Construction tracking: implications of logistics data

Duncan Maxwell and Rachel Couper
Future Building Initiative, Monash University, Melbourne, Australia

Received 25 June 2021
Revised 13 September 2021
3 November 2021
Accepted 27 November 2021

Abstract

Purpose – Construction suffers from "peculiarities" that concern the temporary natures of the construction site, project teams and unique product design. Considering the digital transformation of construction, new solutions are being investigated that can provide consistent data between changing projects. One such source of data manifests in the tracking of logistics activities across the supply chain. Construction logistics is traditionally considered a site management activity focused solely on the "back end" of projects, but an expanded logistics focus can unlock new avenues of improvement. This study aims to understand the requirements and benefits of such a consistent thread of data.

Design/methodology/approach – From a research project with one of Australia's largest contracting companies, this paper details a series of construction tracking tests as an empirical case study in using Bluetooth low energy aware tracking technology to capture data across the manufacture, delivery and assembly of a cross-laminated timber structural prototyping project.

Findings – The findings affirm the tracking of expanded logistics data can improve back-end performance in subsequent projects while also demonstrating the opportunity to inform a project's unique front-end design phase. The case study demonstrates that as the reliability, range and battery life of tracking technologies improve, their incorporation into a broader range of construction activities provides invaluable data for improvement across projects.

Originality/value – As a live case study, this research offers unique insights into the potential of construction tracking to close the data loop from final site assembly back to the early project design phase, thus driving continual improvement from a holistic perspective.

Keywords Logistics, Tracking, Construction, Prototype, Bluetooth, Data

Paper type Case study

1. Introduction

Construction is a complex industry that suffers from inherent peculiarities, particularly when compared to other project-based engineering industries. Primarily, these idiosyncrasies relate to the changing location of construction projects, bespoke designs that must respond to site and stakeholders and changing project teams (Vrijhoef and Koskela, 2005). To overcome these obstacles, greater continuity of knowledge and process is required to provide consistency between projects and across sites.

To this end, the tracking of construction activities provides potential for this type of consistent thread of data to be created. The emergence of embedded sensors and devices presents the construction industry with both the opportunity to collect new forms of data

This research was conducted as part of a CRC-Project funded by industry and the Australian Federal Government that supports industry-led collaboration between industry, researchers and the community.

Construction Innovation
Vol. 23 No. 2, 2023
pp. 322-339
Emerald Publishing Limited
1471-4175
DOI 10.1108/CI-06-2021-0122

but also the challenge of developing new ways of managing, coordinating and analyzing this data (Bilal *et al.*, 2016). However, there are relatively few studies that consider the implications of construction tracking and the data that is generated beyond the technical capabilities of sensor systems. The purpose of this research is to address this gap to better understand the requirements and implications of logistics data from construction tracking systems within a broader construction project value chain.

Rather than considering logistics as an isolated and introspective back-end activity, the aim of this research is to understand the wider value chain implications and potential of using construction tracking data from these project phases to inform front-end project design. These implications relate to how tracking systems are integrated into existing production workflows, the design of elements and how the resulting data from the tracking of construction activities can inform design decision-making at the front-end of projects. Therefore, this study has remained intentionally broad in its focus, addressing the following research questions (*RQ*):

RQ1. How can tracking systems be integrated into industrialized construction workflows?

RQ2. What data can be obtained from the tracking of activities?

RQ3. How can this data influence design decisions at the front-end of projects?

The following sections include a literature review that establishes the context of this study, as well as an explanation of the research methodology of this study. Thereafter, tests conducted within a construction prototyping project are presented, framing a series of construction tracking tests that provide answers to *RQ1* and *RQ2*. This paper concludes with a presentation of findings from the tests and a discussion of possibilities that answer *RQ3* and point to avenues for future research.

2. Literature review

The objective of this literature review is to provide the context of key developments in supply chain management, specifically in relation to logistics tracking. It also touches on the role of prototyping as an investigative tool for construction research, which pertains the nature of the case study analyzed in this paper.

2.1 Supply chains and tracking

"Tracking" as a concept can ostensibly be linked back to 16th Century England, where the concept of registered post was recorded as being established in 1556. Books of record were created to account for letters received, time of receipt and details of the party for whom the delivery was for (Joyce, 1893). Despite this early interest in tracking, it took longer for such approaches to become as widespread as they are today.

Over the past century, material supply chains have become increasingly globalized. Prior to the industrial revolution regional networks supplied goods based on distance trafficable by foot or animal; however, the emergence of industry meant that infrastructure such as railways and canals were created that enabled quicker, cheaper and faster distribution of goods and materials (Pope, 2011). The 20th century saw a number of innovations driven by invention or necessity – the truck provided a form of material distribution stimulus, whereas both World Wars drew attention to the importance of logistics beyond the national scale (Cowen, 2010). This international approach to logistics, combined with the development of shipping palettes, containers and sophisticated warehousing, meant that by the time computers emerged to transform industry, there were increased requirements for the monitoring and control of materials that drew focus to localization tracking of materials. In today's connected world, supply chains are increasingly considered complex systems that require responsive modes of management that are informed by technological control (Millar, 2015). New technologies, coupled with advances in supply chain management, point toward more fine grain data to drive continual improvement through the emergence of "smart logistics" (Anandhi *et al.*, 2019).

2.2 Moving toward industrialized construction

The historical developments of supply chain management and logistics have parallels in construction. Construction suffers from low productivity when compared to other sectors (Abdel-Wahab and Vogl, 2011), caused, in part, by its unique circumstances. The uniqueness of construction is characterized by:

- the fact that the establishment of a construction site is like setting up a temporary factory around the product (Bygballe and Ingemansson, 2014);
- the creation of a series of one-off, unique products that are large and immobile, meaning they must be built (or assembled) on the site of use (Turin, 2003); and
- the establishment of temporary networks and organizations with temporary supply chains (Behera *et al.*, 2015). Such networks that deliver construction projects are typically dependent on many, often small, firms acting as subcontractors (Dubois and Gadde, 2000).

