction Components on Industrial Projects, Journal of Computing in Civil Engineering. 23 (2009). doi:10.1061/(asce)0887-3801(2009)23:1(3).*
[98] *E.J. Jaselskis, T. El-Misalami, Implementing Radio Frequency Identification in the Construction Process, Journal of Construction Engineering and Management. 129 (2003). doi:10.1061/(asce)0733-9364(2003)129:6(680).*
[99] *Y. Li, J. Chen, Computer Vision–Based Counting Model for Dense Steel Pipe on Construction Sites, Journal of Construction Engineering and Management. 148 (2022). doi:10.1061/(asce)co.1943-7862.0002217.*
[100] *X. Su, S. Li, C. Yuan, H. Cai, V.R. Kamat, Enhanced Boundary Condition–Based Approach for Construction Location Sensing Using RFID and RTK GPS, Journal of Construction Engineering and Management. 140 (2014). doi:10.1061/(asce)co.1943-7862.0000889.*
[101] *S.N. Razavi, C.T. Haas, Multisensor data fusion for onsite materials tracking in construction, Automation in Construction. 19 (2010). doi:10.1016/j.autcon.2010.07.017.*



(a) System architecture: relationship between sensors and information system

Product ID	KG2-08	KG2-13	KG2-15	KG2-16	KG2-17	KG2-18	KG2-19
Name	Socket and spigot 22 1/2" bend	Double flange 11 1/4" bend	Restraint coupling 1200–1200	V.J. Adepter 1200–1000	V.J. Adepter 1200–800	Check valve	Butterfly valve
Material	DI	DI	DI	DI	DI		
Diameter (mm)	1200	1200	1200	1200–1000	1200–800	250	800
Nominal length (mm)	285	700		250	225	330	330
Weight (kg)	736	858		345	315	132	500
Quantity (No.)	56	2	100	523	212	124	35
Batch No.	001-07	001-07	01-07	01-07	011-06	04-06	04-06
Item ID	KG2-08-054	KG2-13-002	KG2-15-098	KG2-16-245	KG2-17-167	Kg2-18-093	Kg2-19-023
Type	K9	K9	K12	K12	K12		
Drawing_No.	KL-pumping main-014	KL-pumping main-019	KL-pumping main-013, 14	KL-pumping main-013, 14	KL-pumping main-013, 14	KL-pumping main-013, 022, 023,024	KL-pumping main-013, 017, 019
Specification	12.10-(4)	12.10-(3)	12. 10-(2)	12. 10-(2)	12. 10-(2)	12.12-(1)	12.12-(5)
Manufacturer	Kubota	Stanton	V.J.	V.J.	V.J.	Stanton	Stanton
Instore_Date	04/01/2007	04/01/2007	04/01/2007	04/01/2007	04/01/2007	11/12/2006	11/12/2006
Inspection_done	06/01/2007	05/01/2007	05/01/2007	06/01/2007	05/01/2007	15/12/2006	14/12/2006
Scheduled_construction_date	12/11/07	12/07	11/07	12/07	04/08	04/08	05/08
Construction site	xxx	xxx	xxx	xxx	xxx	xxx	xxx
Site _in_charge	Zhu	Wu	Liu	Zhu	Liu	Hu	Han
Site store	Moro	Panan	Yakela	Moro	Yakela	C_5	Moro
Site_store_received_on	15/02/2007	14/02/2007	05/03/2007	16/02/2007	05/12/2007	11/10/2007	18/01/2008
Site_store_received_by	Agith	Sugi	Asanga	Agith	Agi	Ganyan	Dana
Site_store_issued_on	28/07/2007	12/06/2007	05/05/2007	11/03/2007	12/12/2007	06/02/2008	01/02/2008
Site_store_issued_by	Agith	Sugi	Asanga	Agith	Agi	Ganyan	Han
Special_requirements	No	No	No	No	No	No	No
Remarks							

(b) Sensor collected data (i.e., key features of pipe fitting)

(c) Sensor deployed on the pipe fittings to be tracked

Figure 5.4: One case study of pipe tracking system[90], other examples can be found in [89,90,96,97,98,99,100,101]

Prefabricated structural components are another frequently tracked object. As in Wang et al.,[102] stakeholders along the supply chain can semi-automatically update the production, inventory, quality inspection and installation status of prefabricated structural components with handheld RFID read/write devices. RFID was also used to monitor the progress of a bridge construction.[103] In this system, RFID not only recorded the ID and time log of material arrival but triggered cameras to take photos of the prefabricated components. Similar to piping components, structural components also follow a stringent installation sequence and some components that arrive on site early need to wait for installation. As the number of such components increases, multi-handling is inevitable. Thus, RFID is used to estimate the displacement of prefabricated components to identify unnecessary material handling.[104] Again, RFID technology alone can hardly provide precise location information. Thus, a hybrid system was developed by Song et al.,[105] which integrated RFID and GPS for locating prefabricated structural components. In recent years, some researchers proposed the 'Smart Construction Object (SCO)' concept to describe the sensor-enabled materials,[92] and the prefabricated building elements (e.g., façade and staircases) are a fundamental part of the SCOs. Several case studies were conducted to track the prefabricated SCOs on/off-site.[92,93,106] The real-time information effectively provided visibility of inventory, logistics status and construction progress to site managers for optimised decision making (e.g., materials ordering).

In some recent literature, material tracking is also an indispensable part of comprehensive real-time monitoring systems, which identify and locate multiple

[102] *L.C. Wang, Y.C. Lin, P.H. Lin, Dynamic mobile RFID-based supply chain control and management system in construction, Advanced Engineering Informatics. 21 (2007). doi:10.1016/j.aei.2006.09.003.*
[103] *Y. Ju, C. Kim, H. Kim, RFID and CCTV-Based Material Delivery Monitoring for Cable-Stayed Bridge Construction, Journal of Computing in Civil Engineering. 26 (2012). doi:10.1061/(asce)cp.1943-5487.0000134.*
[104] *D. Grau, Epistemic Model to Monitor the Position of Mobile Sensing Nodes on Construction Sites with Rough Location Data, Journal of Computing in Civil Engineering. 26 (2012). doi:10.1061/(asce)cp.1943-5487.0000120.*
[105] *J. Song, C.T. Haas, C.H. Caldas, A proximity-based method for locating RFID tagged objects, Advanced Engineering Informatics. 21 (2007). doi:10.1016/j.aei.2006.09.002.*
[106] *C.Z. Li, F. Xue, X. Li, J. Hong, G.Q. Shen, An Internet of Things-enabled BIM platform for onsite assembly services in prefabricated construction, Automation in Construction. 89 (2018) 146–161. doi:10.1016/j.autcon.2018.01.001.*

resources (such as workers, equipment and materials) and push the information to a unified information system. For example, the presence of material cartons was registered by fixed RFID readers at the gate of the laydown area, which was synchronised with humidity and temperature information in a centralised local server. [107] Further, the integrated ZigBee and RFID system tracked workers, equipment and materials to identify precursors of near-miss events, such as unauthorised workers operating the equipment. [108] While these systems were trying to integrate different clusters of as-is information, [109] they combined BIM and an indoor localisation system to integrate pre-defined zoning information (i.e., as-planned information) with real-time locations (i.e., as-is information). Construction zones are a critical component that bridges as-is spatial-temporal data of materials with as-planned schedules. By comparing 'where and when the resources should be' and 'where and when they actually are' (i.e., should-be vs as-is), deviation from the plan and the resulting non-value-added activities can be identified and evaluated. From a lean perspective, multiple non-value-added activities that are considered time waste could be related to materials: (1) unnecessary handling of materials; (2) searching for the right resources; and (3) workers waiting for materials. Thus, by measuring the presence of workers and materials, this work evaluated the level of resource–worker matching to identify non-value-added activities, quantify their impacts on productivity and enable continuous improvement. [110]. Details of the reviewed literature are listed in Table 5.1, which highlights what data was collected and how it was collected, integrated and utilised to facilitate management tasks.

[107] *W. Wu, H. Yang, D.A.S. Chew, S. hua Yang, A.G.F. Gibb, Q. Li, Towards an autonomous real-time tracking system of near-miss accidents on construction sites, Automation in Construction. 19 (2010). doi:10.1016/j.autcon.2009.11.017.*
[108] *H. Yang, D.A.S. Chew, W. Wu, Z. Zhou, Q. Li, Design and implementation of an identification system in construction site safety for proactive accident prevention, Accident Analysis and Prevention. 48 (2012). doi:10.1016/j.aap.2011.06.017.*
[109] *A. Montaser, O. Moselhi, RFID indoor location identification for construction projects, Automation in Construction. 39 (2014). doi:10.1016/j.autcon.2013.06.012.*
[110] *J. Zhao, Y. Zheng, O. Seppänen, M. Tetik, A. Peltokorpi, Using Real-Time Tracking of Materials and Labor for Kit-Based Logistics Management in Construction, Frontiers in Built Environment. 7 (2021). doi:10.3389/fbuil.2021.713976.*

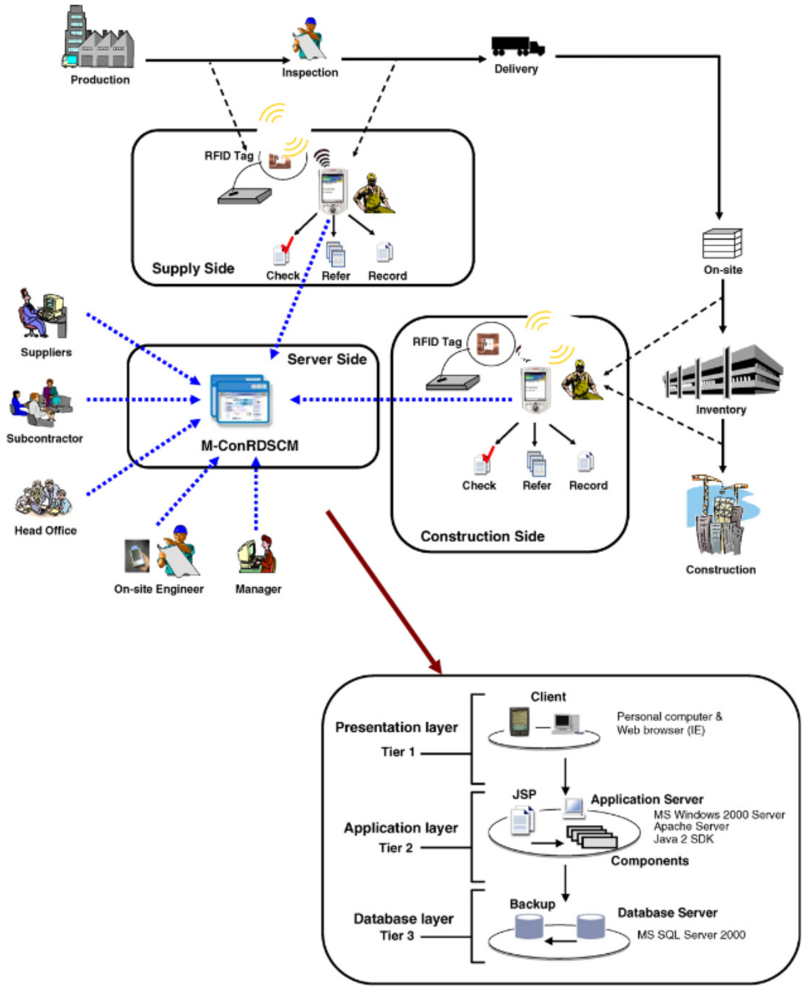


Figure 5.5: One case study of prefabricated structural component tracking system[103], other examples can be found in[92,93,103, 104,105,106]

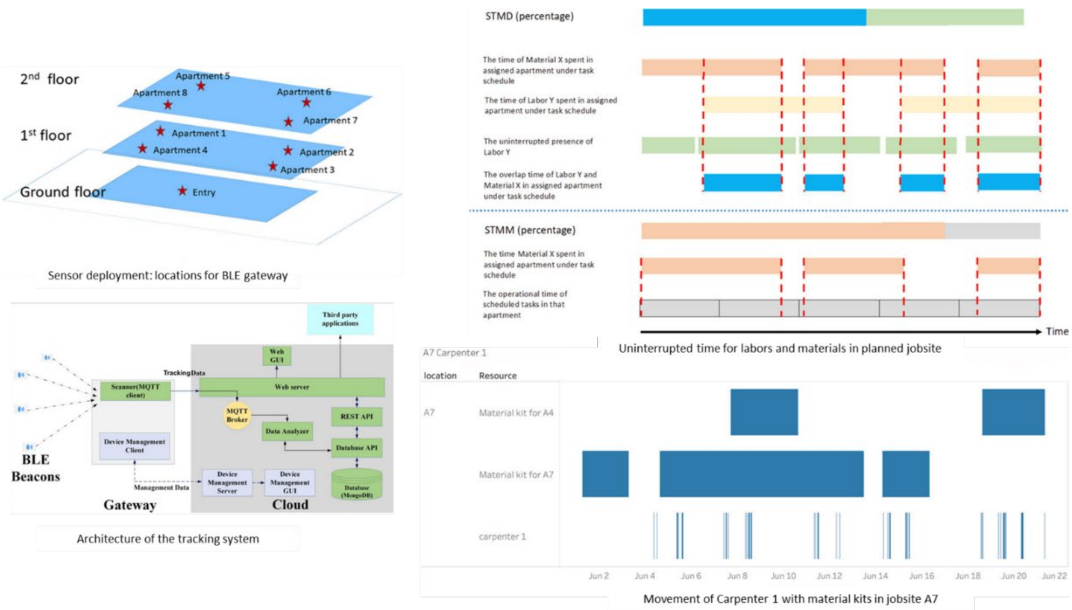


Figure 5.6: One case study of material-kit/worker tracking system to measure the lean wastes related to resource-worker mismatch[106], other examples of comprehensive real-time monitoring systems can be found in[107,108,109]

Table 5.1: Summary of research works on direct tracking of dynamic construction/packaging materials

Title	Year	Collected data	Tracking mechanism	Sensor technology	Info. system	Managerial application
Computer Vision–Based Counting Model for Dense Steel Pipe on Construction Sites[99]	2022	Quantity of steel pipes	Processing images of a bundle of steel pipes	Computer vision	N.A.	Replace the manual counting in onsite inventory taking processes
Using Real-Time Tracking of Materials and Labor for Kit-Based Logistics Management in Construction[109]	2021	IDs and locations of workers from 4 trades (including carpenters, plumbers, plasterers, and bricklayers IDs and locations of the material kits for the workers	Capturing the presence of workers and material kits (i.e., BLE beacons) at pre-defined locations with fixed readers	BLE	A generic linked data framework by semantic web technologies	Track uninterrupted presence of workers/material kits in a work location Understand the time-matching level of workers and materials in work locations Also understand: 1) delivery times of the kits to the first detected location onsite; 2) removal times of the kits from the last detected location onsite; 3) number of times each kit moved between the delivery time and removal time
Automated Data Acquisition for Indoor Localization and Tracking of Materials Onsite[89]	2020	ID and locations of plumbing and HVAC components	Tracking RFID tags with UWB-enabled handheld reader	Integrated RFID and UWB	N.A.	Track materials onsite in real time to assist near-real-time decision making
A Physical Internet-enabled Building Information Modelling System for prefabricated construction[92]	2018	ID and locations of prefabricated building components (e.g., façade, staircases)	Tracking in-built RFID tags with handheld readers	RFID	A generic system comprises of web services and smartphone apps	Schedule lifting/installation activities Track components along the supply chain Analyse energy efficiency and construction progress
Cloud-based materials tracking system prototype integrated with radio frequency identification tagging technology [111]	2016	ID, specifications and time logs of pipe spools	Capturing arrival of material by a fixed RFID reader at the site access point Barcode is used as a complementary technology for RFID	Integrated RFID and barcode	Microsoft Azure platform	Propose a low-cost material tracking solution for small-to-medium business
Intelligent materials tracking system for	2015	ID, date, time, product, loader number and site	Writing and updating information through a fixed	RFID	Generic online material	Track the logistics and installation status of construction materials

[111] H.S. Ko, M. Azambuja, H. Felix Lee, Cloud-based Materials Tracking System Prototype Integrated with Radio Frequency Identification Tagging Technology, Automation in Construction. 63 (2016). doi:10.1016/j.autcon.2015.12.011.

Title	Year	Collected data	Tracking mechanism	Sensor technology	Info. system	Managerial application
construction projects management [112]		location of construction material (generic)	RFID reader at the loading zone		management system	
Data fusion process management for automated construction progress estimation [113]	2015	Spool ID and locations Activity status such as pipe installation, welding and inspection Completion rate of pipes	Tracking spools locations with UWB Marking activity status with UWB tags, e.g., placing UWB tag after pipe is installed, welded or inspected Capturing volumetric data of pipes and compare it with as-planned models	Integrated LiDAR and UWB	**As input:** BIM models Schedule Foreman reports **As output:** Progress estimate Earned value estimate Up-to-date schedule	Estimate construction progress based on as-is data Update schedule and perform earned value analysis
Enhanced boundary condition–based approach for construction location sensing using RFID and RTK GPS[100]	2014	ID and locations of generic construction materials	Tracking RFID tags with GPS-enabled handheld reader	Integrated RFID and GNSS	N.A.	Track materials onsite in real time to assist near-real-time decision making
RFID indoor location identification for construction projects[111]	2014	Workers real-time locations and ID Materials real-time locations and ID	Using passive reference tags in predefined locations to identify handheld RFID reader's location (i.e., workers) Then locating materials with passive FFID tags based on RSSI	RFID	BIM	Track materials indoor with low-cost sensors to find out their presence in pre-defined zones
Design and implementation of an identification system in construction site safety for proactive accident prevention[110]	2012	ID and semantic information about workers, equipment, and materials at the site entrance ID of workers who access/operate equipment Information of materials include ID, name, type, by	Tracking passive RFID tags by handheld ZigBee-enabled reader	Integrated ZigBee & RFID	Local sever with database and remote information centres	Control site access and equipment operation authority Gain insights on training or unsafe behaviour of workers (e.g., equipment operation procedures) and the need for inspection (e.g., machine not tested for a long time)

[112] *N. Kasim, Intelligent materials tracking system for construction projects management, Journal of Engineering and Technological Sciences. 47 (2015). doi:10.5614/j.eng.technol.sci.2015.47.2.11.*
[113] *A. Shahi, M. Safa, C.T. Haas, J.S. West, Data Fusion Process Management for Automated Construction Progress Estimation, Journal of Computing in Civil Engineering. 29 (2015). doi:10.1061/(asce)cp.1943-5487.0000436.*

Title	Year	Collected data	Tracking mechanism	Sensor technology	Info. system	Managerial application
		piece, production company, purchaser and weight				
RFID and CCTV-based material delivery monitoring for cable-stayed bridge construction[103]	2012	ID and manufacturing info. of precast bridges' structural component Time log when materials enters/leaves site gate	Tracking semi-active RFID tags at the entrance and the CCTV is triggered by RFID to capture images and confirm material arrival	Integrated RFID and CCTV	A generic internet-based information management system	Record the material information and the time of arrival Communicate the information to stakeholders for progress monitoring
Epistemic model to monitor the position of mobile sensing nodes on construction sites with rough location data[104]	2012	Displacement of non-bulky prefabricated materials on the construction sites	Tracking RFID tags with a roving unit daily	RFID	N.A.	Understand the actual materials displacement with a reduced location uncertainty in a metallic environment to understand the multi-handling of materials
RFID-facilitated construction materials management (RFID-CMM)–a case study of water-supply project[90]	2011	Material information including ID, material/pipe name, type, batch, quantity, and dimensions Time log when materials enters/leaves site storage area Manufacturer, person-in-charge of its storage, and special requirements	Tracking material in inventory with fixed RFID readers and tracking materials on site with handheld readers during site walk	RFID	Xara online (excel add-in)	RFID is used to integrate a discrete material management system. The applications include: Maintain a key-materials-list with all changes Assist the generation of material inquiries and purchase order Record delivery to site Analyse material availability Manage material stock
Multi-sensor data fusion for onsite materials tracking in construction[101]	2010	Locations pipe spools, safety valves and pipe supports	Tracking active RFID tags with GPS-enabled handheld RFID readers	Integrated GNSS and RFID	Office computer and printers	Integrated sensors are used for location estimation, identificatio, and dislocation detection
Towards an autonomous real-time tracking system of near-miss accidents on construction sites[109]	2010	Presence of material cartons in material storage areas Temperature and humidity in the material storage areas	Tracking passive RFID tags with ZigBee-enabled readers at the access point of material storage areas Temperature and humidity sensors are installed on the RFID readers	Integrated ZigBee and RFID	Local sever with database	Track relative distance of workers, materials and equipment Control access of workers and equipment/vehicles Track dangerous scenarios in real time
Methodology for automating the identification and localisation of construction	2009	ID and locations of steel components (piping and structural steel) in laydown yards	Tracking active RFID tags with GPS-enabled readers in forklift	Integrated RFID and GNSS	PC (offline system)	Automate inventory-taking process Reduce materials repositioning (i.e., intermediate storage)

