ISSN 1980-5411 (On-line version)
Production, 33, e20220082, 2023
DOI: 10.1590/0103-6513.20220082

Research Article

Drivers and barriers for the traceability digitalisation in the Australian construction supply chain

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Abstract

Paper aims: We investigate the drivers and barriers for the traceability digitalisation of the Australian construction supply chain.

Originality: There is a growing interest in the construction industry for embracing digital technologies. Nevertheless, the digital transition in construction industry is still slow, especially for addressing material traceability.

Research method: An exploratory-empirical study was conducted in which we performed the following steps: (*i*) definition of selection criteria; (*ii*) semi-structured interviews with 26 experts (academics, practitioners and stakeholders); and (*iii*) content analysis and propositions.

Main findings: Results allowed the identification of the most critical drivers and barriers for such traceability digitalisation, being consolidated in a conceptual framework that characterises the early and late adopters of digital technologies in the construction supply chain.

Implications for theory and practice: In theoretical terms, 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. From a practical perspective, the more companies advance in the traceability digitalisation, the more aware they will become regarding its drivers/benefits and barriers/challenges. Nevertheless, some highly critical drivers/benefits and barriers/challenges were equally perceived by both early and late adopters.

Keywords

Traceability. Digital transformation. Construction. Supply chain management.

How to cite this article: Tortorella, G. L., Cox, D., Li, W., & Barros, A. (2023). Drivers and barriers for the traceability digitalisation in the Australian construction supply chain. *Production*, *33*, e20220082. https://doi.org/10.1590/0103-6513.20220082

Received: June 28, 2022; Accepted: Dec. 6, 2022.

1. Introduction

The construction industry is expected to become a global engine for economic growth and post pandemic recovery, having a global growth by 42% and yielding US$15.2 trillion by 2030 (Oxford Economics Group, 2021). Construction supply chain is one of the critical enablers for this booming industry but also poses challenges and risks (Hackitt, 2018; Adel et al., 2022). This is mainly due to the typical make-to-order nature of construction supply chain, which is often instable, highly fragmented, and geographically dispersed (Vrijhoef & Koskela, 2000; Gharaibeh et al., 2022). Owing to the permanent inward immigration and acceleration of infrastructural investment, Australia is ranked 5th for the construction growth among both emerging and developed economies (Oxford Economics Group, 2021).

The ability to track and trace, or called traceability, is becoming increasingly important as all materials converging to the construction site from a global supply chain. This is highlighted in the Hackitt Review after the tragic Grenfell Tower incident in London (Hackitt, 2018). The report identified that lacking product traceability is a contributory factor to fire safety systems being compromised. Apart from the compliance risks, the soaring commodity prices (e.g., steel and timber) and prolonging lead time in the building sector have further stressed the need for traceability along the complex construction supply chain so the project progress and budget can be monitored and managed efficiently. Furthermore, traceability can also contribute to improve the sustainability of the building sector through responsible sourcing and life cycle management (Glass et al., 2011). However, the adoption of traceability in the construction industry is significantly lagging behind other sectors and has been urged to accelerate (Hackitt, 2018).

Amid the digitalization era, industries across multiple sectors advance through the use of digital technologies, such as digital-twin, Internet-of-Things (IoT), cloud computing, blockchain, and artificial intelligence. There is a growing interest in the construction industry for embracing digital technologies, and technology providers (e.g., Oracle) have committed significant investments into this sector (Rogers, 2019). Nevertheless, while manufacturing sector has seen benefits of using “digital thread” for improving supply chain efficiency, the digital transition in construction industry is still slow, especially for addressing the need of material traceability (Zhong et al., 2017; Wang et al., 2020; Filippo et al., 2022). Although researchers proposed framework for encourage digitalisation in the construction industry (Hossain & Nadeem, 2019), studies that approach this topic are still scarce. Hence, there is the need to understand why construction supply chain is reluctant and the views of key stakeholders. Against this backdrop, we formulated the following research question:

“*What are the main drivers and barriers for the traceability digitalisation in the construction supply chain?*”

To address this gap and answer the aforementioned question, this paper aims to investigate the main drivers and barriers for the traceability digitalisation in the Australian construction supply chain. For that, we conducted semi-structured interviews with 25 experts from the academia, construction supply chain companies (i.e., contractors, sub-contractors, and material suppliers), and stakeholders (i.e., technology providers and regulatory agencies). The data collection and content analysis were grounded on the concepts from the diffusion of innovation theory (DIT) from Rogers (1995), which states that five attributes affect the rate of innovation adoption, namely: (*i*) relative advantage, (*ii*) observability, (*iii*) compatibility, (*iv*) trialability, and (*v*) complexity. Based on the commonalities found among interviewees arguments, we categorised the main drivers and barriers for such digitalisation. Further, following DIT’s assumptions, the perception on these attributes was used to distinguish the drivers and barriers between companies considered as early and late adopters.

The remaining of this paper is structured as follows. Section 2 presents the background on the fundamental concepts approached in our study. Section 3 describes the applied methodology, whose results are presented and discussed in section 4. Section 5 concludes the article and indicates future research opportunities.