As a result of these unique factors, many studies report that poor performance in construction is rooted in poor logistics management (Meng, 2013). Consequences of the mismanagement of logistics include increases in costs (Hwang *et al.*, 2009), waste (Tischer *et al.*, 2013) and time delays (Thunberg and Persson, 2014). These consequences are why some authors (Bankvall *et al.*, 2010) argue that many of the problems in construction could be mitigated through better supply chain and logistics management.

Construction logistics as a field of inquiry emerged during the 1990s and has maintained relevance for the ongoing improvement of the sector (Egan, 1998). Traditionally, construction has been organized around temporary organizational structures that deliver uniquely designed projects by means of short-term networks (Dubois and Gadde, 2000). These networks create close working relationships between participants within projects but the relationships are notably looser at the company-level (Dubois and Gadde, 2002). The shift from traditional construction toward industrialized construction seeks continual improvement inside and outside of the project domain. Industrialized construction increases the off-site fabrication of building components, which has the consequential effect of contributing to progressively more complex supply chains (Lessing, 2006), reinforcing the need for data to inform supply chain visibility and improvements beyond the immediate site of construction. Lessing's (2006) definition of industrialized construction sees "integrated logistics" underpinned by "systematic measurement of performance and the re-use of this data" as critical to achieving such improvement. Čuš-Babič *et al.* (2014) emphasize the importance of integrating information flows regarding construction materials in industrialized construction projects to improve supply chain transparency and use data for improvement of design, production and assembly.

Recent research has begun to consider the value of evaluating construction logistics from a strategic perspective (Rudberg and Maxwell, 2019). This view moves away from the traditional standpoint that constrains logistics activities and implications to the delivery phase of projects. Instead, logistics strategy takes a broader view, seeking repeatable solutions for implementation across a series of projects, specifically targeting continual improvement to close the loop from delivery back to project design. This approach identifies a demand for tracking and data capture to drive such improvements.

2.3 Introducing tracking sensors: linking the physical and the digital

Alongside new work practices in manufacturing, the data capture technology required to support continual improvements in industry practice is an emerging area of development, especially as the construction sector looks to redefine itself through Industry 4.0 (Kagermann *et al.*, 2013). Contemporary research effort has focused on defining Industry 4.0 for construction (Klinc and Turk, 2019; Sawhney *et al.*, 2020), a core concept of which is the establishment of cyber-physical systems. As such, logistics has been identified as an appropriate area for the implementation of Industry 4.0 through the introduction and integration of technologies that enable real-time tracking of materials, improved transport co-ordination and heightened risk management (Hofmann and Rüsch, 2017). The digital transformation promised by Industry 4.0 creates the conditions for fundamental disruption of traditional logistics activities through the creation of new technologies, business models and finance/information exchange mechanisms (Wurst and Graf, 2021). Where in the past, tracking of activities in traditional logistics organization occurred in isolation of other elements of the supply chain, the connection promised by Industry 4.0 points toward the benefits from a more widespread tracking of activities in construction. Such an approach leads to "smart logistics," defined as a more technologically open approach to material transport, storage and delivery that relies on information sharing and integration of resources to achieve rapid responsivity through Internet of Things (IoT), artificial intelligence and Big Data (Ding *et al.*, 2021).

According to Raza (2013), construction tracking provides seven important outcomes:

(1) *Detection*: simple presence of objects;

(2) *Identification*: by class of object or unique instance;

(3) *Location information*: specific co-ordinates or by area;

(4) *Object tracking*: whether an object is moving or not;

(5) *Object properties*: information on shape, weight, speed, ownership, supplier information, etc.;

(6) *Memory representation*: historic data on object behaviors; and

(7) *Application specific processes*: using tracking tags to manage objects, control them or capture alternate data.

Tracking technology is identified as a key element in creating a successfully networked construction industry that can deliver on the promise of Industry 4.0: the linking of physical and virtual worlds. This tracking technology captures performance data with regards building activity, product performance, as well as occupation monitoring for continual improvement of construction methods as well as building design. Such a system of data collection relies on the creation of wireless sensor networks (WSN) that Dargie and Poellabauer (2010) reveal are created from sensors that "link the physical with the digital world by capturing and revealing real-world phenomena and converting these into a form that can be processed, stored, and acted upon." Broadly speaking, sensors fit into 12 established categorizations (Dargie and Poellabauer, 2010); ten of which, the authors consider relevant to building activity (Table 1).

The creation of WSNs for construction holds the potential to capture a wide range of data that holds the potential to influence the building value chain holistically, from early design inception, construction activity, building occupation to, finally, disposal. Accordingly, building element design must be re-calibrated to incorporate such sensors physically as well as provide process mechanisms for the incorporation of their data in the form of design and process feedback.

Envisioning the comprehensive changes that the internet would bring to business, in 2001, Hightower and Borriello noted that mobile computing would increasingly rely on localization to record data and report that data to centralized systems. As such, the success of WSNs in construction relies on location-awareness, using real-time location systems to understand where data is coming from and what the data relates to. Automated location-sensing creates such a system and is generally achieved by a combination of triangulation, scene analysis and proximity (Hightower and Borriello, 2001). This conjecture has been borne out by recent developments in mobile computing power to drive new modes of logistics tracking and supply chain performance improvements (Xiang *et al.*, 2021).

2.4 Tracking solutions – advantages and disadvantages

A range of technological solutions are helping to deliver automated location data to underpin more widespread object and process tracking. These advances are today only possible because of the technological developments of the past decade that have enabled the technology to decrease in size, cost and power consumption, while increasing in complexity and ability to relay multiple forms of detailed and accurate data over wider ranges (Ni *et al.*, 2004). Prevalent technologies for the automated localization tracking of construction logistics activity use three main systems: global positioning systems (GPS), radio frequency identification (RFID) and Bluetooth.

2.4.1 Global positioning systems. GPS is one of the most popular and widely available tracking technologies. Originating from technology developed by the US Department of Defense, GPS has been opened to civilian use since the 1990s. The most widely used GPS infrastructure is managed by the US Air Force Space Command; however, at the same time, as the US network was created, the Russians also established a network "GLONASS." In 2020, both Chinese (BeiDou) and European (Galileo) are also operational, whereas India and Japan have developed smaller, regionally focused networks.