Title	Year	Collected data	Tracking mechanism	Sensor technology	Info. system	Managerial application
components on industrial projects[97]						
Enhancing construction quality inspection and management using RFID technology [114]	2008	Curing status, inspection status, and compressive test status of the concrete specimen	Manually recording the status in text with a handheld read/write devices (PDAs)	RFID	Online quality management system	Focusing on the material quality, this system helps stakeholders inside/outside test labs to access lab test data through a quality management system
A proximity-based method for locating RFID tagged objects[105]	2007	Approximate 2D location (error within several meters) of generic prefabricated construction materials	RFID tags captured by an off-the-shelf RFID handheld reader with a GPS receiver	Integrated GNSS & RFID	N.A.	Cost-effective positioning of onsite materials
Dynamic mobile RFID-based supply chain control and management system in construction[102]	2007	Production, inventory, quality inspection, and installation status and time logs of prefabricated structural components	Manually recording the status in text with a handheld read/write devices (PDAs)	RFID	Online supply chain management system	Focusing on the critical procedures in the supply chain, a RFID system is used to automatically record material status for onsite/off-site stakeholders
Automating the task of tracking the delivery and receipt of fabricated pipe spools in industrial projects[96]	2006	Pipe spools' ID, piece marked number, spool number, sketch number, and purchase order number	Attach tags after onsite inspection, data is collected by fixed RFID readers mounted on a portal structure	RFID	PC (offline system)	Understand factors influencing accuracy in a construction environment Map out the process improvement of adopting RFID technologies and quantify some of the economic benefits
Implementing radio frequency identification in the construction process[98]	2003	Pipe supports and hangers quantity, purchase order number, release number, and requisition number, condition, and storage location	Tracking RFID tags by handheld read/write devices when materials arrive on site	RFID	A company information system	Provide owners and contractors with operational information (e.g., the time for each procedure) Avoid 'kick and count' procedure for onsite inspection and onsite inventory management
Radio-frequency identification applications in construction industry [115]	1995	Concrete test results	Reading/writing RFID tags to attach in the surface of concrete test cylinders after concrete test cylinders were cast with PDAs	RFID	N.A.	Tracking concrete material inspection and lab tests data

[114] *E.J. Jaselskis, M.R. Anderson, C.T. Jahren, Y. Rodriguez, S. Njos, Radio-Frequency Identification Applications in Construction Industry, Journal of Construction Engineering and Management. 121 (1995). doi:10.1061/(asce)0733-9364(1995)121:2(189).*
[115] *L.C. Wang, Enhancing construction quality inspection and management using RFID technology, Automation in Construction. 17 (2008). doi:10.1016/j.autcon.2007.08.005.*

5.3.3 Tracking material handling equipment

Tracking material handling equipment is another strategy for material tracking. This strategy originates from heavy machinery tracking, which monitors certain equipment (e.g., cranes, excavators and lifts) that undertake repetitive and cyclic tasks (e.g., lifting, earth moving). This operation pattern allows equipment productivity to be evaluated by measuring its cycle times. Since most equipment is used to transport materials, the productivity of equipment could, to some extent, represent the status and quantity of material being delivered. Given this, researchers have explored the potential of tracking equipment operation as a proxy for material flow on site. Under certain circumstances, the equipment productivity could indicate the productivity of material delivery and utilisation by linking ‘machine data’ (e.g., cycle times) to ‘activity information’ (e.g., material delivery productivity) through a reasoning process. However, this process is challenging because the logic for reasoning changes constantly with material types, available material handling equipment and site settings. For example, the installation of heavy structural components usually requires cranes, while non-bulky components, such as windows, often take the lifts. Even for the same materials, its transportation can employ a hybrid method, which uses cranes as a complementary vehicle when the construction lifts are not available (e.g., unfinished levels). Although the prerequisites exist (e.g., investigating the logic for data reasoning), this tracking strategy provides fine-granular information of the material flow with a focus on material handling processes, which is critical to identify bottlenecks in onsite material logistics.

Cranes are indispensable material handling equipment on construction sites, mobilising a wide variety of materials vertically and horizontally. Thus, cranes have drawn a lot of attention in equipment tracking research. Monitoring the crane itself mainly focuses on collecting 2 types of information: the weight on the hook and crane poses/motions. Understanding crane poses/motions is essential for higher-level analysis (e.g., identifying crane-related hazards and recognising crane-related activity). For example, Gutierrez et al. [116]developed a computer-vision enabled crane tracking system to estimate the jib swing, cart movement and hook movement in complex site environments (e.g., different illumination conditions). However, tracking crane poses/motions alone cannot identify the load being lifted, hindering an effective interpretation of the construction activities (e.g., installing a prefabricated building component). To address this issue, weight on the hook was used to interpret the type of materials (as in Figure 5.7). [117] By integrating weight and crane pose/motion data, Sacks et al.[117]managed to understand the 6 actions in each crane operation cycle: (1) rest, attaching/detaching; (2) loading; (3) transportation; (4) motionless or suspending with load; (5) unloading; and (6) empty motions. However, this method requires field studies to obtain the weight ranges of different building components. In addition, as weight ranges of different components overlap with each other, leading to material recognition is not always accurate.

Hence, some works utilised RFID and BLE technologies to inform crane operators and site managers of accurate material information. Strategically, this method is a variant

[116] *R. Gutierrez, M. Magallon, D.C. Hernandez, Vision-based system for 3d tower crane monitoring, IEEE Sensors Journal. 21 (2021). doi:10.1109/JSEN.2020.3042532.*
[117] *R. Sacks, R. Navon, I. Brodetskaia, Interpretation of Automatically Monitored Lifting Equipment Data for Project Control, Journal of Computing in Civil Engineering. 20 (2006). doi:10.1061/(asce)0887-3801(2006)20:2(111).*

of direct material tracking, which considers the crane as a checkpoint to update the status of lifted loads. Thus, the tracking systems with this strategy can be easily integrated with traditional material management systems, while providing insights into the productivity of material handling equipment. For example, Lee et al.[118] deployed RFID tags on the lifted load and used handheld readers (held by riggers) to acquire and inform crane operators of the load information. In addition, Niu et al.[93] installed Bluetooth modules on prefabricated façade and cranes. Once the Bluetooth modules are paired with each other, the material properties (e.g., dimensions and the weight) and assembly guidelines (e.g., orientations) were retrieved and presented to the crane operators. Time logs were also recorded to track the construction progress. Figure 5.8 illustrates the architecture of the Bluetooth-enabled tracking system.

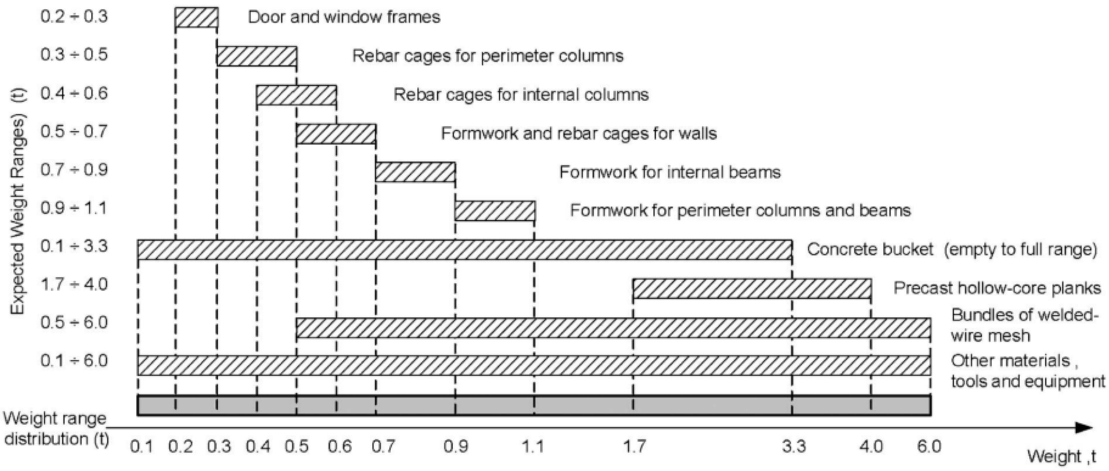


Figure 5.7: Weight ranges for different construction materials, adapted from [119]

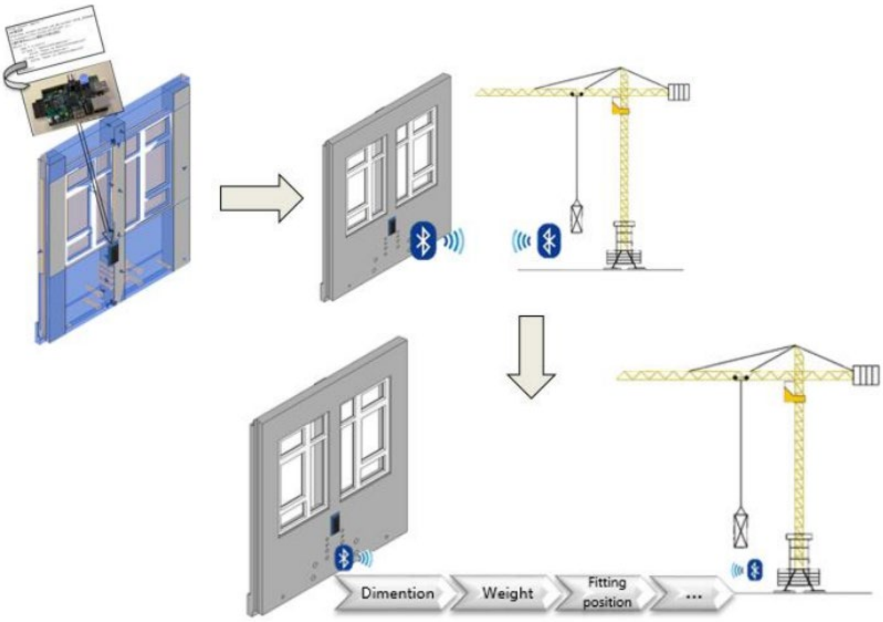


Figure 5.8: Bluetooth module installed in prefabricated façade and cranes to read material information, adapted from[93]

[118] U.K. Lee, K.I. Kang, G.H. Kim, H.H. Cho, Improving tower crane productivity using wireless technology, Computer-Aided Civil and Infrastructure Engineering. 21 (2006). doi:10.1111/j.1467-8667.2006.00459.x.

[119] R. Sacks, R. Navon, I. Brodetskaia, a. Shapira, Feasibility of Automated Monitoring of Lifting Equipment in Support of Project Control, Journal of Construction Engineering and Management. 131 (2005) 604–614. doi:10.1061/(ASCE)0733-9364(2005)131:5(604).

Another way to link crane operations to construction activities is to use the prior knowledge of certain construction activities. In concrete placing activities (e.g., casting columns and slabs), concrete buckets are a necessary crane accessory that transports concrete from mixer trucks to the demand points. Thus, concrete buckets are usually considered a 'method-leading resource' that indicates the start of concrete placing activity and a 'production unit', that measures the activity progress (e.g., how much volume has been cast). [120] Among the reviewed literature, concrete buckets were tracked with computer vision techniques in 3 case studies.[120, 121, 122] For example, Gong and Caldas[120] detected the concrete buckets by separating them from the background to determine the working states of the crane in a column casting activity (e.g., bucket loading, bucket moving, bucket departing). Yang et al.[121] first tracked the trajectory of the crane and then detected the presence of concrete buckets. With known site layout (e.g., locations of mixer trucks, the working zone, and the driveway), the crane trajectory and the concrete bucket presence were used to interpret the crane's working states. Wang et al.[122] extracted concrete bucket models from UAV-acquired 3D depth images and superimposed them with 2D images from a fixed surveillance camera. The synthetic images were then used to detect the concurrent presence of the bucket and the crane that was used to indicate the start of a concrete placing cycle (i.e., bucket starts to be lifted). Figure 5.9 illustrates Wang et al.'s[122] methodology.

[120] *J. Gong, C.H. Caldas, Computer Vision-Based Video Interpretation Model for Automated Productivity Analysis of Construction Operations, Journal of Computing in Civil Engineering. 24 (2010). doi:10.1061/(asce)cp.1943-5487.0000027.*
[121] *J. Yang, P. Vela, J. Teizer, Z. Shi, Vision-Based Tower Crane Tracking for Understanding Construction Activity, Journal of Computing in Civil Engineering. 28 (2014). doi:10.1061/(asce)cp.1943-5487.0000242.*
[122] *D. Wang, X. Wang, B. Ren, J. Wang, T. Zeng, D. Kang, G. Wang, Vision-Based Productivity Analysis of Cable Crane Transportation Using Augmented Reality–Based Synthetic Image, Journal of Computing in Civil Engineering. 36 (2022). doi:10.1061/(asce)cp.1943-5487.0000994.*

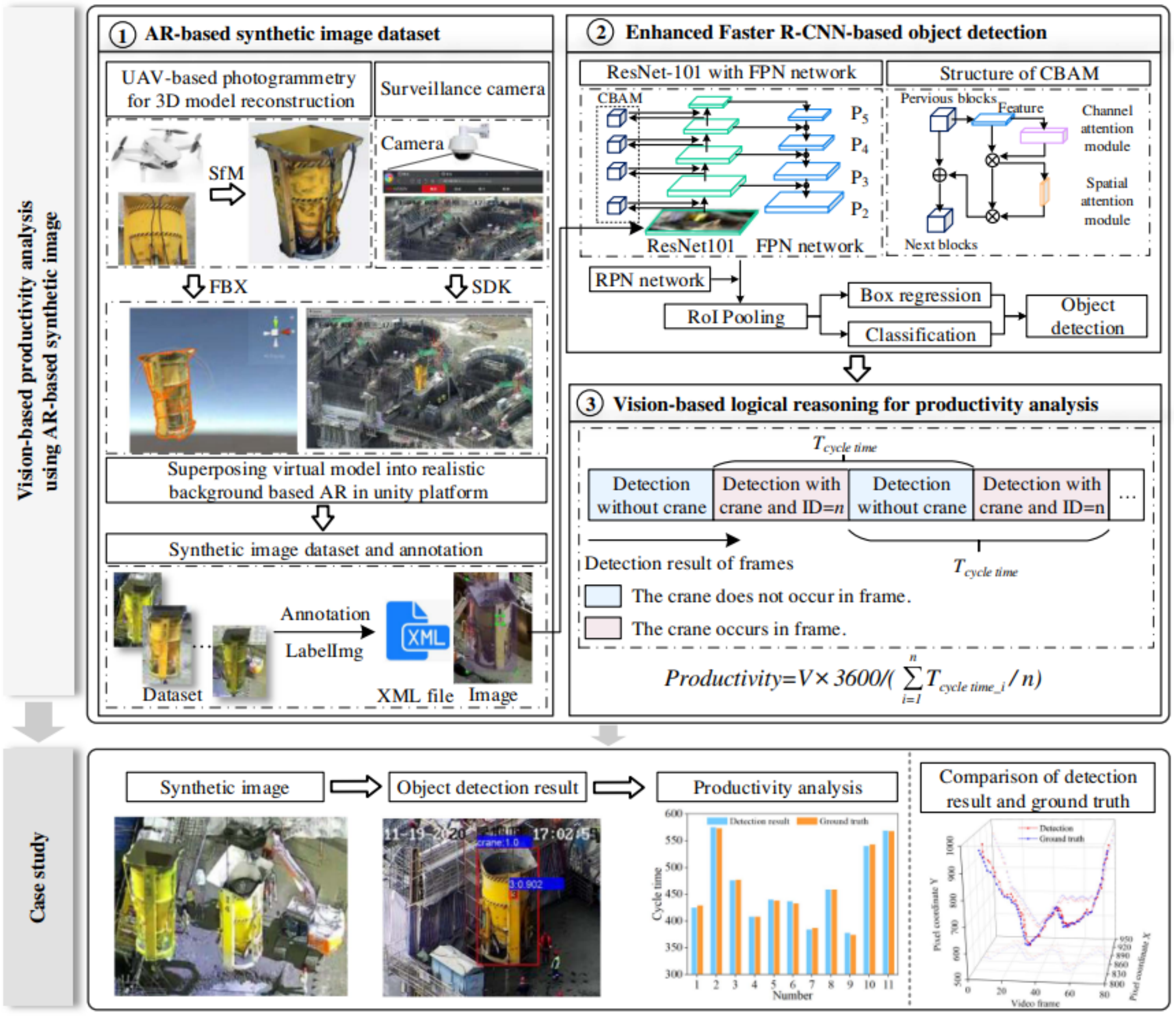


Figure 5.9: A case study of computer-vision-enabled progress monitoring for concrete placing activities[122], other examples can be found in[120,121]

Construction lifts (or elevators) are another important piece of equipment for vertical transportation on construction sites. Carried by carts, non-bulky materials, such as windows,[123] material boxes,[124] painting oil tanks,[88] are moved across floors using construction lifts. To understand the operation of construction lifts (e.g., materials transported and destinations), Costin et al.[123] tagged materials and lifts with RFID tags and deployed readers at lift entrances at multiple levels (as shown in Figure 5.10). The collected information was used to enable productivity evaluation of construction lifts and to quantify the waiting time of materials. Cho et al.[124] attempted to automate lifts' operations by reading RFID tags on materials, retrieving their destination from a local server, and controlling lifts automatically. Attempting to automate both horizontal and vertical indoor transportation of non-bulky materials, Yang et al.[88] developed an automatic cart mover and a remotely-controlled lift to deliver materials in the off-hours without manual handling. As a result, materials were proactively handled hours ahead of their consumption with minimised labour requirements.

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[123] A. Costin, N. Pradhananga, J. Teizer, Leveraging passive RFID technology for construction resource field mobility and status monitoring in a high-rise renovation project, Automation in Construction. 24 (2012). doi:10.1016/j.autcon.2012.02.015.
[124] [C.Y. Cho, S. Kwon, T.H. Shin, S. Chin, Y.S. Kim, A development of next generation intelligent construction liftcar toolkit for vertical material movement management, in: Automation in Construction, 2011. doi:10.1016/j.autcon.2010.07.008.

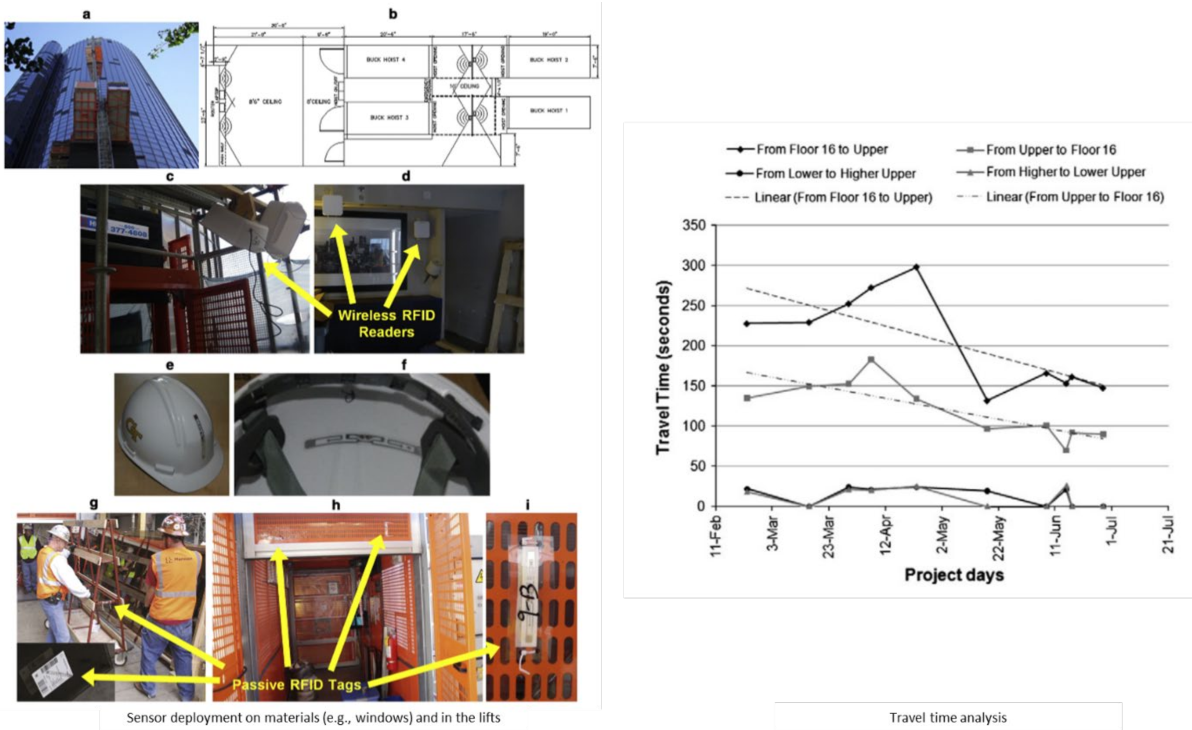

Figure 5.10: A case study of lift tracking[123], other examples (of lift tracking and automation) can be found in [88,124]

In fact, cranes and construction lifts are indispensable means for transporting materials vertically on construction sites. Theoretically, it is possible to understand the flow of most, if not all, onsite materials by monitoring cranes and construction lifts. In light of this, Guven and Ergen [125] attempted to track cranes and lifts as a proxy for masonry works (see Figure 5.11). By constructing an appropriate process model of the masonry works, the operating data of cranes and lifts was linked to their working states, such as transporting loaded masonry block pallets and removing empty pallets to reload masonry blocks. The number of operating cycles and cycle times were further calculated and compared with detailed material delivery plans (e.g., estimated pallet lifting cycles in a working day) to monitor the progress of masonry works.

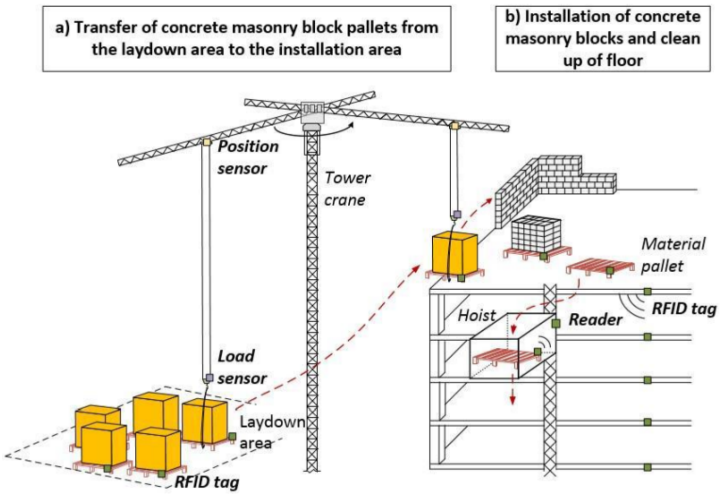

Figure 5.11: Sensor setup for tracking the crane and lift in a masonry work, adapted from[125]

[125] *G. Guven, E. Ergen, A rule-based methodology for automated progress monitoring of construction activities: A case for masonry work, Journal of Information Technology in Construction. 24 (2019).*

Table 5.2 Summary of research works on tracking construction/packaging material handling equipment

Title	Year	Collected data	Tracking mechanism	Technology	Information system	Managerial application/analysis
Vision-based productivity analysis of cable crane transportation using augmented reality–based synthetic image[122]	2022	Presence of concrete buckets Presence of cranes	Capturing concrete buckets with UAV-based RGB-D camera Capturing background with surveillance camera	Computer vision	N.A.	Track cycle time for concrete placing activity in a dam construction
Tracking major resources for automated progress monitoring of construction activities: masonry work case [126]	2021	Load weight on crane hook, angular position of crane boom, crane trolley position, and hook depth Concrete masonry pallets locations (e.g., levels)	Tracking crane with in-built sensors Tracking pallets with passive RFID tags on pallets Readers locate at lift area on different floors	Integrated crane in-built sensors and RFID	A generic prototype application	Track progress and productivity of a selected activity (i.e., masonry works), including the material transportation and material consumption processes
Vision-based system for 3d tower crane monitoring[116]	2021	Displacement of crane jib rotation, cart movement, and hook height	Capturing images with two cameras, mounted on crane jib and cart, respectively	Computer vision	N.A.	Track the movement of tower cranes
Hallway exploration-inspired guidance: applications in autonomous material transportation in construction sites[88]	2021	Obstacles around the cart mover	Coordinating a remotely-controlled lift and an autonomous cart mover via a PC	Laser rangefinders	a local database	Automatically deliver materials in off-hours
A rule-based methodology for automated progress monitoring of construction activities: a case for masonry work[125]	2019	Load weight on crane hook, angular position of crane boom, crane trolley position, and hook depth	Tracking crane with in-built sensors Tracking pallets with passive RFID tags on pallets Readers locate at lift area on different floors	Integrated crane in-built sensors and RFID	Local storage (for sensor data); A central database with manual data transferring	Understand the total number of pallets to the installation area Identify floor to which the pallets are transferred to or removed from Monitor the progress of installation activity completion

[126] *G. Guven, E. Ergen, Tracking major resources for automated progress monitoring of construction activities: masonry work case, Construction Innovation. 21 (2021). doi:10.1108/CI-05-2020-0081.*

Title	Year	Collected data	Tracking mechanism	Technology	Information system	Managerial application/analysis
		Concrete masonry pallets locations (e.g., levels)				Compare of planned vs actual start/end dates and budgeted vs actual work
Smart Construction Objects6	2016	Dimensions, weight, materials, manufacturer, fitting position, floor-ceiling height of prefabricated concrete façade Spatial connection between crane and façade	Capturing crane-material connection with façade in-built Bluetooth module and readers on crane hook	BLE	BIM	Enhance visibility of important components Enable mutual communication between objects (e.g., façade and crane) Connect to BIM for communication
Vision-based tower crane tracking for understanding construction activity[121]	2014	Trajectory of crane Presence of concrete buckets	Capturing videos with fixed camera	Computer Vision	N.A.	Track cycle time for concrete pouring activity for multi-level construction
Leveraging passive RFID technology for construction resource field mobility and status monitoring in a high-rise renovation project[123]	2012	Location of the lift car ID of transported materials	Capturing data with RFID tags on lifts, materials, carts and readers at the lift entrance and working floors	RFID	A generic local database	Track construction lift operations Measure the waiting time of materials and workers Monitor the construction progress through materials delivery
A development of next generation intelligent construction liftcar toolkit for vertical material movement management[124]	2011	Location of lift car ID of transported materials	Capturing data with a lift car equipped with RFID readers with necessary wireless communication functionality and an RFID reader-equipped intelligent mover (IM) that will load/unload the RFID-tagged materials to the lift car	Integrated RFID and ZigBee	A local logistics management server for material delivery plans and a web server for monitoring and analysis	Plan and execute lift operations automatically by reading RFID tags on materials
Computer vision-based video interpretation model for automated productivity analysis of	2010	Presence and locations of concrete buckets	Capturing videos with cameras mounted at a fixed location	Computer vision	A generic application	Monitor the 6 working states of concrete placing (e.g., bucket ready, pour column 1, pour column 2, load bucket, bucket depart) by analysing bucket presence and

Title	Year	Collected data	Tracking mechanism	Technology	Information system	Managerial application/analysis
construction operations120						background to evaluate the productivity of column casting activities
Improving tower crane productivity using wireless technology[118]	2006	Video of the crane hook ID of the lifted load	Filming crane hooks and streaming the video for crane operators Capturing the ID of lifted load by handheld RFID readers	Integrated RFID and surveillance camera	Online server	Enable efficient and effective communication of crane operator and rigging workers
Interpretation of automatically monitored lifting equipment data for project control[117]	2006	The weight on the crane hook Positions of the crane	Capturing the information with in-built sensors	Crane in-built sensors	BIM	Monitor the operating cycle of cranes, with details of each crane action (e.g., loading) A case study of concrete placing is conducted

5.3.4 Capturing installed building elements

Unlike the previous 2 approaches that focus on the process of material delivery, the last strategy detects only the outcome of material delivery, namely whether the materials were installed at the planned location. Using reality capture technologies, the as-is condition of the facility being built is modelled and compared with as-planned models (e.g., BIM models). This comparison identifies already installed building components and highlights the work in progress. In this approach, the as-is models can be developed from point clouds, photos or videos with building components recognised based on their unique shapes, dimensions and surface textures. The as-planned models contain not only product information (e.g., 3D models) but process information (e.g., schedules) so that progress can be automatically monitored by comparing installed items with the schedule.

Technically, retrieving construction progress information from images, videos, or point clouds involves 3 steps: (1) data acquisition, (2) object recognition and (3) deviation detection. Data acquisition involves the photo-taking and laser scanning processes on different platforms, such as trolleys, [127] wearable platforms [128] and stationary platforms. [129] Mounted with laser scanners and cameras, autonomous UAVs and UGVs [130] could capture as-is site data efficiently with enhanced accessibility. Once the data is acquired, location and kinematic data captured by GPS, [131] UWB[127] or IMU[130] are used to register and align the 2D/3D reality capture data with the site coordinate system.

Object recognition retrieves the identification information (e.g., IDs or types of building elements) from 2D/3D reality capture data. There are 2 methods for 2D object recognition (e.g., from photos and videos): (1) On one side, 4D as-planned models are used to benchmark as-is data, where the models are profiled from certain angles to anticipate 'what' should be in the images at a given timeframe. [132], [133] In this way, deviations in construction progress (i.e., absence of objects) can be highlighted. (2) The other method involves machine learning, which recognises different building components (e.g., concrete, bricks, steel components) with object recognition algorithms trained by object templates or a library of pre-classified objects. [134], [135]

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[127] *C. Chen, L. Tang, C.M. Hancock, P. Zhang, Development of low-cost mobile laser scanning for 3D construction indoor mapping by using inertial measurement unit, ultra-wide band and 2D laser scanner, Engineering, Construction and Architectural Management. 26 (2019). doi:10.1108/ECAM-06-2018-0242.*
[128] *Z. Pučko, N. Šuman, D. Rebolj, Automated continuous construction progress monitoring using multiple workplace real time 3D scans, Advanced Engineering Informatics. 38 (2018). doi:10.1016/j.aei.2018.06.001.*
[129] *F. Bosché, M. Ahmed, Y. Turkan, C.T. Haas, R. Haas, The value of integrating Scan-to-BIM and Scan-vs-BIM techniques for construction monitoring using laser scanning and BIM: The case of cylindrical MEP components, Automation in Construction. 49 (2015). doi:10.1016/j.autcon.2014.05.014.*
[130] *K. Asadi, A. Kalkunte Suresh, A. Ender, S. Gotad, S. Maniyar, S. Anand, M. Noghabaei, K. Han, E. Lobaton, T. Wu, An integrated UGV-UAV system for construction site data collection, Automation in Construction. 112 (2020). doi:10.1016/j.autcon.2019.103068.*
[131] *J.S. Álvares, D.B. Costa, R.R.S. de Melo, Exploratory study of using unmanned aerial system imagery for construction site 3D mapping, Construction Innovation. 18 (2018). doi:10.1108/CI-05-2017-0049.*
[132] *M. Kopsida, I. Brilakis, Real-Time Volume-to-Plane Comparison for Mixed Reality–Based Progress Monitoring, Journal of Computing in Civil Engineering. 34 (2020). doi:10.1061/(asce)cp.1943-5487.0000896.*
[133] *M. Golparvar-Fard, F. Peña-Mora, C.A. Arboleda, S. Lee, Visualization of Construction Progress Monitoring with 4D Simulation Model Overlaid on Time-Lapsed Photographs, Journal of Computing in Civil Engineering. 23 (2009) 391–404. doi:10.1061/(asce)0887-3801(2009)23:6(391).*
[134] *K.K. Han, M. Golparvar-Fard, Appearance-based material classification for monitoring of operation-level construction progress using 4D BIM and site photologs, Automation in Construction. 53 (2015). doi:10.1016/j.autcon.2015.02.007.*
[135] *A. Dimitrov, M. Golparvar-Fard, Vision-based material recognition for automated monitoring of construction progress and generating building information modeling from unordered site image collections, Advanced Engineering Informatics. 28 (2014). doi:10.1016/j.aei.2013.11.002.*

Recognising objects in 3D reality capture data has becomne increasingly popular in recent years. There are 3 methods for 3D object recognition (e.g., from point clouds):(1) matching point cloud data with 4D as-planned models, (2) using supervised learning and (3) reasoning with the spatial and contextual relationships of objects. First, matching point cloud data with 4D as-planned models[129], [136], [137], [138] is achieved by clustering the points within one 3D object (e.g., a column). With the advent of BIM, this object recognition method is also referred to as 'scan-to-BIM' or 'scan-vs-BIM',[129] which directly transfers the point cloud to an as-is BIM model. Second, object recognition can be achieved by supervised learning algorithms.[139] Like object recognition from 2D images algorithms, object recognition from 3D point cloud needs object templates or pre-classified object libraries to train the algorithm. Third, the spatial/contextual relationships between objects can be used to label surfaces in point clouds.[140] Such relationships include generic arrangements of building components, such as 'walls are vertical and orthogonal to floors',[141] and contextual knowledge such as the relative size, position, orientation and topology of building components (e.g., windows and façade).[142]

Object recognition methods become increasingly versatile at recognising different installed building elements, ranging from structural components to interior fit-outs. Structural components are often associated with multiple work packages on the critical path. Object recognition algorithms were developed to automatically identify structural columns with different shapes[143] and completion rates[140] in complex construction environments. Further, later studies attempted to recognise structural beams, slabs and walls to report the progress of the structure erection process.[133,136,138] For interior building elements, algorithms were developed to identify lights,[132] doors[128] and cylindrical MEP components,[129] which had more diverse shapes and were located in a more clustered environment than structural components. Combining these efforts, a comprehensive as-is model can be expected to visualise the presence and dimensions of both structural and interior building elements (as shown in Figure 5.12).

[136] *C. Kim, C. Kim, H. Son, Automated construction progress measurement using a 4D building information model and 3D data, Automation in Construction. 31 (2013). doi:10.1016/j.autcon.2012.11.041.*

[137] *P. Tang, E.B. Anil, B. Akinci, D. Huber, Efficient and effective quality assessment of as-is building information models and 3d laser-scanned data, in: Congress on Computing in Civil Engineering, Proceedings, 2011. doi:10.1061/41182(416)60.*

[138] *Y. Turkan, F. Bosche, C.T. Haas, R. Haas, Automated progress tracking using 4D schedule and 3D sensing technologies, in: Automation in Construction, 2012. doi:10.1016/j.autcon.2011.10.003.*

[139] *H. Son, C. Kim, Semantic as-built 3D modeling of structural elements of buildings based on local concavity and convexity, Advanced Engineering Informatics. 34 (2017). doi:10.1016/j.aei.2017.10.001.*

[140] *R. Maalek, D.D. Lichti, J.Y. Ruwanpura, Automatic recognition of common structural elements from point clouds for automated progress monitoring and dimensional quality control in reinforced concrete construction, Remote Sensing. 11 (2019). doi:10.3390/rs11091102.*

[141] *W. Shi, W. Ahmed, N. Li, W. Fan, H. Xiang, M. Wang, Semantic geometric modelling of unstructured indoor point cloud, ISPRS International Journal of Geo-Information. 8 (2019). doi:10.3390/ijgi8010009.*

[142] *S. Pu, G. Vosselman, Knowledge based reconstruction of building models from terrestrial laser scanning data, ISPRS Journal of Photogrammetry and Remote Sensing. 64 (2009). doi:10.1016/j.isprsjprs.2009.04.001.*

[143] *C. Zhang, D. Arditi, Advanced progress control of infrastructure construction projects using terrestrial laser scanning technology, Infrastructures. 5 (2020). doi:10.3390/infrastructures5100083.*

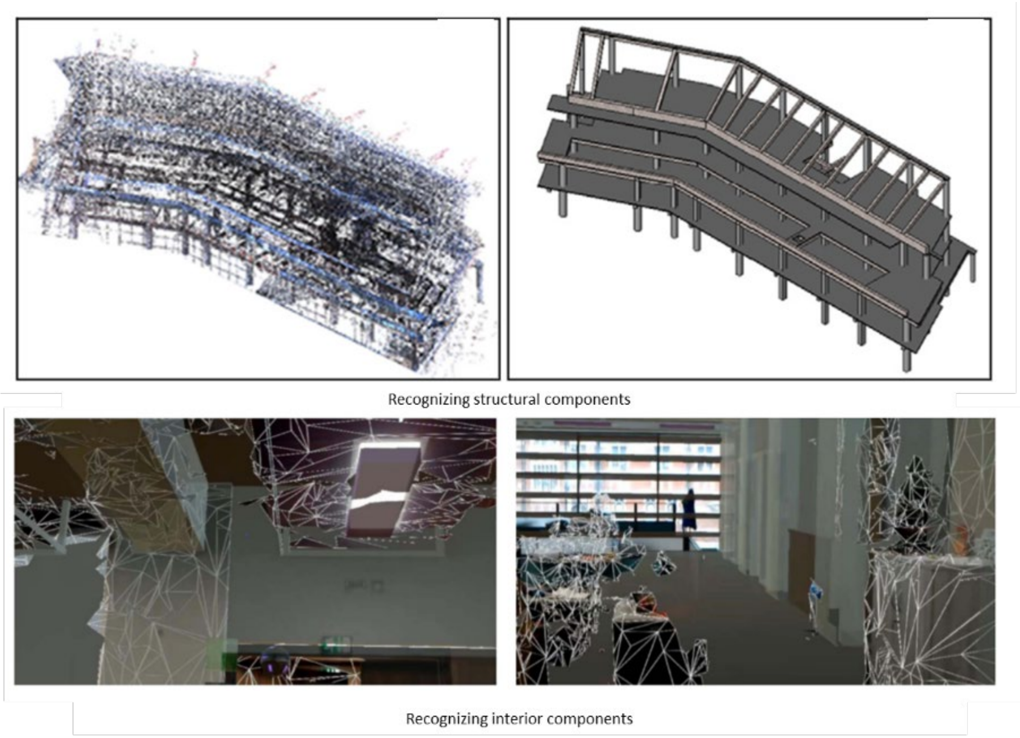

Figure 5.12: Object recognition for structural components and interior building elements, adapted from Kim et al.[136] (top) and Kopsida and Brilakis[132] (bottom), respectively

Deviation detection is achieved by comparing the as-is and as-planned models. There are 2 types of deviations: (1) dimensional deviations, referring to the geometric differences from building elements' designed positions or dimensions, and (2) schedule deviations, which are retrieved from the presence/absence of building elements. Theoretically, detecting dimensional deviations does not necessarily require recognising the building elements. Deviation detection was achieved by comparing the geometries of the as-is model and the as-planned model.[128] Nevertheless, recognising building components enriches the as-is models, which, in turn, enables deviation detection against the rules (e.g., design codes and standards). For example, dimensional deviations from column design codes, such as column height restrictions and rebar boundary conditions, were identified for quality management.[140] By contrast, the schedule deviations were identified by constantly monitoring the installation status of building elements.[136] With status information, timely updates of the construction progress were made to formulate an 'as-is schedule'.[138] In some cases, as-planned and as-is costs can be further linked to the as-is schedule to perform an Earned Value Analysis – constituting a project performance baseline in terms of budgets.[133,140] Visualising the progress and budget information (see Figure 5.13) is expected to support site managers' decision making to optimise project productivity performance.

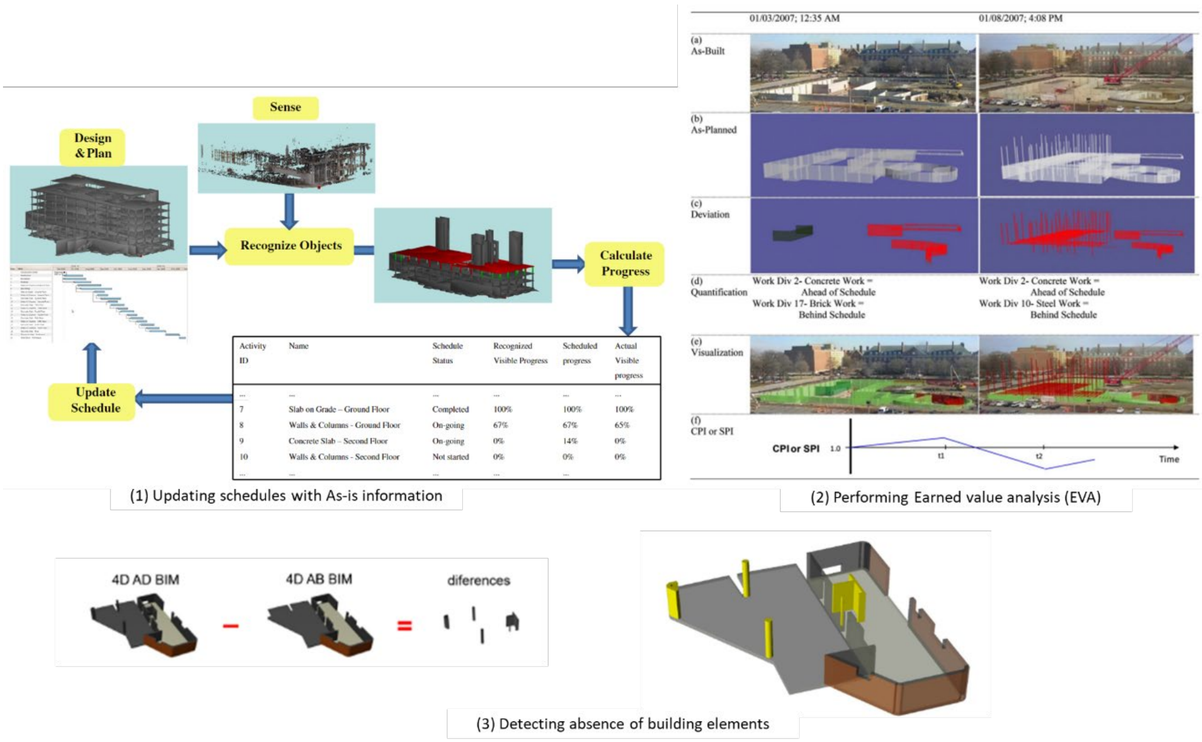

Figure 5.13: Deviation detections: (1) updating schedules with as-is information[138]; (2) measuring EVA performance metrics[133]; (3) identifying deviation of construction progress[128]

However, a significant problem is that the object recognition and deviation detection processes rely heavily on the level of detail of the as-planned product and process models, such as 3D design models, work breakdown structures and cost estimating schemes. Usually, in construction practices, only the general contractor schedule contains major activities associated with structural components. The incomplete planning information decreases the accuracy of the construction progress estimation.

Further, this material tracking strategy has an obvious limitation – it lacks details of the material flow. By monitoring the presence of building elements, site managers may be aware of the schedule deviations but struggle to identify their causes (e.g., bottlenecks in the material delivery process). Meanwhile, technical challenges for computer vision/LiDAR technologies should be considered as well, such as poor illumination conditions, the harsh weather, distortion/occlusion and the need for sensor repositioning and data preparation. These challenges potentially reduce the cost-effectiveness of adopting this strategy in real-world projects. Table 5.3 summarises research that embraces this material tracking strategy.