GPS infrastructure is worldwide, low-cost and provides a relatively high degree of accuracy. A major shortcoming for construction activities is that it is only reliable outdoors, and GPS tracking sensors are expensive (Bhargava *et al.*, 2015). Accuracy is typically around five meters, which is acceptable for many uses, especially tracking items' transport

#	Sensor category:	Example of building activity monitored
1	Temperature	Climate control, thermal comfort
2	Optical	Light meters, visual comfort
3	Acoustic	Site works disruption
4	Motion/vibration	Structural monitors, material transport
5	Mechanical	Tactile sensors, HVAC performance
6	Flow	Ventilation, air changes
7	Position	Material/component localization
8	Electromagnetic	Door/window control
9	Chemical	Plant room/building service safety
10	Humidity	Building façade moisture performance

Table 1. Categorization of sensors and possible application to the building industry

between geographically distant locations; however, this accuracy may not be detailed enough for construction site activity localization.

2.4.2 Radio frequency identification. RFID technology uses electromagnetic fields to detect and identify objects. Tags contain a microchip that has data stored on it and an antenna that communicates with readers. These microchips often hold additional task data, commonly extra product information or handling instructions.

Similar in cost profile to GPS are active RFID tags that are battery powered. These tags are expensive but rely on relatively low-cost infrastructure. At the other end of the cost spectrum, Passive RFID tags (unpowered) that are cheap but rely on costly infrastructure. RFID systems, however, can be difficult to use on construction sights because of interference from steel structural elements and moisture (Lu *et al.*, 2007). The accuracy of RFID is very good, especially over distance, accounting for its widespread use across a variety of industries (Li and Becerik-Gerber, 2011). However, there are a number of limitations that present around issues of collision and frequency (Kaur *et al.*, 2011) that are problematic for the technologies' widespread uptake in in construction particularly the frequency based limitations because of the complex mix of conductive materials used, particularly steel. These environmental factors cause localization problems with RFID in construction and research continues to seeks ways to overcome this significant limitation (Wu *et al.*, 2019).

2.4.3 Bluetooth. In the middle of this spectrum, balancing tag and infrastructure costs are Bluetooth tracking solutions. Bluetooth has been a technology that has used a lot of power in its sensors and devices; however, it has become viable because of the creation of Bluetooth low energy tracking systems that now emit a small amount of power per device. In 2016, the Australian Government research organization Commonwealth Scientific and Industrial Research Organisation (CSIRO) through their "Data61" research group developed Bluetooth low energy aware tracking (BLEAT), furthering the potential of Bluetooth for tracking (CSIRO, 2016). Bluetooth, combined with Wireless local area networks (and where appropriate, specific GPS-enabled devices) provide a potentially sophisticated tracking solution that relies on a range of common, compatible devices. Further, this system holds the potential for multi-function tracking tags as well as their possible application to workers for issues of safety, site monitoring and compliance.

2.4.4 Summary. No single solution has presently emerged as superior, with each offering advantages and disadvantages in tracking the unique circumstances of construction logistics activities. The trade-offs required in the selection of a technological solution essentially concern the functionality of the system, the cost of tracking tags and the cost of creating the tracking network infrastructure. Additionally, much of the tracking technology currently available relies on barcodes and/or QR codes being applied to items; however, these solutions require a line of sight to the code, meaning that large numbers of packages must be scanned manually. Moreover, these code formats are unable to provide detailed localization data as their location is based on the point of last scan.

Of the above systems, BLEAT offers the most significant potential for a comprehensive building sector WSN through its balancing of infrastructure and sensor costs, as well as providing potential for the Bluetooth tags to be equipped with multiple sensing options, as described in Table 1, beyond the localization focus of this study.

2.5 Selecting the tracking solution – Bluetooth's potential for Internet of Things

The mass timber prototyping project that forms the larger framework; in which, this study sits involved multiple industry stakeholders. Two of the stakeholders were active in this logistics tracking study: a multi-national Australian contractor (Partner A) and (Partner B) a construction technology start-up.

Partner B are commercializing the CSIRO's BLEAT technology for the construction industry and were selected by the research team and Partner A because of the cost balance and scope for future sensor upgrading. Partner B aims to integrate the tracking technology and its data in an expanded online, IoT platform that leverages Bluetooth as an industry standard approach for future compatibility of wireless device compatibility. This platform uses the tracking tag data combined with a smartphone app to enable construction site tracking of materials and visualization of construction progress for future building improvement. These factors provide the basis for a response to *RQ3*: How can data influence design decisions at the front-end of projects?

Bluetooth devices are reducing in cost and are effective means for short-range tracking activities. In the case of Partner B, this system is combined with internet connected LoRaWAN gateways to capture short-range data and provide effective long-range capability. This captured data is then fed to Partner B's online platform. This sequence of data capture: short-range Bluetooth tags communicating with internet-enabled gateways that in turn send data to an online aggregating platform, sets in place flexibility for future iterations of tracking tags to function beyond logistics, creating an IoT network for construction. This data holds implications for middle-ware layers of IoT applications, as defined by Haughian (2018), that holds implications for front-end project design and back-end assembly/occupation. Examples could include monetization and billing (automated progress payments as data is captured automatically from installed building components); device management (smart building capability driven by responsive tags); and analytics and machine learning (building performance and design data captured by building performance tags).

The tracking system developed by Partner B was selected for the prototyping exercise in consultation with Partner A largely because of its future potential. The research team then collaborated with both industry partners to run a series of proof-of-concept tests during the design, manufacture and assembly of the mass timber prototype to establish the viability of BLEAT construction tracking and more clearly understand the implications for design.

2.6 Construction prototyping project

The mass timber prototype developed during this research project was the culmination of three years of applied research work. Logistics and supply chain improvement was one research stream of several, and tracking tests sought to integrate with studies being undertaken by the other research streams in the project to develop a better understanding of the challenges of integrating construction management processes.

Prototyping offers a unique opportunity for construction to test and analyze designs and working processes in an environment that is separated from the day-to-day pressures of commercial projects. Prototypes exist to "evaluate physical form, design concepts, performance characteristics and manufacturability prior to, or in lieu of building a real-world product" (Johnston *et al.*, 2016). Within an industrialized construction setting, prototyping becomes especially important, as off-site manufacture processes and products can be tested in controlled environments before making their way to site for assembly. The use of prototyping can inform construction product platforms as a "kit of parts" that are developed for repeated use moving construction beyond bespoke projects. Mass timber construction is particularly well suited to the process of industrialized construction because of its stable and engineered product-nature, environmental performance, increased structural innovation, as well as its ease of machinability and wastage reduction in offsite manufacturing.

3. Research methodology

This study was conducted within a broader project that used a multimethodological framework specifically designed to bridge the gap between academic research and industry implementation (Dainty, 2008). The multimethodological framework was intentionally used to cater for the complexity of the real-world problems encountered by our industry partners. This approach is in keeping with Dainty's argument that by transcending traditional dualisms in research design and adopting a multi-strategy approach as an alternative, researchers can develop a richer understanding of the factors that shape industry practice (Dainty, 2008). The culmination of the study used applied research methods, an approach which aims to improve understanding of a specific problem by collaborating directly with industry partners to establish the real-world "messy" problem for investigation (Hedrick, 1993).

The overall objective of the broader research project was to test mass timber construction processes through the design, manufacture and assembly of a large-scale mass timber prototype. This prototyping project forms the central case study of this paper (Yin, 2003), around which the series of tracking tests were organized. Undertaken over a six-month period in 2019, the empirical study involved several stakeholders (including Partner A and Partner B) as well as multiple, interconnected research streams (hence, the necessity of using methodological pluralism in the research design).

The 80 m^2, 1:1 scale structure was made of prefabricated cross laminated timber (CLT) and glulam components that were manufactured offsite, transported to location and installed by a team specifically recruited for the project. The prototyping project provided a unique opportunity to test multiple factors simultaneously, including (but not limited to) the potential of design for manufacture and assembly (DfMA) in a variety of connection designs, the implementation of paperless assembly instructions on site and, of most relevance to this paper, data collection through construction tracking.

The multi-faceted research agenda underpinning the prototyping exercise enabled the research team to observe the effects each of the research streams had on each other, offering insight into the pursuit of greater construction integration. The independent optimization of a single stream of research was eschewed in favor of collective system improvement. The main sources of logistics data from the prototyping project case study are: data generated by the construction tracking tests, semi-structured interviews and workshops with industry partner participants and prototype project documentation (internal reports, presentations, schedules and design drawings).

As construction tracking is an under-researched field of inquiry, the employment of a multimethodological approach allowed for two phases of research activity and the research design was strategically formulated to ensure each stage informed the next.

The first established the context and scope of the study through an explorative review of relevant literature (as described in the earlier Section 2) and informal research planning consultations with both industry partners. The initial literature review established the background context of the study: the benefit of tracking construction logistics, what tracking technology is available, the advantages and disadvantages of each system. Further, the literature established the potential future implications for construction tracking through the advances of internet-enabled tracking, as is discussed in the next section. The research planning consultations drew on qualitative research methods to establish an industry-led perspective on the key factors contributing to the problem and possible solutions. These informal consultations formed part of the research project planning meetings and sought input from the research project leads from both industry partners to inform the research test design. Partner A provided a synthesis of existing sensitive commercial project execution issues in logistics activities by means of aggregated data from past project reviews, presented to the research team by the research project lead to inform the test design. Further, Partner A provided detailed understanding of their manufacturing processes, as well as contact with their 3rd party logistics providers in order that the tests be designed to integrate with their existing systems. This input provided valuable context to *RQ1*. Data provided by Partner B, related to the technical possibilities of the BLEAT tracking technology, enabling the research test design to be tailored effectively for response to *RQ2* and *RQ3*. The second phase of the research activity used applied research methods through the development of a case study exercise to test a proof of concept on a large-scale construction research prototype – now described in Section 4.

4. Case Study test design: Bluetooth low energy aware tracking

The research design and execution of this second phase of research comprises a case study of construction material tracking tests. These tests consisted of the tracking of logistics activities in the component manufacture, material supply, transport and assembly phases. A case study was selected as the most appropriate mechanism for data capture in responding to *RQ1* and *RQ2*, as each of the four tests covered activities involved in the typical logistics value chain for industrialized construction.

4.1 Design of tracking tests within the mass timber prototyping project

Having previously used RFID tracking and established protocols for its use to track construction elements on large scale projects, this was the first time Partner A had implemented the use of Bluetooth technology for tracking. This lack of familiarity meant that tracking tests assessing system viability were nominated as an important research outcome.

The primary objective of the tests was to demonstrate the viability of introducing BLEAT tracking technology to the manufacture and site assembly of mass timber building components. Further, the tests would reveal the forms and granularity of data able to be captured from the manufacturing and assembly processes to establish its use and impact on future design iterations. Within the controlled prototyping project, the suitability of Bluetooth tracking technology could be assessed before being used on commercial projects.

The form of each tracking test was co-designed through collaborative meetings involving the research team and representatives from Partners A and B that identified four test phases: off-site manufacture/processing of components; third party material supply; transportation; and on-site component assembly.

4.1.1 Test 1: manufacture and component processing. Glued laminated and cross-laminated timber is well suited to factory prefabrication and industrialized construction more broadly. This suitability manifests in the milling and routing required to process large-format timber elements, processes that are suited to automation. Tracking data related to these timber processing phases can reveal location and quantity of timber that is raw and unprocessed; the start and end times of fabrication and duration of individual timber processing stages; sub-component assembly times; and finally detail of throughput flow and storage location of completed timber building elements.