Table 5.3 Summary of research works on tracking target building elements

Title	Year	Collected data	Tracking mechanism	Technology	Info. System	Managerial application
Real-time volume-to-plane comparison for mixed reality–based progress monitoring[132]	2020	Columns, beams, ventilations, panels, and lights in an indoor environment	Capturing 2D images and depth information with wearable RGB-D sensors (on an AR device)	RGB-D sensor	BIM	Capture complex indoor environment (e.g., interior fit-outs) with wearable AR devices and compare the as-is 3D model with as-planned 3D model to monitor construction progress
An integrated UGV-UAV system for construction site data collection[130]	2020	3D mapping of the indoor environment	Capturing 2D occupancy map with LiDAR and 3D segmentation map with RGB camera on IMU-enabled UGV; UAV's front RGB camera as an external eye for UGV to scan inaccessible area for the UGV	Integrated IMU, LiDAR, and RGB cameras	N.A.	Enable an automated 3D mapping method with self-navigated UGV and UAV
Advanced progress control of infrastructure construction projects using terrestrial laser scanning technology[143]	2020	Geometry and location of columns with different shapes	Capturing point clouds with stationary laser scanners	LiDAR	N.A.	Monitor the progress of column installation in large horizontal infrastructure (e.g., dams and bridges)
Automatic recognition of common structural elements from point clouds for automated progress monitoring and dimensional quality control in reinforced concrete construction[140]	2019	Geometry information of cast-in-situ columns, floor and rebars	Capturing point clouds with stationary laser scanners	LiDAR	BIM	Enable the automated color-coding for visual representation of progress in activity level; Generate earned value analysis; Apply dimensional quality control to identify problems such as violations of rebar boundary conditions or column height restrictions;
Development of low-cost mobile laser scanning for 3d construction indoor mapping by using inertial measurement unit,	2019	3D point cloud of the indoor environment	Capturing 2D point cloud with the low-cost laser scanner on a trolley; Tracking the trolley with UWB and IMU sensors;	Integrated IMU, LiDAR, UWB	N.A.	Capture 3D point clouds with low-cost 2D laser scanner and RTLS sensors

Title	Year	Collected data	Tracking mechanism	Technology	Info. System	Managerial application
ultra-wide band and 2d laser scanner127						
Exploratory study of using unmanned aerial system imagery for construction site 3d mapping[131]	2018	3D models of construction site and the building	Digital camera on GPS-enabled UAV	Integrated GNSS and RGB cameras	N.A.	Generate 3D models from photos of construction sites
Automated continuous construction progress monitoring using multiple workplace real time 3d scans[128]	2018	Presence of many types of building elements, including door, partition doors, slabs and walls	Capturing RGB-D data from wearable sensors mounted on workers' helmet in predesigned workspaces; Local coordinate system is inbuilt into the sensor;	RGB-D	BIM	Constantly monitor construction progress (e.g., in a time interval of hours) in predefined workplaces
Appearance-based material classification for monitoring of operation level construction progress using 4D BIM and site photologs[134]	2015	Material classification	Capturing colour and texture information from RGB cameras and manually align BIM objects with photos	Computer vision	BIM	Infer building progress from material information
The value of integrating scan-to-BIM and scan-vs-BIM techniques for construction monitoring using laser scanning and BIM: The case of cylindrical MEP components[129]	2015	Presence of cylindrical MEP components (e.g., pipes)	Capturing point clouds from stationary laser scanners at different locations along corridors	LiDAR	BIM	Recognising the BIM objects in as-planned models that have been constructed and the progress rate
Vision-based material recognition for automated monitoring of construction progress and generating building information modelling from unordered site image collections[135]	2014	Material classification and shape polygon	Capturing colour and texture information from RGB cameras	Computer vision	N.A.	Identify materials and shape polygon from RGB cameras
Automated construction progress measurement using a 4D building information model and 3D data[136]	2013	Presence of concrete building structural components such as columns and beams	Capturing point clouds from a stationary laser scanner	LiDAR with RGB camera	BIM	Integrate activity finish date, status, and actual progress rate into 4D BIM model

Title	Year	Collected data	Tracking mechanism	Technology	Info. System	Managerial application
Skeleton-based 3D reconstruction of as-built pipelines from laser-scan data143F143F[144]	2013	Presence of straight pipes, elbows, and tee pipes	Capturing point clouds from a stationary laser scanner	LiDAR	N.A.	Reconstruct the entire pipeline system to generate a reliable 3D pipeline models
Automated progress tracking using 4d schedule and 3d sensing technologies[138]	2012	Presence of concrete columns, walls, beams, and slabs	Capturing point clouds from a stationary laser scanner	LiDAR	As inputs: Product model (a 3D CAD building structure model and a Revit model with columns, walls, beams, and slabs) Process model (schedules of 20 construction activities in MS project format) Up-to-date schedule as output	Automatically update/calibrate the schedules based on automated object recognition, which meets/exceeds the performance of manual investigations
Efficient and effective quality assessment of as-is building information models and 3D laser-scanned data[137]	2011	Presence and dimensions of exterior faces of a building (e.g., roof and facade)	Capturing point clouds from a stationary laser scanner	LiDAR	BIM	Automatically compare as-is model and detailed design BIM model to acquire dimensional deviations for quality assurance (QA)
Visualisation of Construction Progress Monitoring with 4D Simulation Model Overlaid on Time-Lapsed Photographs[133]	2009	Presence of major building elements (i.e., structures and facades)	Capturing time-lapsed photos from fixed RGB cameras and mapping photos with views of as-planned 3D models	Computer vision	As inputs: Product model (IFC 3D model) Process model (working schedules and sequences) Cost model (estimated/performed cost) Colour-coded pictures showing progress as output	Monitor progress discrepancies and value increments in earned value analysis (EVA)

[144] J. Lee, H. Son, C. Kim, C. Kim, Skeleton-based 3D reconstruction of as-built pipelines from laser-scan data, Automation in Construction. 35 (2013). doi:10.1016/j.autcon.2013.05.009.

5.4 Benefits and challenges of automated onsite material tracking

5.4.1 Benefits of the 3 tracking strategies

The traditional material management method suffers from tedious material searching, counting and inspection procedures. To address these issues, research studies tracked construction materials automatically. Three tracking strategies were developed, which describe the flow of tracked materials from different perspectives: tracking materials, the material handling equipment and installed building elements.

The first strategy (see Section 5.3.2) detected the presence of tracked objects at pre-defined checkpoints (e.g., the site access, the storage area and the workspace). Detection can be fully automated (e.g., deploying a sensor system on site) or semi-automated (e.g., using handheld RFID read/write devices) to update and communicate material locations and statuses. The primary benefit of such tracking practices is to enhance the visibility of materials. In the reviewed literature, enhanced visibility led to better-coordinated material handling (e.g., avoiding multi-handling in the laydown area), data-driven material procurement (e.g., material ordering), improved inventory management (e.g., reduced time wastes for material searching in the laydown area), and a coordinated supply chain (e.g., Just-in-time delivery). Under certain circumstances, the enhanced visibility of materials can improve the control over project delivery, for example, by using the installation statuses of prefabricated building components to reflect construction progress. Additionally, the relationships between materials and work packages, trades or job sites could be revealed by material tracking, which is knowledge for future projects that enables leaner construction practices such as kitting logistics.

Tracking material handling equipment is an alternative strategy for material tracking (see Section 5.3.3). This tracking strategy considers critical material handling equipment (i.e., cranes and lifts) as checkpoints for the transported materials and integrates material information and equipment poses/motions into a unified database. This strategy not only identifies certain logistics statuses of construction materials (e.g., material installed by cranes or transported to working levels by lifts) but evaluates the productivity of material handling processes (i.e., the cycle times of crane/lift operations). Thus, stakeholders can quantify the waiting time of materials or workers and recognise the bottlenecks in the material handling processes (i.e., the causes of material-worker mismatch). In this way, non-value-added activities can be reduced by optimising crane/lift operations. Additionally, this strategy is more flexible in progress tracking (compared with the first strategy), because it applies to both prefabrication and cast-in-situ scenarios. For prefabricated components, crane operations indicate their installation status; while for some bulk materials (e.g., concrete and masonry blocks) and associated construction activities (e.g., concrete placing and masonry works), progress can be tracked by tracking cranes/lifts and their accessories such as concrete buckets and masonry pallets. Hence, on top of the managerial applications of the first strategy, this strategy further enables the productivity evaluation of cranes/lifts and progress tracking for stick-built projects.

While the first 2 strategies focus on material transportation processes, the third one monitors the installation status of materials by capturing the installed building elements (see Section 5.3.4). It tracks the presence of building elements to generate as-is models, which are compared with as-planned models to detect quality issues (i.e., dimensional deviations) and delays (i.e., absence of elements). Although this strategy often involves expensive surveying equipment, it allows for object recognition of both indoor and outdoor elements. With the advent of BIM, this strategy can be highly integrated with BIM tools and the BIM-enabled design/engineering/construction process.

Although the specific applications of the 3 strategies are slightly different, they share similar benefits to construction management. The sensing technologies they employ could automate data management tasks (i.e., data collection, integration and communication) in existing material management and progress management practices. Further, these technologies capture a large volume of real-time data with a fine spatial granularity, which is hardly possible with traditional manual data collection. This data provides valuable insights about site operations, which will significantly improve timeliness and productivity.

5.4.2 Technology and implementation challenges

Despite the prominent evidence of technology advancements, automated, sensor-based onsite material tracking still faces various challenges, which can be categorised into (1) technological challenges and (2) implementation challenges.

Technological challenges related to sensing technologies

Technological challenges refer to the issues related to sensors, data processing algorithms and information systems that collect, process and integrate as-is/as-planned data. For example, some technologies require tedious setup (e.g., programming/tagging for RFID and BLE), frequent sensor repositioning for unblocked lines-of-sight (e.g., photogrammetry), specialised operations (e.g., laser scanning) and regular maintenance (e.g., battery replacement). These activities usually incur additional costs on sensor hardware, labour hours and training. Second, substantial investment in algorithm development is required to accurately transform raw data into valuable information for construction managers. Adjusting and tuning algorithms is often needed to interpret equipment behaviour or recognise building elements based on unique project settings (e.g., different material handling equipment available, site layouts and illumination conditions). Third, for some sensor strategies (e.g., material handling equipment tracking), more than one sensing technology is required. Thus, to integrate data from various sources, a complex information management system that can handle big data of various modalities is essential.

Implementation challenges

Implementing material tracking systems present various challenges throughout a project’s planning, design and construction phases. This section discusses 2 key aspects: the impact of production methods and the requirement for project information.

- ***Impact of production methods***

The production method adopted by a project is another factor influencing the implementation of a tracking system. Materials in traditional production methods (e.g., stick-built) may not be suitable for sensor-based tracking due to the low level of assembly. Typically, as the level of prefabrication increases, the cost-effectiveness and applicability of sensor-based material tracking will be higher. Nevertheless, selecting a production method is a complex decision and usually occurs in the early planning stage, way before the builder and supply chain stakeholders are involved. This means material tracking technologies must be determined after the production method is finalised and often after the builder and suppliers are determined. It is suggested that material tracking is considered a mandatory service from the beginning of the planning stage to maximise stakeholder buy-in.

- ***Requirement for project information***

Project information (such as design models, schedules, site layout plans) is essential for material tracking systems to interpret sensor-captured raw data for analysing operation processes and site conditions. For different tracking strategies, the demands for project information vary. For example, direct material tracking requires site layout, at least, to plan hardware setup (e.g., sensor locations, power supply); tracking material handling equipment involves accurate building models that provide materials details so equipment utilisation data can be correlated to material handling status. To capture installation progress, building models and installation schedules must exist. For the first strategy (i.e., tracking materials), material planning information is needed to anticipate the flow of construction materials, such as purchasing orders and the Bill of Quantity. In reality, however, such project information is not always available or to the desired level of detail and accuracy. In other cases, information exists on paper (e.g., drawings, specifications) and will require human translation to the sensing systems. Figure 5.14 illustrates the project information required by the 3 tracking strategies.

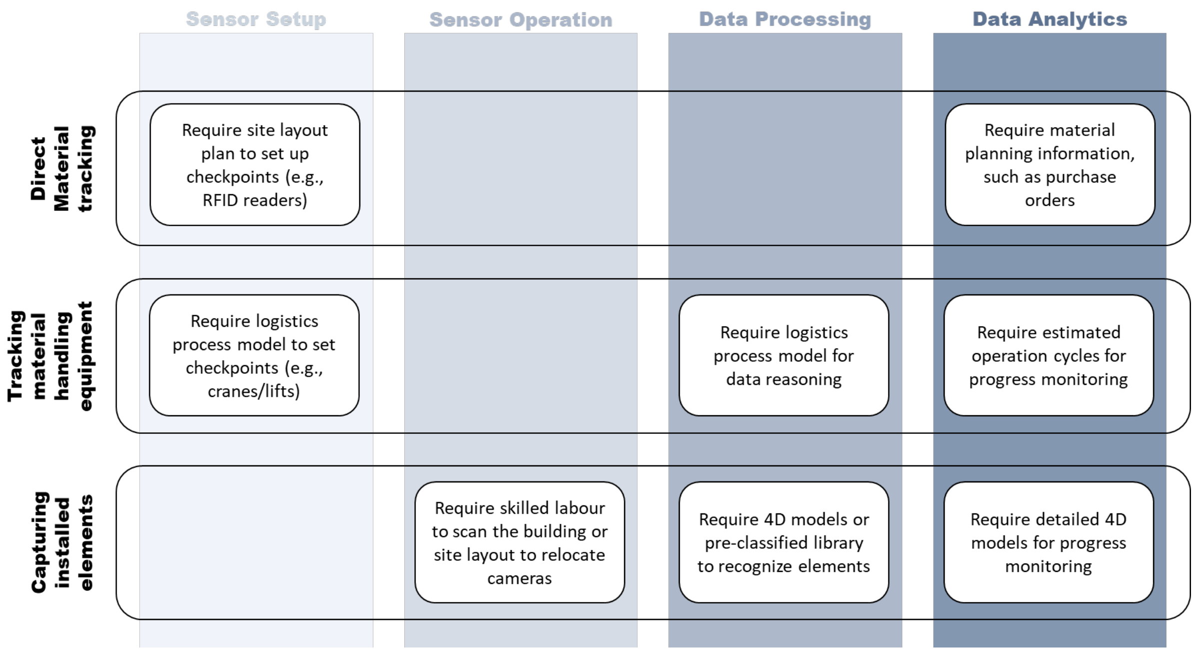

Figure 5.14: Requirements for project information in different tracking strategies

5.5 Challenges and future directions

This section categorises the challenges and potential future research directions for 3 main strategies: tracking materials, transportation/ logistics, and tracking material on-site.

Challenges in tracking materials

- Labelling small materials for tracking is difficult because we need tiny labels or sensors, which may not always be feasible.
- We have to determine the optimal placement strategies for placing labels, especially for materials that must be reused and repurposed through the process (e.g., reinforcement bars or timber that may be cut on-site and used later).
- Although specialised barcode labels are available for extreme conditions, there may be situations where tracking materials (in manufacturing) may not always be feasible.

Challenges in transportation/logistics

- We may lose real-time tracking information during shipping and transportation if we do not have GPS and cellular coverage. Both technologies are essential for capturing location information and transmitting the information to a cloud-based service.
- In addition, we may lose information if the sensors are faulty because of battery issues or ageing. In addition, the data may arrive corrupted because of sensor bias. We need algorithms to ensure the data is reliable and accurate, and to remove data bias.
- Further, the data must go through many subsystems, often from one service provider to another and from one technology platform to another. Hence, interoperability and compatibility of different subsystems is critical to ensure the data arrives correctly and within the time bounds.

Challenges in tracking materials on site

- Relabelling materials after use (remaining/unused materials) on site remains a concern and must be done manually. This may require training and other software/systems to keep track of materials.
- A related challenge is a manual error caused by identifying materials incorrectly and updating the incorrect information into the BIM models.

5.6 Conclusion

Digital twins have revolutionised the construction industry and are more significant with the long lifecycle of built assets. Future construction will have sensors for real-time tracking and monitoring materials, equipment, vehicles and people. Onsite material tracking will be ubiquitous, including raw material utilisation via sensors. This report reviewed sensor technologies for tracking materials, workers, equipment, vehicles and construction progress. The report reviewed the state-of-the-art sensor technologies used in product identification and tracking in the construction industry. In addition, the report covered industry examples of using these technologies in real-world use-cases. The report also included vital findings, challenges and future directions. The report provides industry practitioners with the most appropriate solution for their industrial application in product identification and tracking of materials.

Chapter 6 State-of-the-art in information management systems and blockchain technology for traceability

Authors: Joseph Liu, Siyu Chen, Alistair Barros

6.1 Introduction

Since Satoshi Nakamoto [145] invented blockchain and introduced Bitcoin in 2008, this decentralised and trustless peer-to-peer (P2P) technology has become one of the primary revolutionary forces in business. It is predicted to be widely used by many industrial and service sectors. Specifically, the current worldwide construction industry is interested in blockchain technology because of its potential to improve construction data's traceability, transparency and immutability while also enabling cooperation and trust throughout construction supply chain management (CSCM). [146]

A building project often involves a complicated and dispersed supply chain. For example, shipping prefabricated modules to Melbourne for a small-scale building project may be more than 1,000 km from somewhere else in Australia and may involve more than 150 workers. Accountability is required to ensure the exchange of accurate data on quality, safety, progress, costs, resources and payments. Managing such a fragmented supply chain requires collaboration. [147]

Although some modern supply chain management platforms (SCMPs) have long been committed to reducing costs, increasing efficiency, optimising resources and eradicating fragmentation in the industry, accountability and collaboration are still lacking, which results in disputes, cost overruns, decreased productivity and accidents. [148] For instance, different suppliers may use different supply chain management systems and tracking methods to track their construction materials in one construction project. Integrating these data from different systems and providing accurate and timely information is still a problem.[149] It can affect the overall efficiency of the construction project. Blockchain technology can address current issues by making the construction supply chain (CSC) transparent, traceable and irreversible for all project participants. While we are yet some years away from commercialising blockchains, the technology's future appears bright.

Academic papers about blockchains in the CSC are still scarce. However, we will likely witness a spike in blockchain publications that can offer various applications for the CSC, transport and logistics in the coming years. For instance, Saberi et al. [150] explored the main barriers to deploying blockchain technologies, especially smart contracts, to satisfy supply chain management (SCM) goals. Kshetri [151] utilises a

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[145] *Nakamoto, S.: Bitcoin: A peer-to-peer electronic cash system. Decentralized Business Review p. 21260 (2008)*
[146] *Qian, X.A., Papadonikolaki, E.: Shifting trust in construction supply chains through blockchain technology. Engineering, Construction and Architectural Management (2020)*
[147] *Lin, Q., Wang, H., Pei, X., Wang, J.: Food safety traceability system based on blockchain and epcis. IEEE Access 7, 20698–20707 (2019)*
[148] *Lu, W., Li, X., Xue, F., Zhao, R., Wu, L., Yeh, A.G.: Exploring smart construction objects as blockchain oracles in construction supply chain management. Automation in Construction 129, 103816 (2021)*
[149] *Cheng, J.C., Law, K.H., Bjornsson, H., Jones, A., Sriram, R.: A service oriented framework for construction supply chain integration. Automation in construction 19(2), 245–260 (2010)*
[150] *Saberi, S., Kouhizadeh, M., Sarkis, J., Shen, L.: Blockchain technology and its relationships to sustainable supply chain management. International Journal of Production Research 57(7), 2117–2135 (2019)*
[151] *Kshetri, N.: Can blockchain strengthen the internet of things? IT professional 19(4), 68–72 (2017)*

multiple case study methodology to examine the influence of blockchain on different aspects of supply chain management objectives by presenting successful industry examples for each purpose. Moreover, Babich and Hilary [152] provide an in-depth examination of blockchain technologies in supply chain management and their prospective applications in this sector, which include data aggregation, supply chain risk management and inventory management. Further, firms such as Deloitte, Mckinsey and Amazon are paving the way for professionals and academics into the world of blockchains. Several use cases in the CSC demonstrate the untapped potential of blockchain technology, like freight monitoring, mobility as a service and increased supply chain transparency. [153,146] This chapter contributes to these efforts by summarising recent scholarly discussions, industrial use cases and potential future developments.

We tried to address the following research questions:

1. What are the weaknesses in existing information systems?
2. What are the challenges for blockchain technologies in the supply chain?
3. How does blockchain technology change the CSC, and in which aspect or dimension?
4. Apart from the present use cases, what more uses and research streams are possible for blockchains in the CSC?

6.2 Weaknesses in existing information systems

Systems contextualisation

Given the complexity of construction processes – seen through the long-running lifecycle of building projects and the diversity of providers, suppliers and stakeholders – we provide our understanding of the construction domain and digital systems used. Understanding construction, even at a general level, exposes important implications for traceability. It broadly contextualised our data gathering, although it should be understood that no prior context or assumptions directly influenced the questions posed to interviewees.

Although the processes for many domains (e.g., retail) can be understood, at the highest level, through a singular value chain, construction comprises multiple perspectives and value chains.