Tracking tests during this first phase involved the placement of three gateway routers inside and external to the factory setting (Figure 1) to capture and relay data from the BLEAT tags fitted to timber elements. Consultative briefing of factory floor workers was

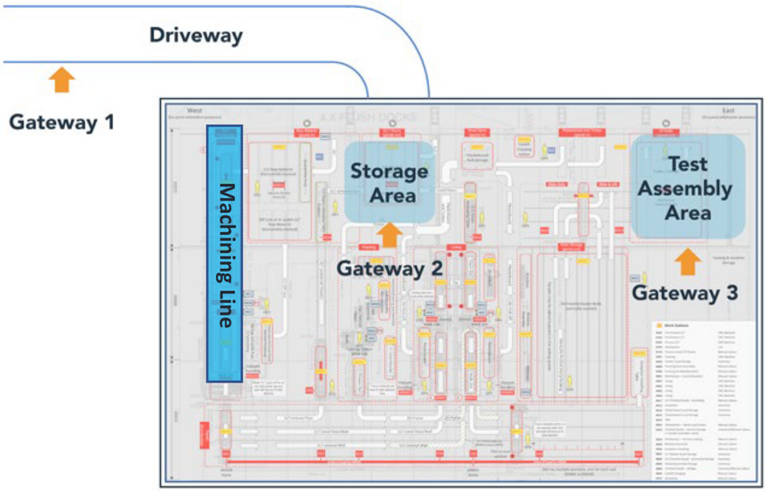

Figure 1.
Arrangement of tracking gateways around factory

conducted to establish the best working processes for the milling and fitting of the BLEAT tracking tags to timber elements (Figure 3).

Gateway 1 (Figure 1) was installed to capture data for any tagged material arriving or leaving the factory. Other gateways (Figure 1) were located internally to capture data related to the processing stages of the mass timber elements (Gateway 2) as well as a preliminary test assembly (Gateway 3). By being adjacent to the unprocessed timber storage, timber machining production line and the finished timber element storage locations, Gateway 2 was able to capture data related to these three phases of manufacturing. Gateway 3 was positioned at the opposite end of the factory floor to pick up data related to an initial prototype assembly test that was run inside the factory.

For the integration of tracking tag installation and activation process with factory floor manufacturing, collaborative discussions were held between the researchers, Partner B and the machining team of Partner A to plan and design the milling of the pockets that would hold the tracking tags (Figure 3) and the tags' activation. It was determined that the pockets needed to be located where the tags could be installed and switched on without impacting manufacturing flow adversely. This was an important factor, as the design of this exercise was critical in planning for future commercial implementation of this activity and reducing its impact on factory flow.

4.1.2 Test 2: third party material supply. The second construction tracking test sat outside of Partner A's direct production activities, focusing on integration with third-party suppliers. Test 2 was developed to understand the complexities of requiring third parties to apply and activate the BLEAT tags in their processes. An aspect of the research activities included the design of base level protocols, comprising simple and straightforward instructions, to allow supply partners to integrate Partner A's initial construction tracking requirements into their internal processes.

One of Partner A's suppliers was selected for the tests, a structural steel connection fabricator in Brisbane who would send finished connection components to Partner A's factory in Sydney. These tags would then be picked up on arrival at Gateway 1 (Figure 1). The test design consisted of selecting steel elements for tracking that represented a diverse range of form, size and weight, creating a picking list to clearly communicate elements for tagging to the supplier (Figure 2) and writing instructions for the application and onboarding of the Bluetooth tracking tags. Tags were then sent by post from Partner B's office in Melbourne to Brisbane for the application to the steel using high-grade fixing tape.

Having been picked up by Gateway 1 on their arrival to Sydney, these components were then delivered to the prototype test assembly area and identified by Gateway 2. The prototype components consisting of tagged individual timber elements and sub-assemblies, as well as these tagged third party supplied steel connections, were then assembled inside the Sydney production facility to test production tolerance and to capture basic assembly tracking data. This trial assembly verified all components were present and manufactured correctly and provided baseline assembly data for all research streams for comparison with the full assembly that was to be conducted in Melbourne. All prototype components were then packed to be transported to Melbourne for the full assembly.

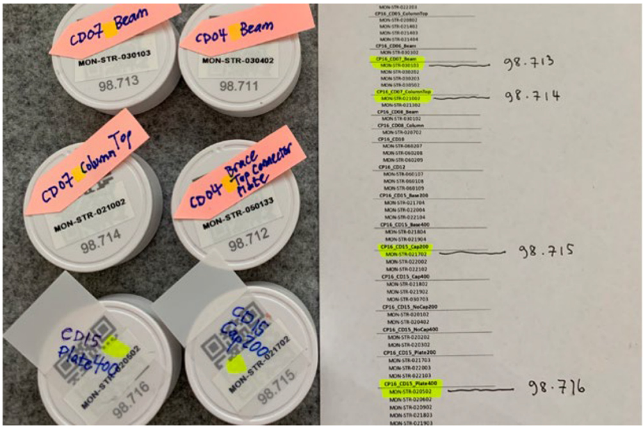

Figure 2.
"Picking list" of steel components with matched tracking tag ID numbers

Figure 3.
Assembled and tagged timber components

4.1.3 Test 3: transportation. While GPS tracking tags can provide global location data in themselves, BLEAT systems rely on a relay system (provided by fixed gateway routers in indoor manufacturing locations or on-site) to provide such information. This presents challenges for tracking in transit. However, the emergence of Bluetooth-enabled smartphones presents an opportunity to create an advantageous and simple work around.

To track the construction prototype materials in transit, the logistics transport contractor's trailer was equipped with a smartphone that would log the BLEAT tags' readings during transit and communicate the location data with a GPS location tag from the smartphone itself, to Partner B's server via 4G. This test would be run while the construction elements were being transported by truck over 1,000 km between Sydney and Melbourne, providing verifiable real-time location data from the smartphone along the route. This test was to provide localization data between the final tag communication on exit at Gateway 1 (Figure 1) and arrival in Melbourne.

4.1.4 Test 4: assembly. The case study prototype project test assembly was conducted at Monash University's Clayton campus in Melbourne. A warehouse was temporarily converted into a construction site, with material set down areas, a mobile crane and a demarked site assembly area. Several stop motion cameras were also installed to document the construction process.

At the assembly site in Melbourne, two gateways were installed. One to provide tracking data from material delivery and set down, the other to capture data as elements were craned from the set down area to installation. To complete data capture, the Bluetooth tracking tags required deactivation upon successful installation (Figure 4). The test was designed so that a researcher would "offboard" the tracking tags at this stage to minimize impact on the site assembly team with a primary research goal concerning assembly speed and efficiency testing. It was acknowledged that future research tests should require site assembly workers to undertake this offboarding process to understand the practical implications of this action.

5. Findings: implications of construction tracking and new forms of data

The data provided by the tracking tests reveal the significant potential for future development of construction tracking. As noted, an integrated and industrialized construction mindset demands an emphasis on continual improvement of both product and process. While the importance of data in manufacturing processes is widely acknowledged, the construction sector has a poor legacy when it comes to data capture. The case study tests

Figure 4.
Completed prototype

point toward a future where data is captured to inform two types of improvement: the optimization of specific/isolated processes and improvements that are more gradual in nature, focusing on integration of multiple steps in the supply chain. While tracking has become commonplace in logistics transport activities, the tests reveal the other stages of activity where material tracking can deliver valuable information for construction activity – off-site manufacturing, material supply and site assembly tasks. As data emerges from each of these stages, improvements are likely to be readily considered from the perspective of individual task optimization. However, the case study tests, and research approach demonstrates that the most significant benefits are likely to be derived from a more synthetic and integrated approach when considering data driven improvements.

In summary, this study's findings respond to the research questions as follows:

RQ1. How can tracking systems be integrated into industrialized construction workflows?

The tests found that with appropriate training and clear communication, tracking systems can be easily integrated into construction elements and workflows. The tests demonstrated that the tracking system could be integrated through consultation for internal manufacturing workflows, effective written instructions for external supply partners and identified limitations and improvements required for assembly teams to offboard the system:

RQ2. What data can be obtained from the tracking of activities?

The tracking data captured during these activities demonstrated the granularity of location data to be appropriate for the construction system. At the current technological stage, Partner B's tracking tags provide data pertaining to element locations during manufacturing, transport and arrival at site. Future hardware will bring greater granularity, providing more detailed site location capability that is currently handled by positioning of gateways:

RQ3. How can this data influence design decisions at the front-end of projects?

The tests conducted during the mass timber prototyping project suggest that data generated from tracking logistics activities will inform and improve Partner A's internal design activities. From tracking component manufacture to site installation, comes information for designers that will influence future component performance improvements, particularly with regards DfMA and design for logistics and handling making for greater efficiency through design.

More specifically, this research finds that one of the most significant opportunities for data provided by the tracking of construction activities is in front-end design activities. Industrialized construction demands and benefits from a strategic consideration of activities. This strategic view reframes construction away from project-thinking, toward platform-thinking, where data processes, and products are captured, coordinated and designed for continual improvement. This platform approach creates a centralized, continually improving repository of knowledge that is held separately from day-to-day project implementation activities. When logistics is considered strategically, benefit is derived from modular and reusable approaches held within such a platform for implementation in the early project design phase. Similarly, the data capture in the research prototyping described in the case study, reveals that the output data from manufacturing through to assembly could be isolated and refined at the platform level for specific project design improvements.

6. Discussion: tracking test outcomes

The construction tracking tests were synchronized with the manufacture, delivery and assembly of the prototype. The tests allowed an assessment to be made of essential supply chain management protocols in a controlled research-focused environment. Each test phase provided valuable insight in response to the research questions at each of Partner A's off-site manufacturing processes, third party supply activities, transportation and on-site assembly tasks. A discussion of the test outcomes at each of these stages now follows, with a discussion of the study's limitations.

6.1 Integration with internal activities

A series of collaborative briefings, presentations and workshops created a clear and close working relationship between the researchers, the design and manufacturing teams of Partner A and the operational data tracking representatives of Partner B. The result of the collaborative test design meant that in practice the tracking tags were incorporated into the machined timber components of the prototype without issue. Both machining stages and worker processes were successfully adapted to ensure placement and onboarding of the tags. The tracking tags were also modeled into the digital twin during the design phase not only allowing design and manufacturing co-ordination but pointing toward valuable future opportunity for data integration to allow the Bluetooth tracking tags future communication with the Digital Twin model. The housings for the tags were cut into the components using the automated manufacturing equipment. Tags were successfully placed into the components and onboarded by workers using instructions communicated via Partner B's smartphone app. The commercial development of this smartphone app, and Partner B's online IoT platform, was directly informed by these interactions in the acknowledgment of the research project adding further value beyond the immediate proof of concept research tests. Gateways were installed in Partner A's manufacturing facility providing base-level tracking data of manufacturing stages. Future versions of Partner B's technology (proposed to be available in 2021) will provide greater granularity of manufacturing stage tracking. This test confirmed the appropriateness and ease of integration of the BLEAT tracking technology for mass timber production.

6.2 Third party supplier integration

Structural steel connection elements to fix the CLT components together were tracked from a third-party supplier warehouse in Brisbane to Partner A's manufacturing facility in Sydney. Tracking tags were posted to the supplier with basic instructions for their application to the steel and onboarding. This test demonstrated the simplicity of the integration with material suppliers and showed the possibility for such tracking activities to provide data on supplier performance as well its potential for more complex international supplier manufacturing tracking in the future. If this test was expanded to include similar installation of gateways within the third-party manufacturing plant, then greater visibility would be provided of progress prior to distribution.

6.3 Material transportation tracking

Automated material tracking occurred between the Sydney manufacturing facility and the Research Institution's installation site in Melbourne. Both facilities had gateways installed and departure/arrival times were logged as the prototype materials were transported south to Melbourne. This test was structured to provide real-time tracking data between facilities through the smartphone located in the transport truck's cab reading the BLEAT tag signals. Unfortunately, the smartphone that was sent from Partner B's HQ in Melbourne to Partner A in Sydney was not delivered in time by Australia Post. Consequently, this test was a partial failure, as transport times were only logged at departure and arrival, not real-time. However, Partner B has previously conducted successful real-time transport tests. Real-time transport tracking will allow "Just-in-Time" construction site deliveries as well as automated predictive and responsive scheduling based on progress and site conditions (Lu *et al.*, 2007). Such an approach would drive more responsive modes of site management allowing construction schedules to quickly change as a result of unpredictable weather patterns or other unexpected delays. Further potential exists for accelerometers to be incorporated in the tags to provide historical handling information, giving assembly teams material impact and damage alerts, providing an important source of component design feedback.