In the first place, the inception and establishment of construction projects occur through a requirements analysis featuring business needs, cases and feasibility studies. These are analysed through a variety of analysis documents, drawings and specifications (e.g., conceptual design prepared by designers and architects), leading to detailed design specifications (e.g., product specifications by architects) and engineering detailing (e.g., engineering plans developed by civil engineers). The various drawings and specifications are developed through computer-aided design software tools and benefit from integration with Building Information Modelling (BIM) systems. In particular, BIM systems provide object types, referred to as digital twins, and relationships corresponding to different elements on drawing models. They allow

[152] Babich, V., Hilary, G.: What operations management researchers should know about blockchain technology. SSRN Electronic Journal. Available at: http://dx. doi. org/10.2139/ssrn 3131250 (2018)
[153] Casey, M.J., Wong, P.: Global supply chains are about to get better, thanks to blockchain. Harvard business review 13, 1–6 (2017)

the products, components and materials (including their structural breakdowns) to be linked to the objects, which provide the structural details and conditions of construction and use. Moreover, the objects (digital twins) can be defined at different levels of prescription, from general structural detailing to detailing that corresponds directly to materials supplied in the market. Hence, BIM systems provide a standard data reference and integrity for construction drawings and specifications as well as for the processes used to develop them.

The design and structural detailing for construction projects falls within the demand value chain. Two broad and concurrent triggers flow from this phase of the value chain. The first is production planning, which involves developing and approving a project plan or project specification. This details the measurable construction line items within time periods and budget allocations. It also specifies supply and deliver to site points for materials, engagement of contractors and subcontractors through designated trades and roles, and reporting and auditing protocols. The second is the procurements and fulfilments activities through which the supply for materials includes requisitioning and approvals, tenders and quotations, singleton and cyclic delivery, invoicing and payments.

Both BIM and enterprise resource planning (ERP) systems are relevant for these 2 phases of the value chain. Both systems provide back office processes to generate production plans and so overlap. BIM processes are more tightly coupled to construction specification processes, while ERP systems are broad-ranging in terms of enterprise back office support, integrating processes for human resource management, financial and management accounting, asset management etc.

Regardless of which system is preferred for production planning, BIM data and processes must be integrated with those of ERP systems, given ERP systems are used for the core administrative processes of the construction ‘enterprise’ – i.e., managing procurements and fulfilments, accounting and payments. Importantly, the level of objectification across BIM and ERP systems is different. BIM objects are more fine-grained being related to drawing and specification objects, while for ERP systems, objects are related to assets. For example, an individual window element is regarded as a material/asset in an ERP system while in a BIM system, the window and its elements such as glass panels, metal wrapping fittings and screws are different objects, with distinct structural specifications, which are composed together.

Fulfilment (supplier to delivery) activities fall into a supply-side value chain. For construction projects, materials and composite parts of construction typically require offsite, near-site or onsite manufacturing, in line with contemporary trends of modular manufacturing. While ERP systems are instrumental for manufacturing processes, domain-specific manufacturing tools are also utilised. Moreover, the supply side processes are supported by further enterprise systems: supply chain management systems (SCM) and transportation management systems (TMS). The procurements side is coordinated by contractor/client organisations while fulfilment is coordinated by contractor and tier 1/2/3 suppliers depending on the materials involved. Although the fundamental materials being ordered, quoted for, supplied and delivered carry one-to-one object alignment, instrumental objects such as purchase orders, shipment orders, containers, invoices and payments combine materials in different ways for different administrative and service delivery purposes. Hence, one-to-many, many-to-one, and many-to-many object correlations apply across the supply chain processes, further compounding the meaning, perspective and scope of traceability.

Construction work entails merging demand and supply chain chains, leading to a delivery chain. This is where project plans and procurement/fulfilment processes must be synchronised so scheduled work can proceed, with the required human and equipment resources as well as building materials in place. Construction, being essentially physical and human-collaborative, carries physical work, which is periodically tracked through administrative processes. That is, BIM and ERP systems have distinct administrative roles – BIM/ERP is used for project management and ERP is used for payments, invoice and interfacing to supply and manufacturing processes. Hence, traceability for construction activities also must qualify whether it involves physical tracing on construction sites or tracing through administrative processes and their supply side integration.

Late payments

A recent study by BACS Payment Services showed 75% of UK businesses wait a month beyond their stipulated contract terms before being paid.[154] UK companies claimed this is the greatest threat to their survival. Some companies are forced to close due to a lack of working capital. Late payments have negative consequences up and down the supply chain.[155] It is difficult for clients and contractors to complete their projects on time, on budget and on spec. And if they send a contractor to the wall, numerous projects may be jeopardised. Deteriorating reputations and relationships and negative effects of creditworthiness and finance cause the productivity of construction supply to plummet. Also, construction companies in the UK today spend an average of 130 hours per year chasing late construction payments.[154]

Switching to advanced information systems such as blockchain-based applications may prevent late payment. Many late payment bottlenecks would be eliminated if all contract parties could operate from the same system with the same data. Digital technology is critical to reaching this goal.

By taking advantage of blockchain and cloud technologies, different participants on the CSC can conduct payment processes more efficiently and collaboratively due to using a single platform. For example, SAP (a supply chain management service provider)[156] is trying to use blockchain technology to improve the efficiency of payments and cross-company collaboration for each partner in its platform.[157] They created a shared digital ledger among supply chain partners and automated making prompt payments to other partners on the chain if a certain number of terms in contracts are met. By using blockchain technology, companies can increase profitability, and everyone has real-time visibility of the payment process from any location. It also can eliminate the requirement for endless reconciliations, spreadsheets, heated phone calls and email trails.

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[154] https://uk.payapps.com/blog/late-payments-in-construction-the-supply-chain-domino-effect
[155] Hamledari, H., Fischer, M.: Role of blockchain-enabled smart contracts in automating construction progress payments. Journal of Legal Affairs and Dispute Resolution in Engineering and Construction 13(1), 04520038 (2021)
[156] https://www.sap.com/hk/products/supply-chain-management/supply-chain-planning.html
[157] https://supplychaindigital.com/technology-4/sap-introduce-blockchain-supply-chain-platform

Locating materials

Suitable materials management is crucial for middle- to large-sized construction projects to maximise project and productivity performance. [158] Missing critical construction materials leave construction workers idle, and makes it difficult to complete projects on schedule. When vital materials are lost, the consequences can be devastating. One of the main challenges in managing construction equipment and materials is tracing and tracking them through the supply chain and knowing where they are on the site.

Fortunately, emerging technology can now automatically predict the location of materials to within metres. For example, some studies show using the QR code scanning function can track materials such as steel beam for every checkpoint.[26] Using RFID or other IoT sensors can also track large construction equipment such as cranes or elevators.

However, these methods are still not perfect and can be improved. For instance, using QR codes may not accurately track materials because this method needs human involvement. [159] After scanning the QR code, some construction workers may input the wrong information for certain construction materials. Such information will be uploaded to a centralised supply chain system later, and these errors can affect the accuracy of the tracking material. Moreover, different suppliers may use diverse tracking methods or systems, so the project owner may not be able to track all construction materials through one system. [160]

Sensor data

In recent years, researchers and industry experts have explored the potential of computing technology, data sensing and information modelling to enhance material tracking and project planning in construction. They have built new industry paradigms and standards for decision making within the lifecycle of projects.[149,160, 161] This proliferation of sensor data in project implementation, planning, control and monitoring can be found in most project types because the technology has become more affordable and ubiquitous.

Currently, collecting timely and adequate project data on the CSC requires more than one class or type of sensor to be applied to a sensor network (or grid). [162] Data transmitted and collected through single sensors over middle and large areas may suffer from latency, loss and reliability issues. Due to technological shortcomings, most sensors cannot attain 100% data quality dependability. [163] As a result, instantaneous usage of such data may result in problems. One author identified several factors that may lead to noise in the data collected. [164] Most of the elements are due to machine

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[158]Benachio, G., Freitas, M., Tavares, S.: Green supply chain management in the construction industry: A literature review. In: IOP Conference Series: Earth and Environmental Science. vol. 225, p. 012011. IOP Publishing (2019)
[159]Akinade, O.O., Oyedele, L.O.: Integrating construction supply chains within a circular economy: An anfis-based waste analytics system (a-was). Journal of Cleaner Production 229, 863–873 (2019)
[160]Kasim, N.: Intelligent materials tracking system for construction projects management. Journal of Engineering & Technological Sciences 47(2) (2015)
[161]Shrestha, P., Behzadan, A.H.: Chaos theory–inspired evolutionary method to refine imperfect sensor data for data-driven construction simulation. Journal of Construction Engineering and Management 144(3), 04018001 (2018)
[162]Althoubi, A., Alshahrani, R., Peyravi, H.: Delay analysis in iot sensor networks. Sensors 21(11), 3876 (2021)
[163]Lanko, A., Vatin, N., Kaklauskas, A.: Application of rfid combined with blockchain technology in logistics of construction materials. In: Matec Web of conferences. vol. 170, p. 03032. EDP Sciences (2018)
[164]Korpela, K., Hallikas, J., Dahlberg, T.: Digital supply chain transformation toward blockchain integration. In: proceedings of the 50th Hawaii international conference on system sciences (2017)

or human error, or measurement error because of the physical limitations of sensors that result in truncation error. For example, a sensor in an RFID tag can stop working for a while, causing gaps in data collection.[161] The sensor may oversample, which usually happens after sensor freezing, and can lead to faster data collection to compensate for the missing data and create redundancy. Further, one study claimed that using IoT devices and technologies to track construction materials has security issues. [165] For example, RFID sensors can easily be breached, and adversaries can also collect information on construction material from these sensors.[161, 166] Lastly, different suppliers may use various IoT sensors to track materials. It can also be challenging to clean and correlate data and then transmit it to a unified supply chain management platform.

Data interoperability

Data interoperability is becoming more critical in modern CSCM because of trends in competition and cooperation.[159] However, there are a few challenges for data sharing and integration. First, the data sharing format is different among diverse supply chain partners in a construction project. Having a data standard is essential in such a context. Except for the GS1 standards,[167] deploying one standard for all participants in the CSC is becoming increasingly challenging. Different partners have their concerns for their data. Second, there are questions about how the data or information could be effectively and securely transferred between companies. Traditional communication methods seem inadequate to provide reliable, quick, seamless and secure data sharing. More effective and efficient communication intermediaries or channels must be deployed. Third, there are issues with order-oriented and product-oriented data. Generating, gathering and appraising data in the exchange process are aspects of this challenge. In other words, we need to figure out what data is required and why among diverse supply chain tiers.

If we could improve the data interoperability among different partners on the supply chain, self-organising and autonomous logistics systems on the supply chain will be more agile because they can automate processes (self-executing and self-decision-making). This is a relatively new research trend, and its purpose is to deploy more efficient and cost-effective supply chain systems. Blockchain technology presents great potential in connecting data because of its advantage in handling data security and privacy and responsibility tracking. [168] It is foreseeable that blockchain technology can automate agreement-based processes and promote self-organising and autonomous supply chain management systems and improve the added value.

[165] *Gao, Q., Guo, S., Liu, X., Manogaran, G., Chilamkurti, N., Kadry, S.: Simulation analysis of supply chain risk management system based on iot information platform. Enterprise Information Systems 14(9-10), 1354–1378 (2020)*
[166] *Golkhoo, F., Moselhi, O.: Automated construction materials data acquisition using digital imaging and rfid. In: Proceeding of the 6th International Construction Specialty Conference, CSCE, Vancouver, BC, Canada (2017)*
[167] *https://www.gs1.org/standards*
[168] *., Chen, Z., Xue, F., Kong, X.T., Xiao, B., Lai, X., Zhao, Y.: A blockchainand iot-based smart product-service system for the sustainability of prefabricated housing construction. Journal of Cleaner Production 286, 125391 (2021)*

6.3 Challenges for applying blockchain technologies on CSC

6.3.1 Blockchain technology

Blockchain technology is a potential solution for a variety of sectors. The first use of blockchain technology was in 2008, introduced in a white paper on Bitcoin by Satoshi Nakamoto.[145] A blockchain is a digital ledger encrypted and stored on multiple nodes in a private or public network (computers).[36] The blockchain comprises a consensus mechanism, cryptography and a distributed database. A consensus mechanism synchronises all data transactions across the public or private blockchain network, and it is used to verify transaction data to ensure the immutability of the blockchain.[169] Cryptography is a form of hashing algorithms used to encrypt transaction data to ensure the data is difficult to tamper with. A distributed database includes all computers supporting distributed ledgers, which record transaction data in each participant's ledger.

The main features of blockchain are transparency and decentralization.[147,148,169] For decentralisation, each block of the network contains timestamps and data about the preceding block of transactions, creating a distributed ledger in the network. When a new transaction is initiated, details of the transaction are transmitted to the blockchain network for validation and verification. This occurs only if all the nodes of the chain agree on the trade in the data block are valid by using a standard communication protocol. If validated and verified, the block is attached to the chain, and the copy of each node of the blockchain is updated accordingly. Once in a blockchain block, a single participant cannot delete or change those transactions.

For transparency, how outsiders detect into the working system is defined as transparency.[155] Blockchain technology is suitable for enhancing transparency due to its distributed nature and because it is tamperproof.[146] With distributed real-time data sharing, participants can verify and identify whether the treatment, quality, location or other types of data and procedures are qualified. Digital ledgers build a trusted relationship network within the blockchain.

Blockchain platforms include permission blockchain and permissionless blockchain.[148] Hyperledger Fabric[170] is an example of a permissioned blockchain; only authorised users can access block data and validate transactions. Permissionless blockchains, such as Ethereum or Bitcoin, are decentralised and allow users to access block data on the chain. Although permissionless blockchain is more decentralised and open, permissioned blockchain can support higher throughputs by utilising and designing consensus protocols. In general, permissioned blockchains are more applicable for time-sensitive CSC applications by traceability, transparency, decentralisation, immutability, smartness and privacy.

6.3.2 Diverse systems and project-based nature

Diverse companies from various trades is characteristic of CSC. A diverse group of parties also includes architects, suppliers, contractors, engineers and developers. In the middle of a large-scale project, hundreds of companies typically provide

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[169]Luo, H., Das, M., Wang, J., Cheng, J.: Construction payment automation through smart contract-based blockchain framework. In: ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction. vol. 36, pp. 1254–1260. IAARC Publications (2019)

[170]Androulaki, E., Barger, A., Bortnikov, V., Cachin, C., Christidis, K., De Caro, A., Enyeart, D., Ferris, C., Laventman, G., Manevich, Y., et al.: Hyperledger fabric: a distributed operating system for permissioned blockchains. In: Proceedings of the thirteenth EuroSys conference. pp. 1–15 (2018)

components, construction materials and a wide range of construction services. These multi-domain and multi-participant characteristics induce the high fragmentation of the construction industry, and different companies use different CSC systems in a project.[149] Moreover, companies utilise various software applications and hardware platforms.[171] This can pose challenges in the technology aspect for integrating the CSCs and transmitting them to blockchains.

Further, the ephemeral nature of construction projects makes it difficult to integrate data from supply chains into blockchains. Although some processes on the CSC may be similar for different construction projects, most construction projects may need to create new prototypes or products, and companies may require reconfiguring for each project. Also, sharing the necessary information on chains and integrating diverse systems from suppliers requires coordination and trust.[146] Supply chains are highly dynamic and construction project teams change frequently. As a result, it is improbable that project participants will work together long enough to build enough trust to willingly share information, creating a challenge for blockchain to get the information required from each partner.[149] Customisable, flexible and secure supply chain systems may encourage integration for different short-term partners. Blockchain technology must depend on such flexible CSC systems. Otherwise, it will be difficult for blockchain to integrate data from different companies on the chain.

6.3.3 Monitor onsite activities

After construction materials arrive on the site, a few activities are worth monitoring to ensure the construction quality.[172] For instance, onsite assembly management service plays an integral part in construction inspections, operations and supervision.[148] The complexity and diversity of instruction for construction materials may enable workers to install them in an inappropriate manner or in the wrong place. Some studies claimed that using sensors devices such as QR codes can optimise assignment by allocating the works to appropriate workers or monitoring workers activities in BIM.[173] However, merely integrating BIM and these sensor devices is not enough to ensure data security, trust and privacy among stakeholders.[148] For instance, cloud-based BIM data and models can be tampered with, making data changes untraceable. Sensors such as GPS and RFID may report noise or run out of power, reducing data quality.

Blockchain may be able to solve the these issues, via a distributed data ledger that is shared with all participants and transactions are mutually agreed upon in a peer-to-peer network.[174] One possible solution is to build a middleware agent that responsibly authenticates, verifies and queries external data sources and later transmits them to blockchain for use by smart contracts. However, monitoring onsite activities, collecting data accurately, and finally disseminating it to blockchains can be challenging. But

[171]Hinkka, V., T¨atil¨a, J.: Rfid tracking implementation model for the technical trade and construction supply chains. Automation in Construction 35, 405–414 (2013)
[172]Irizarry, J., Karan, E.P., Jalaei, F.: Integrating bim and gis to improve the visual monitoring of construction supply chain management. Automation in construction 31, 241–254 (2013)
[173], C.Z., Chen, Z., Xue, F., Kong, X.T., Xiao, B., Lai, X., Zhao, Y.: A blockchainand iot-based smart product-service system for the sustainability of prefabricated housing construction. Journal of Cleaner Production 286, 125391 (2021)
[174]Tezel, A., Papadonikolaki, E., Yitmen, I., Hilletofth, P.: Preparing construction supply chains for blockchain technology: An investigation of its potential and future directions. Frontiers of Engineering Management 7(4), 547–563 (2020)

solving this issue can improve data authenticity and quality in construction supply chain management.

6.3.4 Privacy access control

Diverse supply chain partners have different concerns for their data. The most significant advantage is the improved efficiency of distributing knowledge and information on the supply chain using blockchain technology. This technology dissemination mechanism will enhance maintenance and after-sales service. The partners may not want tracking or material data transmitted to other companies. It is possible competitors will use others' data, which can hurt on a business level. Therefore, deciding whether some data is visible to other partners in the CSC requires some quantitative or qualitative research. In addition, putting different data to blockchains and eventually providing privacy access control for some participants can be a challenge.[148]

Blockchain networks can have 3 categories:[146] private blockchains strictly controlled by the operators; semi-distributed consortium blockchain authorised by federation administrators; and public blockchains that do not need any access properties such as Ethereum and Bitcoin. Adopting different blockchains for different supply chain tiers may provide more flexibility and customisation for the CSC, due to data privacy and governance for each partner. However, merging different types of blockchain into a unified blockchain system on CSC would also be a challenge.

6.3.5 Limitations of blockchain technology

Despite current and potential blockchain applications in logistics, transportation and supply chains, blockchain technology still has limitations that prevent it from becoming widely commercialised.[146, 175] Most blockchains now have transactional latency (the time it takes to add data to the chains) and size (the number of bytes per transaction) limits, making them less nimble than their decentralised or centralised counterparts like Mastercard or Visa.[176] Although credit cards can process an average of 5,000 transactions per second, a single Bitcoin transaction might take several minutes or even days, depending on traffic. Further, blockchains such as Bitcoin were designed to facilitate high-value rather than high-volume transactions. In construction supply chains and transport, the blockchains cannot fulfill such high volumes transaction requirements.

Another constraint is that a node's private key can be compromised (in this context, a node represents a transport intermediary or supply chain tier). Lost or damaged keys can make the blockchain unusable. Eventually, the high costs of deploying blockchain technology, and issues surrounding data governance and privacy, make this kind of technology challenging. One study categorises barriers to using blockchain as systems-related, intra-organisational, inter-organisational and external obstacles.[177] Integrating blockchain technologies with existing data management systems in construction supply chain transport and logistics systems such as WMS, CRM, SRM and ERP is expected to represent a turning point in blockchain adoption. We need to

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[175]Behera, P., Mohanty, R., Prakash, A.: Understanding construction supply chain management. Production Planning & Control 26(16), 1332–1350 (2015)
[176]Pournader, M., Shi, Y., Seuring, S., Koh, S.L.: Blockchain applications in supply chains, transport and logistics: a systematic review of the literature. International Journal of Production Research 58(7), 2063–2081 (2020)
[177]Garcia-Torres, S., Albareda, L., Rey-Garcia, M., Seuring, S.: Traceability for sustainability–literature review and conceptual framework. Supply Chain Management: An International Journal (2019)

consider how the blockchains of different enterprises may be integrated to create a unified blockchain system.

6.4 Recommendation on using blockchain technologies on CSC

Considering the characteristics of blockchain technology, such as transparency and decentralisation, these characteristics can have unique applications, disadvantages and advantages. After analysing a certain number of blockchain applications and thematic clustering of the literature, there are 3 types of blockchain applications: tracking, transferring and contracting.

6.4.1 Tracking

When tracked items arrive at a predetermined checkpoint in the distribution network, tracking systems transmit a message to the tracking database. The passage of a checkpoint is usually recorded using automatic identifying technologies such as RFID or barcode.[166] Tracking systems are required to link information systems and physical reality in the CSC and implement paperless and more accurate information systems.[178]

Internet of Things (IoT) relates to tracking in blockchain applications. IoT technologies had begun to focus on instant peer-to-peer information dissemination before the emergence of blockchain technology.[146] For example, the world's largest container carrier firm, Maersk, utilised blockchain in transport and logistics collaboration with IBM.[179] The blockchain-enabled process can track shipping containers in time, location, temperature or other information by using various sensors or GPS. Tracking also activates another function: recording. The cross-border consignment took only minutes to track, thanks to blockchain technology, whereas it previously took many days.[180] Blockchain technology reduced tremendous costs on labour resources and recording work.