6.4 Installation duration

Access restrictions because of health and safety limitations during the prototype assembly phase prevented the tags from being "off-boarded" immediately after component installation. Difficulties in the off-boarding process (tags having to be manually accessed and switched off) meant that researchers, rather than the site installation team, conducted this task. This test was categorized as a technical failure but highlighted the importance of ensuring that Partner B's off-boarding processes are suited to the working methods of construction site assembly teams. A remote, smartphone-enabled off-boarding process would be more streamlined, allowing site installers to use a smartphone to deactivate tracking tags on installed members. Alternatively, tags with greater technological capability could respond to movement (through accelerometers or gyroscopes) and switch themselves off to record installation time.

6.5 Limitations and drawbacks

The primary limitation of this logistics tracking study is that it involved a single scenario of analysis – the tracking of primary structure and its connections – with two stakeholder participants. Construction projects are complex in their range of material elements and number of participants, and further research is required to understand how a broader tracking network will emerge.

Part of this future research will be to test how logistics tracking technology can be integrated in the existing processes of the stakeholders' workforce and to identify future training needs and develop detailed protocols for tracking integration with third party material suppliers.

In terms of the BLEAT technology trialed, while there are some clear advantages discussed over other tracking systems, the beacons used in this trial were a first-generation model that relies on battery power and requires manual switching on/off by the workforce. The tags were used on material that was easily machined with clear production processes, as opposed to complex systems that would be more challenging to track, such as building services installations.

These limitations point to valuable future research that will test the next generation of BLEAT technology in concert with more complex construction assembly systems.

7. Conclusion

The construction tracking tests undertaken during the prototyping research project identify BLEAT technology to be appropriate for industrialized mass timber construction systems, particularly because of its ease of integration with existing processes and the technologies' future potential for multi-capability sensors beyond localization. Further, the tests highlight the potential for the technology to provide new data to drive further logistics improvements through design, particularly with regards DfMA.

The four construction tracking test phases resulted in several industry-led changes. Partner B is now refining their off-boarding process in response to the outcomes of the prototyping project, highlighting the invaluable contribution of applied research in bridging the gap between academic research and industry implementation. Construction tracking data captured by the BLEAT tags was also defined as a valuable source of DfMA data for Partner A, to improve and verify early design decisions based on manufacturing and assembly phase outcomes. The linking of construction tracking to early design decision-making further validated the applied design research approach of the prototyping project, seeking holistic improvements from the overlaps between research streams rather than the optimization of individual areas.

The main contribution of this study lies in the integrative nature of the tracking tests that demonstrate the value of tracking logistics for improved design outcomes. While an isolated testing approach may have provided more "pure" test outcomes, by pursuing an approach that sought deep and specific integration with the individual activities of design, manufacturing, supply, transport and assembly tasks, a broader range of opportunities and issues were identified for future improvement as well as commercial application of the system.

Future avenues of research lie in the monitoring of design improvements based on the data provided by the construction tracking, as well as investigating more avenues of data through a broader scope of construction tracking tests. More research is required regarding the technological development of the BLEAT technology as well, which will enable more fine-grain localization data to be captured, allowing greater detail of manufacturing tracking, material storage and selection as well as on-site positioning and installation. These tests will see tags equipped with increased functionality, e.g. building performance or movement sensors, which will enable data to be captured beyond the construction logistics phases into building occupation.

References

Abdel-Wahab, M. and Vogl, B. (2011), "Trends of productivity growth in the construction industry across Europe, US and Japan", *Construction Management and Economics*, Vol. 29 No. 6, pp. 635-644.

Anandhi, S., Anitha, R. and Sureshkumar, V. (2019), "IoT enabled RFID authentication and secure object tracking system for smart logistics", *Wireless Personal Communications*, Vol. 104 No. 2, pp. 543-560.

Bankvall, L., Bygballe, L.E., Dubois, A. and Jahre, M. (2010), "Interdependence in supply chains and projects in construction", *Supply Chain Management: An International Journal*, Vol. 15 No. 5, pp. 385-393.

Behera, P., Mohanty, R.P. and Prakash, A. (2015), "Understanding construction supply chain management", *Production Planning and Control*, Vol. 26 No. 16, pp. 1332-1350.

Bhargava, P., Krishnamoorthy, S., Shrivastava, A., Nakshathri, A.K., Mah, M. and Agrawala, A. (2015), "Locus: robust and calibration-free indoor localization, tracking and navigation for multi-story buildings", *Journal of Location Based Services*, Vol. 9 No. 3, pp. 187-208.

Bilal, M., Oyedele, L.O., Qadir, J., Munir, K., Ajayi, S.O., Akinade, O.O., Owolabi, H.A., Alaka, H.A. and Pasha, M. (2016), "Big data in the construction industry: a review of present status, opportunities, and future trends", *Advanced Engineering Informatics*, Vol. 30 No. 3, pp. 500-521.

Bygballe, L.E. and Ingemansson, M. (2014), "The logic of innovation in construction", *Industrial Marketing Management*, Vol. 43 No. 3, pp. 512-524.

Cowen, D. (2010), "A geography of logistics: market authority and the security of supply chains", *Annals of the Association of American Geographers*, Vol. 100 No. 3, pp. 600-620.

CSIRO. (2016), "Bluetooth low energy aware tracking", available at: https://research.csiro.au/dss/bluetooth-low-energy-aware-tracking-bleat/ (accessed 12 March 2020).

Čuš-Babič, N., Rebolj, D., Nekrep-Perc, M. and Podbreznik, P. (2014), "Supply-chain transparency within industrialized construction projects", *Computers in Industry*, Vol. 65 No. 2, pp. 345-353.

Dainty, A. (2008), "Methodological pluralism in construction management research", in Knight, A. and Ruddock, L. (Eds), *Advanced Research Methods in the Built Environment*, John Wiley and Sons, Hoboken, NJ.