Once tracking information can travel to the next tier of contractors faster than previously via blockchain, suppliers can lower inventory turnover dates and enhance other indexes related to the efficiency of supply chain management. According to one study, instant tracking could save 70% cost of after-sales. Especially in CSCs, with the IoT's integration, a blockchain solution for tracking elements has been introduced to improve quality, cost, speed, flexibility and sustainability.[146] The marriage of blockchain and IoT could make it easier to share resources and services, enabling the formation of marketplaces and the cryptographically verified automation of time-consuming procedures on supply chains.

6.4.2 Contracting

Using digital technology in industry contracts might help parties avoid unnecessary contract writing and inspections. Incomplete or imperfect contracts can cause problems between parties. Thus, some experts strive to solve and improve frameworks and algorithms so that smart contracts can cover an enormous variety of more precise terms for contracts. A smart contract is a unique characteristic of

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[178] Hinkka, V., T¨atil¨a, J.: Rfid tracking implementation model for the technical trade and construction supply chains. Automation in Construction 35, 405–414 (2013)
[179]https://www.nytimes.com/2017/03/04/business/dealbook/blockchain-ibm-bitcoin.html
[180]Kshetri, N.: 1 blockchain's roles in meeting key supply chain management objectives. International Journal of Information Management 39, 80–89 (2018)

blockchain, which operates in a digital environment with the capability to create programs and algorithms that may be wholly or partially executed or executed when specific circumstances are met.[155] This technology can replace troublesome and complicated interpersonal interaction. For example, if the construction site's temperature is higher than a certain level, the client pays a certain amount to the contractor. Also, one study developed crane leasing contracts by using blockchain technology on the IBM blockchain platform; participants in the chain can rent and receive money more efficiently without interpersonal interaction.[181]

Generally, blockchain technology can help improve supply chain contracts. Smart contracts are dedicated to offering the most reliable and thorough terms of the agreement within the legal framework of the most widely and regulated use. Optimised contractual treaties can increase the system's feasibility and credibility. Further, the smart contract can cut upfront construction project efforts, lowering costs directly. Using blockchain technology and smart contracts to improve contracting, partners would expend less effort and money on building peer-to-peer repeated cooperation to enhance trust. They need only trust the blockchain trading system, designed well.

6.4.3 Transferring

One of the most common blockchain applications transferring cash flows[155]. Many financial organisations employ blockchain because its peer-to-peer transaction recording approach makes centralised processing in traditional banking systems easier to manage.[164] Suppliers usually cannot receive payments on time from the project owner. This negative factor adversely impacts the CSC and seriously affects contractors' and clients' ability to finish their projects on schedule. Also, it is a problem that affects the entire industry, and it will only get better if everyone improves.

With blockchain technology, partners can improve their cash flows (e.g., suppliers can receive their money faster). For example, some construction workers in China can already use blockchain applications to receive their salary faster. [182] This technology also prevents transaction and data fraud because all the transactions on a block are continuously validated. Moreover, utilising smart contracts without centralised entities (e.g., logistics service providers or banks) on supply chains to control operations can increase the transparency of transactions and thus trust among participants.

Blockchain can also protect information and digital assets from infringement, copying or theft. Therefore, it increases trust among participants.[176] By monitoring the audit trail of transactions or ensuring terms indicated in contracts are completely fulfilled once all the requirements on smart contracts are met, the greater traceability and transparency provided by blockchains can help resolve disputes. Using blockchain technology promises an increased speed of transactions between international and local exchanges, especially in the CSC. It allows for peer-to-peer transactions and money transfers in a worldwide trading environment.

6.5 Conclusion and future work

[181] *Wang, J., Wu, P., Wang, X., Shou, W.: The outlook of blockchain technology for construction engineering management. Frontiers of engineering management pp. 67–75 (2017)*
[182] *https://www.ledgerinsights.com/chinese-city-uses-blockchain-for-migrant-worker-salary-transparency/*

While many industry experts consider applying blockchain technology across the CSC has a bright future, some say blockchains have an inflated expectation, which might exacerbate the consequences of unsuccessful adoption of blockchains across the supply chain. However, although some attempts to use blockchain technology have failed, there have also been many successful blockchain applications across the supply chain, as discussed in this report. We can see many aspects where blockchain can contribute to the CSC. Blockchain will find a role in practice and gain widespread acceptance like many other emergent technologies. In future work, we will explore using Amazon Blockchain Managed Services and build a prototype using blockchain to improve aspects such as tracking or traceability of the CSC.

Chapter 7 Stakeholder's perspectives: drivers and barriers

Authors: Guilherme L. Tortorella, Declan Cox, Alistair Barros, Wen Li

This chapter describes the methodological procedures performed to analyse the semi-structured interviews with academics, practitioners (contractors, sub-contractors and material suppliers) and stakeholders (regulatory agencies, solution and technology providers and government institutions) regarding the traceability digitalisation of the Australian construction supply chain. Using these results, we identified the most critical drivers, benefits, barriers and challenges for such traceability digitalisation. We consolidated these results in a conceptual framework that characterises the early and late adopters of digital technologies to support traceability practices and systems in the Australian construction supply chain.

7.1 Methodology

As the digitalisation of construction supply chain traceability is still underexplored, we used a qualitative approach corroborating to the exploratory and descriptive nature of our study.[183, 184] Following Ketokivi and Choi[185], the study used *a priori* theorisation to frame the research design; findings are therefore not statistically generalisable. That offered an in-depth understanding of the drivers, barriers, challenges and benefits from digitalising the construction supply chain traceability, producing novel insights.

The methodological design consisted of 3 main steps: (*i*) definition of selection criteria; (*ii*) interviews with experts; and (*iii*) content analysis and propositions. These steps are detailed next.

7.1.1 Definition of selection criteria

The following criteria were established to select interviewees. First, because we wanted to confront theoretical and practical perceptions on the subject, we involved experts from 3 main categories: (*i*) academics who have investigated the digitalisation of the construction supply chain for at least 5 years, (*ii*) experienced practitioners (i.e., minimum of 10 years of experience) who have played key leadership roles (e.g., manager, director or engineer) in companies from different tiers (i.e., contractors, sub-contractors and suppliers), and (*iii*) stakeholders, which comprised solution and technology providers, regulatory agencies and government institutions. The combination of different perspectives would enable a wider understanding of our research problem. To mitigate the potential bias existing in interviewees' responses, we cross-compared their opinions based on their respective category (academics, practitioners and stakeholders). We considered arguments that were equally mentioned by experts and avoided utilising the ones that were clearly associated with

[183] *Voss, C., Tsikriktsis, N., Frohlich, M. (2002). Case research in operations management. International Journal of Operations & Production Management, 22(2), 195-219.*
[184] *Barratt, M., Choi, T., & Li, M. (2011). Qualitative case studies in operations management: Trends, research outcomes, and future research implications. Journal of Operations Management, 29(4), 329-342.*
[185] *Ketokivi, M., Choi, T. (2014). Renaissance of case research as a scientific method. Journal of Operations Management, 32(5), 232–240.*

the context in which the expert is inserted. Two of the authors individually analysed interviews' transcripts to increase the reliability and mitigate biased findings.

Finally, we identified and invited 26 experts to participate in the research. Experts presented balanced characteristics in terms of experience, background and roles, meeting the pre-determined selection criteria, and ensuring the quality and legitimacy of their opinions.[186]

The data collection method that helped to achieve the shape of interviewees was also based on theoretical sampling. According to Corbin and Strauss[187], its purpose is to "collect data from places, people, and events that will maximise opportunities to develop concepts in terms of their properties and dimensions, uncover variations, and identify relationship between concepts". The difference between theoretical sampling and conventional sampling is that theoretical sampling is responsive to the data rather than established before the research begins, i.e., it is about discovering relevant concepts and their properties and dimensions.

Additionally, previous qualitative studies[188, 189, 190] recommended a minimum sample size of at least 12 to reach data saturation among a relatively homogeneous population, which matches with our sample size. Thus, we claim that our sample size was large enough to describe the phenomenon of interest and address the research question at hand, avoiding repetitive data, and attaining theoretical saturation.[191] Experts accepted to join the interviews after receiving a consent form and a plain language statement, in which they were informed that their participation was voluntary, and any information provided would be kept anonymous.

7.1.2 Interviews with experts

Data was collected through online interviews between August and November 2021. Individual interviews followed a semi-structured protocol of questions (see Appendix B) that allowed open answers. Questions were grouped into 4 parts. The first part comprised interviewees' professional background. The second part sought information on their current traceability practices and technologies. The third part aimed at identifying the barriers and challenges for further digitalisation of traceability in the construction supply chain, while the fourth part involved assessing the drivers and benefits.

Data analysis was completed during the second half of November 2021. Interview coding, cross-interview analysis and fact checking were adopted to interpret data. All interviews were audio-recorded and followed the same sequence of questions, lasting from 45 to 75 minutes. No ideas from earlier interviews were introduced into

[186] *Shetty, S. (2020). Determining sample size for qualitative research: What is the magical number. InterQ. Available at: https://interq-research.com/determining-sample-size-for-qualitative-research-what-is-the-magical-number/ (accessed on January 26th 2021).*
[187] *Corbin, J., Strauss, A. (2008). Basics of qualitative research. Thousand Oaks, CA: Sage.*

[188] *Guest, G., Bunce, A., & Johnson, L. (2006). How many interviews are enough? An experiment with data saturation and variability. Field Methods, 18(1), 59-82.*
[189] *Fugard, A., & Potts, H. (2015). Supporting thinking on sample sizes for thematic analyses: a quantitative tool. International Journal of Social Research Methodology, 18(6), 669-684.*
[190] *Braun, V., & Clarke, V. (2016). (Mis) conceptualising themes, thematic analysis, and other problems with Fugard and Potts'(2015) sample-size tool for thematic analysis. International Journal of Social Research Methodology, 19(6), 739-743.*
[191] *Vasileiou, K., Barnett, J., Thorpe, S., & Young, T. (2018). Characterising and justifying sample size sufficiency in interview-based studies: systematic analysis of qualitative health research over a 15-year period. BMC Medical Research Methodology, 18(1), 1-18.*

subsequent ones, as recommended by Guest et al.[192] Interviews were attended by at least 2 authors, thus increasing the ability to handle contextual information confidently.[193]

Authors transcribed, analysed and discussed information; we then merged summaries after reaching consensus on the main findings.[194] To code our findings, we used excerpts from the transcripts and interpreted the information obtained from interviews. This produced a narrative made up of the transcriptions plus ideas and insights. Idiosyncratic responses were disregarded in the interest of focusing on dominant patterns among interviewees. All aspects of those research design choices were made to reduce the subjectivity.

7.1.3 Content analysis and propositions

In this step, we performed a content analysis of information gathered in interviews to develop a chain of evidence[195] that supported the formulation and categorisation of our findings. Information was grouped into 2 main categories: (*i*) drivers and benefits, (*ii*) challenges and barriers. Further, those categories were stressed according to 5 innovation attributes[196] that may affect the digitalisation of construction supply chain traceability:

a. Relative advantage: degree to which an innovation is perceived as being better than its predecessor. Innovations with a clear and unambiguous advantage over the one that it supersedes are more likely to be adopted.[197]
b. Observability: degree to which an innovation's results are visible to the adopters. The more positive outcomes from the innovation's implementation are observable, the higher its chances of adoption.[198]
c. Compatibility: degree to which an innovation fits with the existing values, experiences, and needs of potential adopters. The more compatible the innovation, the greater the adoption trend.[199]
d. Trialability: degree to which an innovation may be experimented with on a limited basis. Because innovations require investing time, energy and resources, those that can be tried before full implementation are more readily adopted.
e. Complexity: degree to which an innovation is perceived as difficult to understand and use. When key users perceive innovations as simple to use, the likelihood of adoption increases.[200]

After such categorisation, items were checked for commonalities among the speech of the different types of interviewees (i.e., academics, practitioners and stakeholders). For that, we analysed the frequency of citation (quantitative analysis) and emphasis

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[192] *Guest, G., Namey, E., Taylor, J., Eley, N., McKenna, K. (2017). Comparing focus groups and individual interviews: findings from a randomized study. International Journal of Social Research Methodology, 20(6), 693-708.*
[193] *Dubé, L, Paré, G. (2003). Rigor in information systems positivist case research: current practices, trends and recommendations. MIS Quarterly, 27(4), 597-635.*
[194] *Miles, M., Huberman, M. (1994). Qualitative data analysis: An expanded sourcebook. Thousand Oaks: Sage Publishing.*

[195] *Carter, N., Bryant-Lukosius, D., DiCenso, A., Blythe, J., Neville, A. (2014). The use of triangulation in qualitative research. In Oncology Nursing Forum, 41(5).*
[196] *Rogers, E. (1995). Diffusion of Innovations. New York: Free Press.*
[197] *Scott, S., Plotnikoff, R., Karunamuni, N., Bize, R., & Rodgers, W. (2008). Factors influencing the adoption of an innovation: An examination of the uptake of the Canadian Heart Health Kit (HHK). Implementation Science, 3(1), 41.*
[198] *Kaminski, J. (2011). Diffusion of innovation theory. Canadian Journal of Nursing Informatics, 6(2), 1-6.*
[199] *Greenhalgh, T., Robert, G., Macfarlane, F., Bate, P., & Kyriakidou, O. (2004). Diffusion of innovations in service organizations: systematic review and recommendations. The Milbank Quarterly, 82(4), 581-629.*
[200] *Straub, E. (2009). Understanding technology adoption: Theory and future directions for informal learning. Review of Educational Research, 79(2), 625-649.*

(qualitative analysis) of those items within each type of interviewee. Following [201] indications, items that were mentioned in at least one-third of the interviews within a specific type of interviewees were denoted as 'low frequency', while the ones that were cited by more than one-third (33.3%) were deemed 'high frequency'. For the emphasis analysis, we examined the transcripts once again to check the depth of the evidence and examples provided during the interviews. This allowed us to determine whether the emphasis of the interviewees' arguments about those items were 'low' or 'high'. Both assessments were performed by at least 2 researchers and, whenever a disagreement occurred, a third researcher was consulted to untie the decision.

The criticality of each item was defined based on their respective combination between frequency and emphasis levels. Low criticality was assigned for items whose both frequency and emphasis were low. Moderate criticality was determined whenever an item displayed either a low frequency and high emphasis, or vice versa. High criticality was assigned for items whose both frequency and emphasis were high. The criticality analysis allowed us to prioritise drivers/benefits and barriers/challenges in each innovation attribute.

We then compared the frequency of mentioning of highly critical items between organisations that have already initiated the adoption of digital technologies (early adopters) and the ones that are still struggling with such digitalisation (i.e., late adopters) to support traceability systems and practices in the construction supply chain. Such comparison meant we could identify trends in drivers/benefits and barriers/challenges for digitalising traceability across the construction supply chain. The core results are discussed below.

7.2 Results and discussion

We consolidated 79 elements (44 drivers/benefits and 35 barriers/challenges). Those elements were grouped according to their orientation in relation to the DIT's attributes, as indicated in Table 7.1. Further, the emphasis and frequency of each element were determined within each type of interviewees (i.e., academics, practitioners and stakeholders), so that we could identify their criticality levels. In general, 22 out of the 79 elements were considered highly critical. Out of those, 13 were drivers/benefits and 9 were barriers/challenges, as displayed in Figure 7.1.

For relative advantage, 5 drivers/benefits stood out: (*i*) *greater efficiency and productivity*, (*ii*) *improved sustainability*, (*iii*) *value gained*, (*iv*) *enhanced quality*, and (*v*) *more accessible product information*. Those elements were solely acknowledged as highly critical by practitioners and stakeholders, being the DIT attribute with the largest number of highly critical drivers/benefits. This result highlights the importance given by practitioners and stakeholders to the perceived advantage from incorporating digital technologies into construction supply chain traceability. In turn, academics, practitioners and stakeholders agreed that *cost of investment (particularly for SMEs)* should be a highly critical barrier/challenge for digitalising the construction supply chain traceability from a real advantage perspective.

[201] *Pagliosa, M., Tortorella, G., & Ferreira, J. C. E. (2019). Industry 4.0 and Lean Manufacturing: A systematic literature review and future research directions. Journal of Manufacturing Technology Management, 32(3), 543-569.*

From a compatibility standpoint, 3 drivers/benefits (i.e., *introduce government mandate*, *enhance supply chain collaboration*, and *educated local workforce*) were considered highly critical, while 2 barriers/challenges (i.e., *limited data accessibility/sharing*, and *end-to-end supply chain requirements*) were deemed highly critical. It is worth mentioning that of those 5 highly critical elements, academics pointed to 4 of them, and practitioners and stakeholders indicated 3 each.

In terms of complexity, the drivers/benefits *support premanufacturing strategies*, *provide a visualisation system of data/models*, and *common data environment (standardisation of data)* emerged as highly critical (the first 2 raised by academics and the third suggested by stakeholders). In turn, from the 10 barriers/challenges consolidated, only the *existence of many different systems (software interoperability)* was highly critical for both academics and stakeholders. Curiously, practitioners did not indicate as highly critical any of the drivers/benefits and barriers/challenges.

Trialability was the DIT attribute with least number of elements raised from the interviews. In total, 3 drivers/benefits and 2 barriers/challenges were listed. From those, only the barrier/challenge denoted as *lack of technical knowledge* was regarded as highly critical by stakeholders.

Finally, with respect to observability, the driver/benefit *greater supply chain transparency (better monitoring of deviations /identify opportunities for improvement)* was widely deemed as critical by academics, practitioners and stakeholders. In turn, this attribute presented the largest number of highly critical barriers/challenges, suggesting a particular concern with the visibility of the results implied by digitalising construction supply chain traceability. Four barriers/challenges were both emphatically and frequently mentioned: (*i*) *reactive responsiveness*, (*ii*) *short-term relationships*, (*iii*) *unbalanced risk across the supply chain*, and (*iv*) *unbalanced bargaining power*.

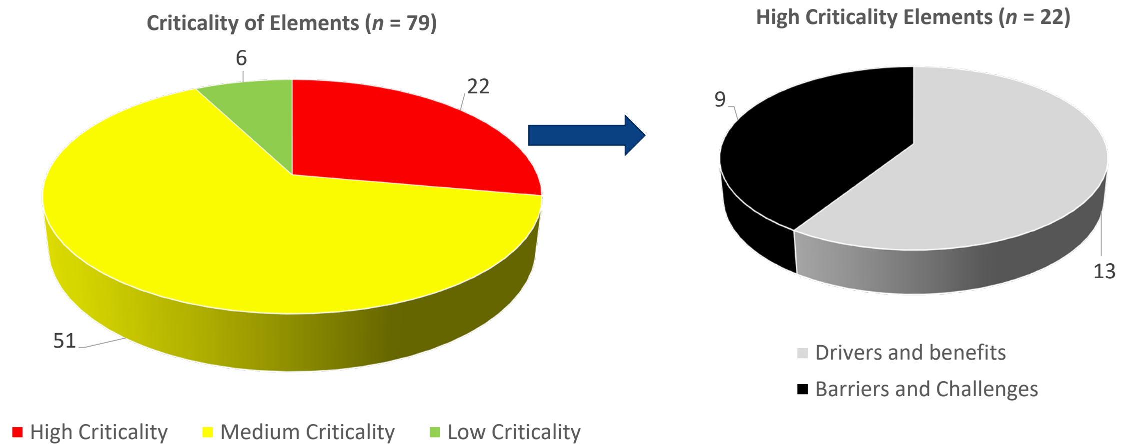

Figure 7.1: Distribution of criticality levels among all driver/benefits and barriers/challenges

Table 7: Commonalities among interviewees

DIT's attributes		Elements	Academics		Practitioners		Stakeholders	
			Emphasis	Frequency	Emphasis	Frequency	Emphasis	Frequency
Relative advantage	Drivers and benefits	Safer construction	HIGH	LOW	HIGH	LOW	HIGH	LOW
		Greater efficiency and productivity	HIGH	LOW	HIGH	HIGH	HIGH	HIGH
		More ethical material sourcing			HIGH	LOW	HIGH	LOW
		Improved sustainability	LOW	LOW	HIGH	HIGH	HIGH	HIGH
		Value gained	HIGH	LOW	LOW	HIGH	HIGH	HIGH
		Reduce delays in delivery	LOW	LOW	HIGH	LOW		
		Enhanced quality			HIGH	HIGH	HIGH	LOW
		Better scheduling	HIGH	HIGH	HIGH	HIGH	HIGH	LOW
		Provide accurate progress updates			HIGH	LOW	HIGH	LOW
		More accessible product information	LOW	LOW	HIGH	HIGH	HIGH	LOW
		Move towards a circular economy			HIGH	LOW	LOW	LOW
		Automated payments			LOW	LOW	LOW	LOW
		Better resource location information			HIGH	LOW	HIGH	LOW
		Less demanding refurbishments			HIGH	LOW		
		Verification of products			LOW	LOW		
		Secure information	LOW	LOW				
		Provide asset performance information	HIGH	LOW	HIGH	LOW		
		Improved operation and maintenance information	HIGH	LOW	HIGH	LOW		
	Barriers and challenges	Cost of investment (particularly for SMEs)	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
		Not every material is worth tracking	LOW	LOW			HIGH	LOW
Compatibility	Drivers and benefits	Attain compliance and certification	LOW	LOW	HIGH	LOW	LOW	LOW
		Introduce government mandate	HIGH	HIGH	HIGH	HIGH		
		Provide installation assurance			HIGH	LOW		
		Improved communication channels			HIGH	LOW		
		Enhance supply chain collaboration	HIGH	HIGH	HIGH	LOW	HIGH	HIGH
		Less disputes					HIGH	LOW