Dargie, W. and Poellabauer, C. (2010), *Fundamentals of Wireless Sensor Networks: Theory and Practice*, John Wiley and Sons, Hoboken, NJ.

Ding, Y., Jin, M., Li, S. and Feng, D. (2021), "Smart logistics based on the internet of things technology: an overview", *International Journal of Logistics Research and Applications*, Vol. 24 No. 4, pp. 323-345.

Dubois, A. and Gadde, L.-E. (2000), "Supply strategy and network effects – purchasing behaviour in the construction industry", *European Journal of Purchasing and Supply Management*, Vol. 6 Nos 3/4, pp. 207-215.

Dubois, A. and Gadde, L.-E. (2002), "The construction industry as a loosely coupled system: implications for productivity and innovation", *Construction Management and Economics*, Vol. 20 No. 7, pp. 621-631.

Egan, S.J. (1998), *Rethinking Construction*, Department of Trade and Industry, London.

Haughian, B. (2018), *Design, Launch, and Scale IoT Services: A Practical Business Approach*, Apress, New York, NY.

Hedrick, T.E. (1993), "The nature of applied research", *Applied Research Design: A Practical Guide*, SAGE, London.

Hightower, J. and Borriello, G. (2001), "Location systems for ubiquitous computing", *Computer*, Vol. 34 No. 8, pp. 57-66.

Hofmann, E. and Rüsch, M. (2017), "Industry 4.0 and the current status as well as future prospects on logistics", *Computers in Industry*, Vol. 89, pp. 23-34.

Hwang, B.-G., Thomas, S.R., Haas, C.T. and Caldas, C.H. (2009), "Measuring the impact of rework on construction cost performance", *Journal of Construction Engineering and Management*, Vol. 135 No. 3, pp. 187-198.

Johnston, B., Bulbul, T., Beliveau, Y. and Wakefield, R. (2016), "An assessment of pictographic instructions derived from a virtual prototype to support construction assembly procedures", *Automation in Construction*, Vol. 64, pp. 36-53.

Joyce, H. (1893), *The History of the Post Office from Its Establishment down to 1836*, R. Bentley and Son, London.

Kagermann, H., Wahlster, W. and Helbig, J. (2013), "Recommendations for implementing the strategic initiative industrie 4.0". Federal Ministry of Education and Research.

Kaur, M., Sandhu, M., Mohan, N. and Sandhu, P.S. (2011), "RFID technology principles, advantages, limitations and its applications", *International Journal of Computer and Electrical Engineering*, Vol. 3, pp. 151-157.

Klinc, R. and Turk, Ž. (2019), "Construction 4.0 – digital transformation of one of the oldest industries", *Economic and Business Review for Central and South – Eastern Europe*, Vol. 21, pp. 393-410,496.

Lessing, J. (2006), "Industrialised house-building: concept and processes".

Li, N. and Becerik-Gerber, B. (2011), "Life-cycle approach for implementing RFID technology in construction: learning from academic and industry use cases", *Journal of Construction Engineering and Management*, Vol. 137 No. 12, p. 1089.

Lu, M., Chen, W., Shen, X., Lam, H.-C. and Liu, J. (2007), "Positioning and tracking construction vehicles in highly dense urban areas and building construction sites", *Automation in Construction*, Vol. 16 No. 5, pp. 647-656.

Meng, X. (2013), "Change in UK construction: moving toward supply chain collaboration", *Journal of Civil Engineering and Management*, Vol. 19 No. 3, pp. 422-432.

Millar, M. (2015), *Global Supply Chain Ecosystems: Strategies for Competitive Advantage in a Complex, Connected World*, Kogan Page, London.

Ni, L.M., Liu, Y., Lau, Y.C. and Patil, A.P. (2004), "LANDMARC: indoor location sensing using active RFID", *Wireless Networks*, Vol. 10 No. 6, pp. 701-710.

Pope, J.A. (2011), *Supply-Chain Survival in the Age of Globalization*, Business Expert Press, New York, NY.

Raza, R. (2013), "Three dimensional localization and tracking for site safety using fusion of computer vision and RFID", PhD Thesis, Michigan State University.

Rudberg, M. and Maxwell, D. (2019), "Exploring logistics strategy in construction", in Farhad, A., Kathryn, E.S., Gregor Von, C. and Dimitris, K. (Eds), *International Conference on Advances in Production Management Systems (APMS)*, *Austin, TX*, Springer International Publishing.

Sawhney, A., Riley, M. and Irizarry, J. (2020), *Construction 4.0: An Innovation Platform for the Built Environment*, Routledge, London.

Thunberg, M. and Persson, F. (2014), "Using the SCOR model's performance measurements to improve construction logistics", *Production Planning and Control*, Vol. 25 Nos 13/14, pp. 1065-1078.

Tischer, A., Besiou, M. and Graubner, C.-A. (2013), "Efficient waste management in construction logistics: a refurbishment case study", *Logistics Research*, Vol. 6 No. 4, pp. 159-171.

Turin, D.A. (2003), "Building as a process", *Building Research and Information*, Vol. 31 No. 2, pp. 180-187.

Vrijhoef, R. and Koskela, L. (2005), "Revisiting the three peculiarities of production in construction", *13th Conference of the International Group for Lean Construction*, *Sydney*.

Wu, C., Wang, X., Chen, M. and Kim, M.J. (2019), "Differential received signal strength based RFID positioning for construction equipment tracking", *Advanced Engineering Informatics*, Vol. 42, p. 100960.

Wurst, C. and Graf, L. (2021), *Disrupting Logistics: startups, Technologies, and Investors Building Future Supply Chains*, Springer, Cham.

Xiang, L.Y., Hwang, H.J., Kim, H.K., Mahmood, M. and Dawi, N.M. (2021), "The use of big data analytics to improve the supply chain performance in logistics industry", in Kim, H. and Lee, R. (Eds), *Software Engineering in IoT, Big Data, Cloud and Mobile Computing*, Springer International Publishing, Cham.

Yin, R.K. (2003), *Case Study Research: Design and Methods*, SAGE, Thousand Oaks, CA.

Corresponding author
Duncan Maxwell can be contacted at: duncan.maxwell@monash.edu