DIT's attributes		Elements	Academics		Practitioners		Stakeholders	
			Emphasis	Frequency	Emphasis	Frequency	Emphasis	Frequency
		Better customer experience			HIGH	LOW		
		Improve consumer confidence					HIGH	LOW
		Educated local workforce	HIGH	HIGH			LOW	LOW
		Improved technology readiness	HIGH	LOW	LOW	LOW	LOW	LOW
		Improve response to trade war issues			HIGH	LOW		
	Barriers and challenges	Contract mechanisms limit innovation			HIGH	LOW		
		Industry change management is required	HIGH	LOW	HIGH	LOW	HIGH	LOW
		Limited data accessibility/sharing	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
		Hesitancy to adopt technology	LOW	HIGH	LOW	LOW		
		End-to-end supply chain requirements	HIGH	LOW	HIGH	HIGH	HIGH	HIGH
		Specific technical skills					LOW	LOW
		Poor data handover					HIGH	LOW
		Misperception of prefabrication	LOW	LOW				
		Limited local software companies	LOW	LOW				
		Low digital maturity			HIGH	LOW	HIGH	LOW
		Industry is engineer-to-order	HIGH	LOW	HIGH	LOW		
		Long term relationships required for manufacturing			HIGH	LOW		
Complexity	Drivers and benefits	Less resources required			HIGH	LOW	HIGH	LOW
		Move to more standardised components			HIGH	LOW		
		Support premanufacturing strategies	HIGH	HIGH	HIGH	LOW	HIGH	LOW
		More efficient information transfer	HIGH	LOW	HIGH	LOW		
		Provide a visualisation system of data/models	HIGH	HIGH	HIGH	LOW	HIGH	LOW
		Easily accessible, real-time model					HIGH	LOW
		Less lost data through a project			LOW	LOW	HIGH	LOW
		Common data environment (standardisation of data)	HIGH	LOW	HIGH	LOW	HIGH	HIGH
		Rationalised supplier base			HIGH	LOW		
	Barriers and challenges	Distinctions in traceability processes			HIGH	LOW		

DIT's attributes		Elements	Academics		Practitioners		Stakeholders	
			Emphasis	Frequency	Emphasis	Frequency	Emphasis	Frequency
		No common language across the supply chain	HIGH	LOW	HIGH	LOW		
		Skilled labour requirements	HIGH	LOW	HIGH	LOW	HIGH	LOW
		Difficulty tagging individual elements	HIGH	LOW	HIGH	LOW		
		Manufacturing processes' limitations			HIGH	LOW		
		Complicated relationships with offshore suppliers	HIGH	LOW	LOW	LOW		
		Existence of many different systems (software interoperability)	HIGH	HIGH	HIGH	LOW	HIGH	HIGH
		Issues with RFID signal transmission	HIGH	LOW	HIGH	LOW		
		Longevity of databases					HIGH	LOW
		Poor data structures	HIGH	LOW			LOW	LOW
Trialability	Drivers and benefits	Growing interest in trialling technology			LOW	LOW		
		Positive experiences fostering more trials			HIGH	LOW	HIGH	LOW
		Workers will trial engaging products	HIGH	LOW				
	Barriers and challenges	Lack of technical knowledge	HIGH	LOW			HIGH	HIGH
		Unsuccessful trials are costly and time consuming			HIGH	LOW		
Observability	Drivers and benefits	Large organisations to encourage trade uptake of solutions	HIGH	LOW	HIGH	LOW		
		Greater supply chain transparency (better monitoring of deviations /identify opportunities for improvement)	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
		Provide a point of difference to competition	HIGH	LOW				
	Barriers and challenges	Reactive responsiveness	LOW	LOW	HIGH	LOW	HIGH	HIGH
		Short-term relationships	HIGH	HIGH	HIGH	HIGH	HIGH	LOW
		Unbalanced risk across the supply chain	HIGH	HIGH	HIGH	HIGH	HIGH	LOW
		Highly cost oriented thinking	HIGH	LOW	HIGH	LOW	HIGH	LOW
		Commercial agreement limitations	LOW	LOW				
		Lack of leadership	LOW	LOW			HIGH	LOW
		Falsifying data/ accurate labelling			HIGH	LOW		
		Unbalanced bargaining power	HIGH	LOW	LOW	LOW	HIGH	HIGH
		Variable construction process readiness			HIGH	LOW	HIGH	

Note$_1$: Items mentioned by ≤ 33.3% of interviewees were considered lowly frequent, while items whose frequencies were > 33.3 were denoted as highly frequent.

Note$_2$: Emphasis level was qualitatively based on the strength of arguments or examples provided during the interviews.

Note$_3$: Green cells indicate highly critical driver/benefits and barriers/challenges.

Then, we compared the frequency of mentioning of the 13 highly critical drivers/benefits between early and late adopters. As displayed in Figure 7.2, early adopters seemed to more frequently mention those drivers/benefits than late adopters. On average, early adopters mentioned these drivers/benefits 61% of the time, while late adopters cited them in only 39% of cases. Two of the highly critical drivers/benefits were only claimed by early adopters: *support premanufacturing strategies* and *provide a visualisation system of data/models*. A similar trend was observed for the 9 barriers/challenges denoted as highly critical (see Figure 7.3). Early adopters commented about these barriers/challenges in 63% of cases, whereas late adopters suggested them only 37% of the time. Further, 2 barriers/challenges – *end-to-end supply chain requirements* and *existence of many different systems (interoperability)* – were mentioned only by early adopters.

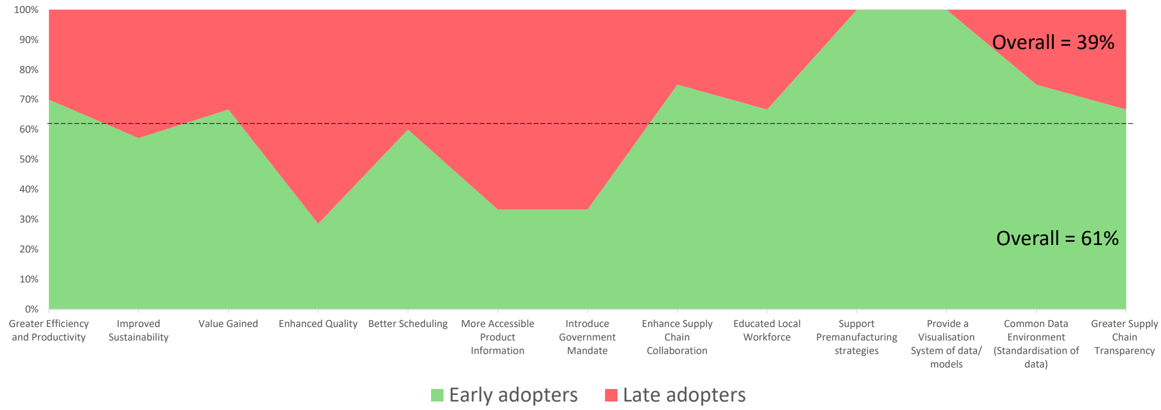

Figure 7.2: Frequency of mentioning of highly critical drivers and benefits between early and late adopters

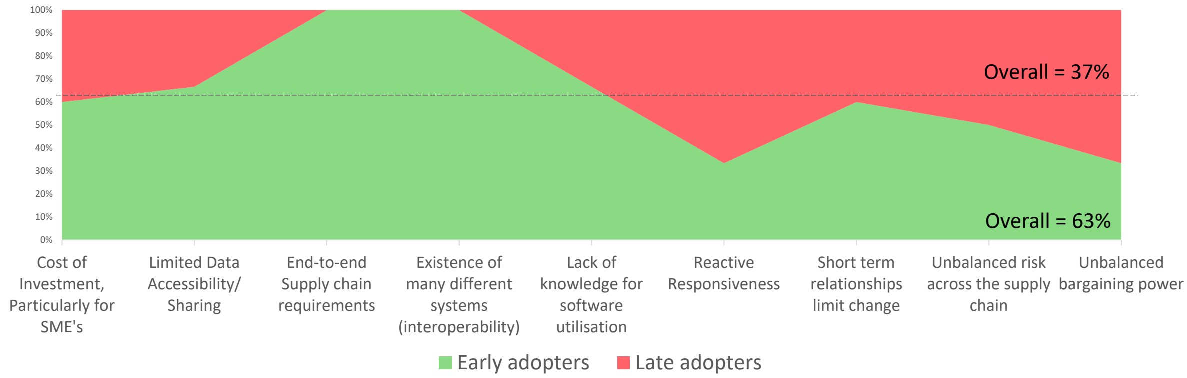

Figure 7.3: Frequency of mentioning of highly critical barriers and challenges between early and late adopters

The predominance of early adopters' perceptions in the frequency of mentioning highly critical drivers/benefits and barriers/challenges suggests a higher awareness about digitalising traceability systems in the construction supply chain. Following the concepts from hierarchy of competences proposed, [202] whose ideas were later extrapolated to the organisational context[203], this outcome may be associated with 4 competency levels: (*i*) unconsciously incompetent, (*ii*) consciously incompetent, (*iii*) consciously competent, and (*iv*) unconsciously competent. In our case, late adopters are expected to lack proficiency and be unaware of the necessary skills to digitalise construction supply chain traceability. This might explain the lower awareness level and, hence, frequency of mentioning the highly critical driver/benefits and barriers/challenges. In this sense, late adopters could be

[202] *May, G., & Kruger, M. (1988). The manager within. Personnel Journal, 66, 57–65.*
[203] *Thompson, J., & Martin, F. (2010). Strategic management: awareness & change. Cengage Learning EMEA, London.*

positioned in the first stage of the hierarchy of competences, i.e., unconsciously incompetent. On the other hand, early adopters have already been exposed to some digitalisation initiatives, making them more familiar with the topic and aware of the drivers/benefits and barriers/challenges, although they are not yet proficient. As such, we argue early adopters are likely to be consciously incompetent.

Nevertheless, some drivers/benefits (e.g., *improved sustainability*, *better scheduling*, *more accessible product information*, and *educated local workforce*) and barriers/challenges (e.g., *short-term relationships limit change*, *unbalanced risk across the supply chain*, and *cost of investment – particularly for SMEs*) were equally mentioned by both early and late adopters. This might indicate that the relevance of those drivers/benefits and barriers/challenges is equally acknowledged regardless the company’s stage in the hierarchy of competences. In other words, those drivers/benefits and barriers/challenges may be even more prominent and, hence, should be firstly addressed in traceability digitalisation.

7.3 Summary

This study aimed to identify the drivers/benefits and barriers/challenges for digitalising construction supply chain traceability. Based on data collected through semi-structured interviews with experts (academics, practitioners and stakeholders), we consolidated 79 elements: 44 drivers/benefits and 35 barriers/challenges. Of these, 22 elements (13 drivers/benefits and 9 barriers/challenges) were highly critical to successfully digitalise traceability systems.

Experts apparently deem more prominently drivers/benefits that promote real advantages relating to current traceability practices and systems. When considering the barriers/challenges, the degree to which the digital traceability's results are visible to the adopters seems to be an important issue, being able to impair digitalisation. Some highly critical drivers/benefits (e.g., *enhance supply chain collaboration* and *greater supply chain transparency*) may be fully achieved only if the entire construction supply chain really engages in traceability digitalisation. At the same time, some barriers/challenges (e.g., *short-term relationships* and *unbalanced risk across the supply chain*) may be inherent to the way the construction supply chain is designed and, hence, more difficult to overcome.

Further, companies that already have some initiatives (early adopters) may be better able to understand and visualise the drivers/benefits and barriers/challenges than others that have not started (late adopters). This suggests the more companies advance in traceability digitalisation, the more aware they are about its drivers/benefits and barriers/challenges. Nevertheless, some highly critical drivers/benefits and barriers/challenges were equally perceived by both early and late adopters, which may indicate their greater relevance.

The study has some limitations. First, from a data collection point of view, we gathered information from 26 experts. Although this sample size is reasonably sufficient for a qualitative study, it does not allow for statistically generalisable findings. Thus, future studies should enlarge the sample size and diversity, enabling use of more sophisticated multivariate data analysis techniques whose results can complement ours.

Second, larger samples would allow us to empirically verify how companies’ contextual characteristics may influence the likelihood of adoption. Further, operational performance could also be included as a variable, to identify the relationship between traceability digitalisation and performance improvement.

Finally, developing an implementation roadmap that could guide supply chain agents towards digitalised traceability systems could be another opportunity for future studies. This roadmap would help to systematise and articulate the digital transformation in an organised way, minimising useless efforts and increasing the odds of successful implementation.

FUTURE RESEARCH PLANS

This scoping study aided in the understanding of the state-of-the-art of traceability technology solutions and their current usage, development and challenges in the construction industry. However, further study is essential to transform the construction supply chain by introducing automation and digitisation for tracking and tracing construction materials and activities. Suggestions and ideas for further research are broadly categorised into 4 directions shown below:

I. Roadmap for sector-wise transformation:

We found adoption of digitalisation is slow and reluctant in the construction industry because the nature of its supply chain is highly unstable, fragmented and very different compared with other industries. We conducted interviews and research surveys with key stakeholders, mainly from industrial partners and academics associated with our research team, excluding SMEs, relevant experts, education providers, etc. Hence transforming the construction supply chain requires a deeper and better understanding of the industry and a roadmap for digitalisation. This research direction aims to understand the construction supply chain further, examine how we can leverage digitisation as a traceability solution for a streamlined workflow, and develop roadmaps for digitalising the construction supply chain in Australia. This can be achieved by following research methods:

- Identify the influential contextual variables (e.g., company size, tier level, product family, etc.) for digitalising the construction supply chain. In this phase, companies from the Australian construction supply chain will be surveyed, and answers will be analysed using multivariate data techniques to identify clusters of technology implementation and their associated characteristics.
- Verify how to deploy behavioural changes (i.e., sociocultural factors) required for a successful digitalisation across the construction supply chain. For that, we will conduct a multi-case study in companies that have been leading the digital transformation in the construction supply chain to cross-compare the existing managerial behaviours in these companies.
- Structure roadmaps for digitalising the construction supply chain in Australia. In this phase, we will conduct focus groups and interactive panels with experts (academics and stakeholders) to consolidate the different paths for digitalisation in the Australian construction supply chain.

The outcome of the research direction will be a roadmap of state-of-the-art construction supply chain processes indicating key contextual variables that should be kept in mind, concerns on adopting digital traceability solutions, and suggestions on how digital transformation will make the supply chain process seamless, efficient and productive. This further research will help industry partners and policy makers identify areas where they can implement digitalisation for higher productivity and effective project flow. The project will also assist technology-related companies in developing products or services, considering key stakeholders' concerns.

II. Digital traceability solution development:

Many traceability solutions have been developed in the past decades, whose type, specifications and applications are discussed in this scoping study. Utilising these solutions for onsite material and construction activities tracking and tracing were reviewed by looking into past research, developing case studies and conducting interviews and surveys with key stakeholders. We found digital traceability has a high impact on the overall productivity of project performance, but barriers and difficulties require further research and development. For example, many stakeholders pointed out that the existing traceability solutions are costly, making it hard for industry partners to adopt. The product identification method and sensors were not designed and adjusted to suit the characteristics of construction materials. In addition, product traceability information and provenance data have not been exchanged among the key stakeholders. Hence, this research direction aims to develop cost-effective technological solutions for automated material tracing for the construction supply chain. This can be achieved by following research activities:

- Develop cost-effective product identification methods for tracking highly critical building elements like steel, timber, concrete, wall panel, façade, cladding, etc. Although we have abundant options for production identification (e.g., barcode, QR code, RFID), they haven't been widely deployed for building materials. Our case studies found most product identification methods were not fully digitalised and were potentially lost along the supply chain. This research direction calls for further developing sensor technologies specifically for building materials and supply chains.
- Integrate with central building information management models and platforms for sharing product traceability information. We concluded BIM will likely remain a useful adjunct to demand chain and supply chain management for the foreseeable future. The key research question is to solve the compatibility among different digital tools and data interoperability.
- Explore the possibility of blockchain technologies for tracking, contracting and transferring. The combination of blockchain and IoT could result in an effective and efficient tracking service, enabling the formation of marketplaces and the cryptographically verified automation of time-consuming procedures on supply chains. Blockchain and smart contracts can also improve trust and efficiency among supply chain partners who would expend less effort and money on building peer-to-peer repeated cooperation to enhance trust. For example, the research team could explore using Amazon Blockchain Managed Services and build a prototype that uses blockchain to improve the traceability of the construction supply chain.

The outcome of this project will be the development of better and cost-effective digital traceability solutions, a framework for the sector-wise classification of traceability solutions in the construction supply chain, and an integrated and secured information system. The project will benefit the CRC by disrupting state-of-the-art traceability in the construction sector and transforming it into automated, digitised solutions. Industry partners can speed up their decision making processes and deliver high-quality projects to clients. The project will also help technology-related companies refine their products and create new opportunities for incoming players.

III. <u>Pilot study and living lab:</u>

The proposed traceability solution to track and monitor construction supply chain activities needs validation before wide adoption across the building sector. Interviews revealed industry partners are hesitant to invest in digital traceability solutions because of uncertainty about whether the proposed solution will aid project performance. Further, trialling solutions is costly and time consuming, making it harder for industry partners to cooperate with tech-related companies.

This project idea will focus on testing/trialling the proposed digital traceability solutions in the construction supply chain to check their feasibility and effectiveness. Ideally, we can turn an actual building project into a living lab by deploying proposed digital traceability solutions. The living lab will enable researchers and industries to collect empirical evidence on the efforts and costs of using digital traceability methods. More importantly, we can benchmark digitalised supply chains with a comparative conventional one by monitoring supply chain-related KPIs, such as lead time, productivity, project delays, etc. Alternatively, this can be achieved partially by experiments in a lab environment or by creating a simulation model and retrospectively using accurate industry project data. Although the latter option will lack real-world validation, both options will provide researchers with a platform to test their ideas and identify areas for further research and continuous improvement.

The outcome of this project idea will be a set of validated traceability solutions for the construction supply chain. Through this project, tech-related companies can demonstrate the capability and benefits of their product or service and identify improvement opportunities to make their solutions better and more efficient. The real-world demonstration will boost the confidence of industry partners to adopt fully digitalised traceability solutions for better project management and decision making.

IV. Education and training:

Digital traceability solutions are new and innovative, so there are technical knowledge and skills gaps in understanding and operating them. This is one of the main reasons industry partners prefer traditional traceability solutions i.e., paper-pen or emails approach. Inevitably, the additional cost will be incurred to learn the new technology, and skilled/ technical workforces will be needed to operate the solutions. An important consideration is how the results of this scoping study can be disseminated to the industry to change how industry works. These findings urge us to review how we teach supply chain management to students and the future workforce in the construction industry. Hence, the following activities are proposed:

- *Review current curriculum design and develop course materials for construction supply chain management.* A few key considerations are identified related to traceability and the construction supply chain: 1) Risk – the willingness of the organisation to handle potential problems internally or to delegate the risks to other parties. This requires identifying risks, estimating their likelihood and consequence and developing methods to mitigate risks; 2) Digital Technologies – provide new ways of managing the risk process through risk management tools and methods for mitigating existing risks and leading to new risks. They also provide new ways to monitor performance along the supply chain; 3) Sustainability covers the environmental and social impact of the design, construction and operation process. Ideally, these should be considered from a lifecycle perspective, and traceability provides essential information; 4) Lean Construction is concerned with delivering the full desired project results in the least impactful way possible. This approach examines what has to be provided to whom, by when and to which level of quality, with the least amount of waste.
- *Develop workshops and training programs for upskilling.* Further from the education pathways through TAFE and universities, a short/intensive course can be developed for post-work-experience students to equip them with edging knowledge on digital traceability in the construction supply chain.

APPENDIX

Appendix A Review of product identification technologies for building materials

Structural steel

Structural Steel is a type of steel used in making construction materials. It comes in different shapes, and most take elongated forms. Standards govern the size, shape, composition and mechanical properties. Barcode labels and RFID labels or sensors are commonly used to track structural steel.

Figure A1: Tracking structural steel using barcode and RFID [204, 205]

Timber

The process of tracking includes the following steps: (1) A forest is first identified for logging; (2) a harvester will handle the work of cutting trees; and (3) a forwarder will collect the logs and ship them to the mill via truck. The forwarder is responsible for stamping the logs for further processing. The stamp acts as a code for further handling the wood and usually includes the area where it came from, the forest owner and the person responsible at the logging site. At the mills, logs pass through a measuring station to ensure the correct delivery by the forwarder; this is usually done by entering the code (on the wood) to verify against the identification database. The identification lacks timing information and is tracked by keeping track of starting and ending timings of harvesters and forwarders activities. Barcodes, RFID, tracer paints, chemical fingerprinting, chalk and paint, and GS1 codes are used for tracking timber. Figure A2 shows various methods of marking the timber.

[204] *https://lsc-pagepro.mydigitalpublication.com/article/Automatic+Identification+Technologies+and+Steel/763230/73306/article.html*
[205] *https://www.steelprojects.com/en/solutions/features/shipping-management-workshop-assistant/*

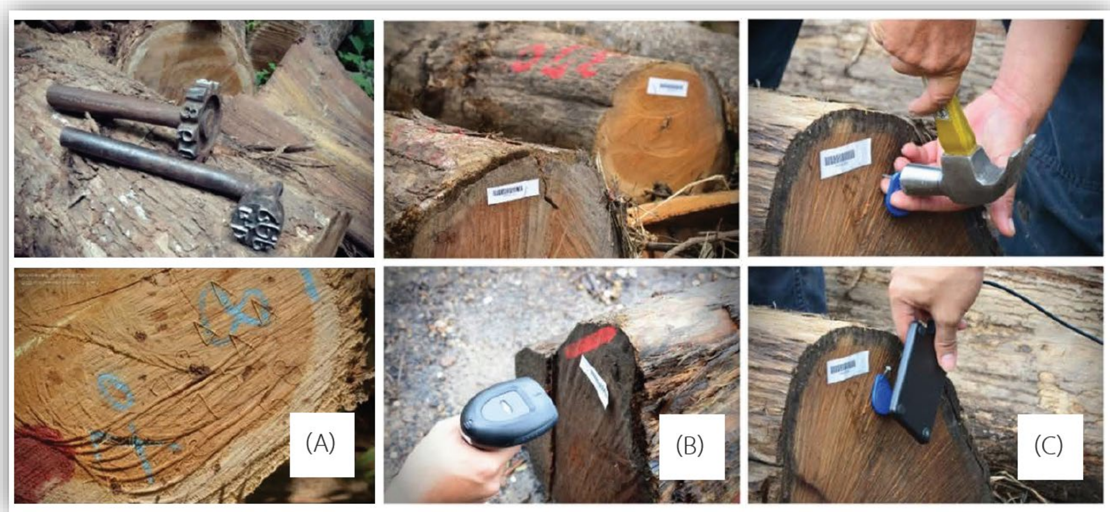

Figure A2: Examples of tracking timber [206]

Figure A3 shows the chain of custody of wood from the forest to the consumer.

Figure A3: Chain of custody [207]

1. Tag attached to trees
2. Tag attached to derived parts
3. Product sorting
4. Transport
5. New information added in the sawmill
6. Tags attached on semi-finished products
7. Tags on final products
8. Consumers can use the final product.

[206] *https://www.jtfr.forestku.com/jn_file/5030012020JTFR_V1N1_P5.pdf*
[207] *http://virtual.vtt.fi/virtual/cost/Zagreb/2015-03-27_CRA-ING(Menesatti)-COST%20Zagabria_Menesatti.pdf*

Tracking information at each stage becomes essential. With blockchain's open traceability, we can trace information from one stage to another. Figure A4 shows how information moves from one stage to another when the wood moves from the forest to the final product. Figure A4 also shows how different technologies (RFID, Barcode and QR code) can be used at different supply chain stages.

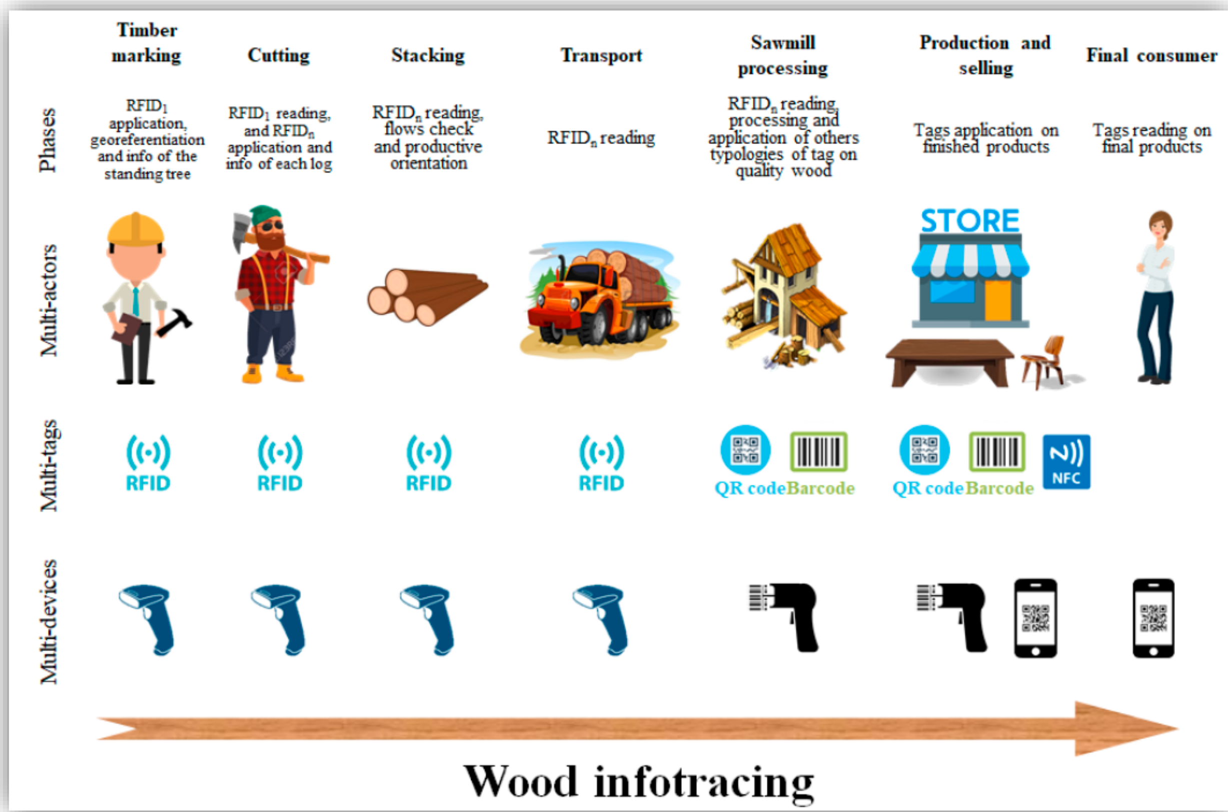

Figure A4: Electronic open-source traceability of wood along the supply chain [208]

Prefab timber

Prefabricated timber helps to improve efficiency while reducing labour costs and is also environmentally friendly. In this process, the materials are built off site using 3D modelling and precision-controlled computer numeric control (CNC) machines.[209] There are 2 main types of prefabricated timber products: building kits and finished modules. Building kits are elements that are assembled on site during construction. In contrast, finished modules are often assembled into a single building. There are 4 main types of wood systems in mass construction:

1. Cross Laminated Timber (CLT) – 3 to 7 boards stacked in alternating directions
2. Glued Laminated Timber (GLT) – 2 or more layers of boards glued together
3. Nail-Laminated Timber (NLT) – Timber stacked together on edge with nail
4. Parallel Stranded Timber (PST) – Composite material produced from wood strands (stiffest and strongest) engineered to for making large beams.

[208] *https://www.mdpi.com/1424-8220/18/9/3133/htm*
[209] *https://www.naiop.org/Research-and-Publications/Magazine/2019/Spring-2019/Business-Trends/Prefabricated-Wood-Construction-Shows-Promise*

For example, RFID has been used in prefab timber to identify products and track materials. Potential information that could be included in the RFID tags include:[210]

a. size: thickness, length, width, and volume
b. area: gross area and net area (with windows, doors, openings included/deducted)
c. construction type: framed or mass timber
d. dominant material type: timber species, CLT GLT, plywood, oriented strand board
e. design density (kg/m^3)
f. special characteristics: # of lamellas, lamella thickness
g. stress grade
h. surface finish grade: industrial, industrial and finished, finished both sides
i. adhesive type (for engineered timber materials)
j. surface coatings
k. main connectors
l. termite/fungal treatment.

Doors and windows

Like timber and prefab timber, we can use RFID and barcode labels to track doors and windows used in construction. For example, RFID tags were used to track the movements of doors and windows on the shop floor by creating zones and tracking item movements, including shipping.[211]

Roofing

Domestic roofs are mainly built with timber and covered with different materials. RFID has been successfully used to detect the defective membranes to track the covering materials. The RFID chip is embedded into POWERply® Endure® membrane[212, 213] rolls, and a technician can scan for any issues with membrane sheets. The chips inside these membranes are resistant to the short-term effects of installation in cold or hot asphalt. Figure A5 provides an example.

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210 https://www.fwpa.com.au/images/marketaccess/2018/RFID_Guide_in_Prefabricated_Timber_Construction_PNA381-1516a.pdf
211 https://www.barcodesinc.com/barcodesedge/case-studies/windows-doors-manufacturer-sets-new-standard-in-order-accuracy-with-complete-rfid-solution/
212 https://www.rooferscoffeeshop.com/post/technology-embedded-in-the-roof
213 https://info.tremcoroofing.com/powerply

Figure A5: POWERply® Endure® membrane with RFID hip (Roof-ID)

Piping and fittings

Visible and permanent markings provide critical assistance in identifying piping and fitting materials in constructions sites. Examples include marking pipes with ink, laser barcode marking and indenting, as shown in Figures A6 and A7.

Figure A6: Examples of product identification and traceability in piping and fittings [214, 215]

214 https://www.wermac.org/pipes/marking_requirements_pipe_flanges_fittings_valves_fasteners.html

215 https://www.thefabricator.com/tubepipejournal/article/tubepipeproduction/laser-system-marks-tube-pipe-profile-on-the-fly-complements-mill-operations

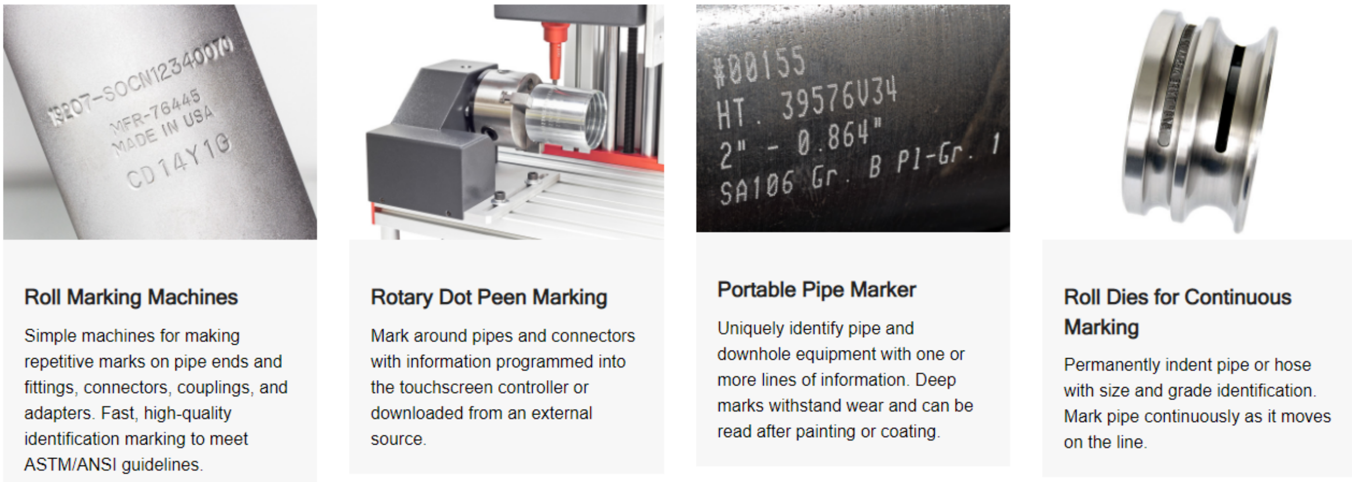

Figure A7: Examples of product identification and traceability in piping and fittings [216]

Cables

Both commercial and residential buildings use a variety of networking and cabling wires for delivering power, data and control signals. Having accurate product identification and traceability plays an essential role in maintaining the buildings. There are primarily 6 types of cables:[217]

1. single conductor cables (computer equipment, cooking appliances, video network)
2. non-metallic sheathed cables (residential electrical)
3. armoured cables (high data transfer)
4. instrumentation cables (communication between operators and instruments on construction site, rugged)
5. low voltage cables (electrical signals for video surveillance, lighting, automation and fire alarm)
6. communications cables (electronic circuits, intercoms).

We have both barcode labels and RFID tags available for identifying cables. Often RFID tags are used in cases where access to cables is complicated, and with RFID, a technician can scan for cables, as shown in Figure A8.

Figure A8: Examples of cable identification and tracing in buildings [218, 219, 220]

[216] https://www.pannier.com/pipe-tube-marking-systems/
[217] https://www.constructionplacements.com/types-of-wire-and-cable-used-in-building-construction/
[218] https://www.global-tag.com/product/fibery-rfid-nfc-tag-electric-cables/
[219] https://blog.hellermanntyton.com/company/4815/rfid-cable-ties-making-product-labelling-more-efficient-and-secure
[220] https://www.labtag.com/shop/product/wrap-around-wire-cable-labels-1-x-1-25-eba-118not/

Precast concrete

Precast concrete involves casting concrete into moulds and curing it in a controlled environment. The concrete is then transported to the construction site and placed. RFID sensors have been widely used to track precast concrete by embedding them inside the concrete and storing necessary information for traceability, as shown in Figure A9. RFID sensors also enable construction workers to scan for concrete materials and easily access data wirelessly after being placed in the buildings. Web-based platforms are available to manage and track precast concrete production. Using RFID sensors, we can know the status of each precast concrete during manufacturing, shipping and installation. BIM tools can be utilised to access RFID databases and update the BIM models. Figure A9 shows an example of precast concrete with RFID sensors.

Figure A9: Precast concrete identification and tracking [221]

In-situ concrete

In-situ concrete is either formed on site or in a nearby concrete mixing plant and is directly poured into shutters to settle into a final form. When the concrete is transported from a nearby plant, assessing the quality of the concrete becomes critical. For this, we can use a range of sensors for measuring concrete conditions and communicating the conditions to a cloud server where AI algorithms generate analytics in real time. The truck’s condition information is communicated continuously using 4G communication and GPS. A camera can visually scan and assess the quality at the construction site. As shown in Figure A10, AI algorithms combine information to provide a decision making ability for supervisors and workers at the construction site.

[221] *http://www.canbuild.com.hk/rfid*

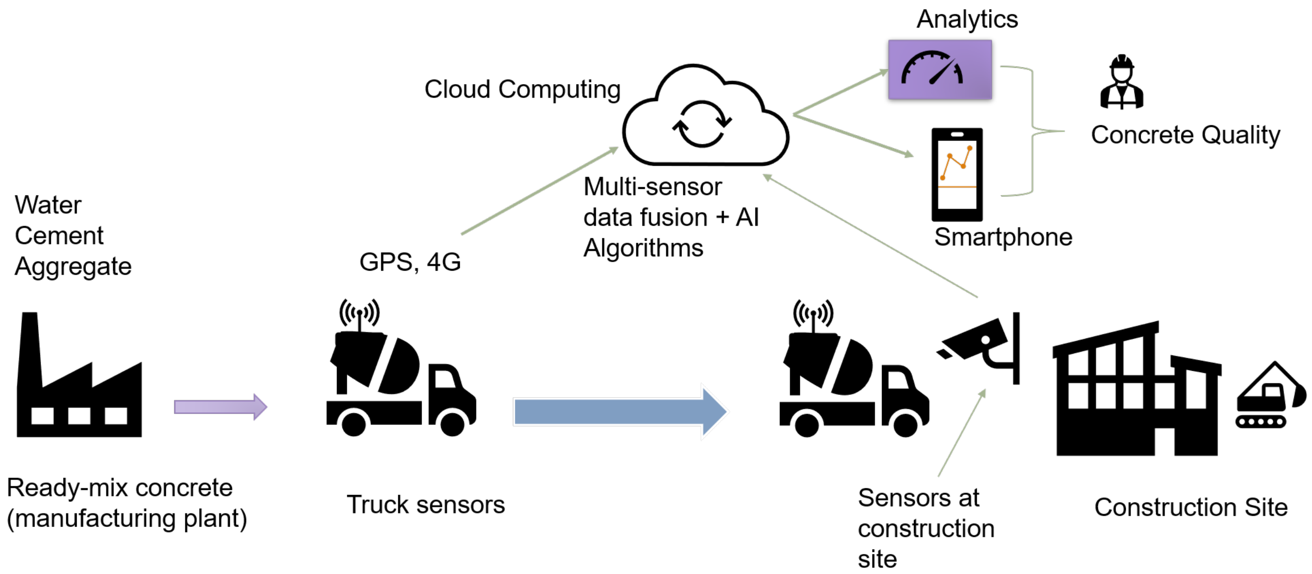

Figure A10: In-situ concrete quality assessment

Commercial tracking solutions

The table below provides an overview of some of the commercial solutions available in the market for tracking materials, workers, equipment and construction progress.

Company	Technology/solutions	Link
Techno Source, Australia	Employee attendance, material tracking, asset tracking	https://www.technosource.com.au/industry-solutions-construction
Track'em, Australia	Materials management and tracking software barcodes, RFID, GPS mapping technology (heatmaps, traffic, geofences) inventory management apps and software	https://trackem.com.au/materials-tracking/
Go Codes, USA	QR codes, barcodes, RFID, lots	https://gocodes.com/features/
Intelliwave technologies, Canada	Cloud-based web and mobile construction SaaS solution that digitises your supply chain and materials management.	https://www.intelliwavetechnologies.com/site-materials-management/
Intellitrac, Australia	Excavators, bobcats, graders, bulldozers, asphalt paver, dump trucks, street sweepers; GPS trackers for workers	https://www.intellitrac.com.au/AssetTrackingConstruction.html
Ynomia, Australia	BLE-based tracking materials, equipment, and people throughout a live construction site in real-time; supply chain visibility	https://ynomia.io/technology

Appendix B Interview protocol

Objective: To identify the main drivers, barriers, opportunities, benefits and current initiatives on digitalising the construction supply chain traceability.

Key dimension checklist:

1. Characterisation of companies and interviewees
2. Verification of current traceability practices and
3. Assessment of current level of technology
4. Identification of barriers and challenges for further digitalisation of traceability
5. Identification of drivers and benefits for further digitalisation of traceability
6. Gaps and areas for future development.

Main Contractors/ Sub-contractors/ Material Suppliers Protocol

1. What is your professional background? Please, provide a brief description of your professional experience.

2. Please tell us more about your organisation.

   - Where is the organisation located and who do you provide for?

   - How large is the organisation?

   - Where are your suppliers located/ where do you source your materials?

   - What does your organisation deem a reasonable investment in new technology to improve construction traceability?

3. Please let us talk about technology currently used to digitalise the construction supply chain traceability at your organisation.

   - From the list of Industry 4.0 technologies listed below, please indicate which ones your organisation has integrated into digitalising your construction supply chain traceability? Please provide examples of the traceability processes your organisation uses this technology for.

Industry 4.0 Technologies	Please tick mark if adopting
Internet of Things (IoT)	☐
Wireless sensors	☐
Augmented reality/ simulation	☐
Bug data	☐
3D printing	☐
3D scanning	☐
Cloud computing	☐

Digital twin	☐
Artificial intelligence (machine/ deep learning)	☐
Blockchain	☐
Drone	☐
GPS	☐
Remote control/ monitoring	☐
RFID	☐
Cybersecurity	☐

- How long have you been adopting these technologies?
- What stages of the construction value chain are digitalised by your organisation when tracking and tracing supplies?
- Can your traceability processes be accesses centrally? Please explain your answer.
- What has motivated your organisation to utilise this technology?
- What benefits have you observed from utilising this technology?
- What barriers or challenges have you observed in the digitalisation of construction supply chain traceability?
- What are the current gaps in your automation? How do you envision improving the digitalisation of your supply chain traceability? Please provide some examples.

Tech providers protocol

1. What is your professional background? Please provide a brief description of your professional experience.
2. Please talk to us about your organisation.
   a) Does your organisation provide software or hardware to assist in the digitalisation of construction supply traceability?
   b) How many organisations do you provide your service to? Where are they located?
   c) What is the protocol for an organisation to access your services? Please, explain your response.
3. Please tell us about the technology your organisation provides to digitalise construction supply chain traceability.

a) What Industry 4.0 technologies does your organisation provide to assist in the digitalisation of construction supply chain traceability? Please explain what traceability processes your technology supports.

b) How long have you been providing this technology?

c) What benefits have you observed from providing this technology?

d) Have there been any barriers or challenges that you have observed in providing this technology to construction supply chain traceability? Please provide examples.

e) What are the future opportunities for construction supply chain traceability? What areas are you looking at within industry and industry projects?

Regulatory body + other protocol

1. What is your professional background? Please provide a brief description of your professional experience.
2. What is your role in the digitalisation of construction supply chain traceability?
3. What are the challenges that you face in undertaking this role? (challenges in respect to recommendations from building reviews)
4. Could you provide examples of any positive or negative experiences you have encountered in the digitalising of construction supply chain traceability?
5. How have you adapted in the past few years to support digitalisation of construction supply chain traceability? Please provide examples.

Outcomes

Categorisation in accordance with the Diffusion of Innovation Theory:

Category	Characteristics (why)	Digital traceability initiatives
Innovators		
Early adopters		
Early majority		
Late majority		
Laggards		

Expected outcomes from the content analysis:

	Relative advantage	Compatibility	Complexity	Trialability	Observability
Main contractor					
Sub-contractor					
Raw material supplier					

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