2. Background

2.1. Traceability in construction sector

Traceability is a critical requirement for the effective management of construction projects, given the scale of coordination across diverse providers, suppliers, and stakeholders in long-running, concurrent, and commercially sensitive processes. It applies to physical resources, by way of materials, equipment, and people that flow and interact through the processes (Olsen & Borit, 2013). Given the administrative and digitalised aspect of construction, traceability also applies to informational artifacts, such as forms, documents, and digital records. To track and trace these requires more than determining the proximities of resources and informational artifacts, in terms of location and time. It also needs to be understood in relation to processes and constraints, expectations, and deviations (Arkley & Riddle, 2005; Zhong et al., 2017).

In general, traceability is framed through specific requirements in which materials, resources and equipment need to shift across locations to be available for undertaking activities in processes and fulfilling their outcomes. The obvious case of this is the movement of materials as part of construction work on sites, through which materials are used to construct foundations or building structures (Melo et al., 2013; Wang et al., 2020). However, construction involves several intersecting value-chains which lead to the movement of materials or directly involve their movements, consistent with business model structuring of asset-intense domains (Berg et al., 2021).

Construction-related supply chains include design-to-procurement, manufacturing-to-supply, site construction, and acceptance-to-maintenance (Pegoraro & Paula, 2017). Hence, the need for traceability arises from resource and informational artifact movements across the multitude of activities in such value chains (Lee et al., 2021).

A coherent strategy for traceability entails not only cognisance of the processes across the lifecycle of construction projects and their different value chains, but, therein, the ability to refer to and access, specific requirements, captured through different informational artifacts (Arkley & Riddle, 2005; Osorio-Gomez et al., 2020).

2.2. Construction supply chain and digitalisation initiatives

The design and structural detailing for construction projects fall within the demand value chain (Wu et al., 2022). Two broad and concurrent triggers flow from this phase of the value chain. The first is production planning through which a project plan/specification is developed and approved. This details the measurable construction line items within time periods and budget allocations, and with supply and deliver to site points of materials, engagement of contractors and subcontractors through designated trades and roles, and the requisite reporting and auditing protocols. The second is the procurements and fulfillments activities through which the supply for materials includes requisitioning and approvals, tenders and quotations, singleton and cyclic delivery, invoicing, and payments. For the activities of these two phases of the value chain, both BIM and enterprise resource planning (ERP) (Magal & Word, 2012) systems are relevant.

Both systems provide back-office processes for production plan generation and hence carry overlaps. BIM processes are more tightly coupled to construction specification processes while ERP are broad-ranging in terms of enterprise “backoffice” support, integrating processes for human resource management, financial and management accounting, asset management etc. Regardless of which type of system is preferred for production planning, BIM data and processes need to be integrated with those of ERP systems, given that ERP systems are used for the core administrative processes of the construction “enterprise” – i.e., managing procurements and fulfillments, accounting, and payments. It is important to note that the level of objectification across BIM and ERP systems are different, which present traceability challenges. 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 (Kerosuo et al., 2015; Celik et al., 2023).

The fulfillments (supplier to delivery) activities fall into a supply-side value chain. For construction projects, materials and composite parts of construction require typically offsite, near-site or on-site manufacturing, in line with contemporary trends of modular manufacturing. While ERP systems are instrumental for manufacturing processes, domain-specific manufacturing tools are also utilised (Fettermann et al., 2019). Moreover, the supply side processes are supported by further enterprise systems by way of supply chain management systems and transportation management systems. The procurements side is coordinated by contractor/client organisations while the fulfillments 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, on site, entails a merger of demand and supply, leading to a delivery chain (Nascimento et al., 2018). This is where project plans and procurement processes need to be synchronised so that scheduled work can proceed, with the required human and equipment resources as well as building materials in place (Avelar et al., 2019). Construction, being essentially physical and human-collaborative carries physical work, which is periodically tracked through administrative processes – i.e., BIM and ERP systems given the distinct administrative roles both play with BIM/ERP used for project management and ERP used for payments, invoice and interfacing to supply and manufacturing processes (Babič et al., 2010). Hence, traceability for construction activities also needs to be qualified as to whether it involves physical tracing on construction sites or tracing through administrative processes and their supply side integration (Krainer et al., 2018).

In addition to software solutions, distributed platforms of the IoT are allowing for increased automation of traceability. Under the IoT, physical object movements and contexts (e.g., temperature and lighting) monitored and controlled through sensors and actuators, and data is transceived, via gateways, with Cloud systems, providing intelligent analytics and decision support (Fettermann et al., 2018; Narayanamurthy & Tortorella, 2021). The IoT vision extends the scope of coordination to business contexts, where business processes are integrated with physical operations in support of more coherent traceability (Buchwald & Anus, 2020). Examples for an IoT for construction include: the tracking of worker, equipment, and material movements for conformance with project schedules and site access constraints; real-time fault detection of materials and reporting to the relevant workers, site managers and suppliers; and autonomous wayfinding of stock supply to assembly points (e.g., sites, buildings, levels, and spaces) given highly variable construction progress. More recently, proposals have emerged for business processes to be embedded to run directly on IoT devices to support real-time, low-latency traceability actions - on site (Lu, 2017).

3. Methodology

As the digitalisation of construction supply chain traceability is still underexplored, a qualitative approach was carried out corroborating to the exploratory and descriptive nature of our study (Voss et al., 2002; Barratt et al., 2011). Following Ketokivi & Choi (2014), the study used *a priori* theorization to frame the research design; findings are therefore not statistically generalizable. That offered an in-depth understanding of the drivers, barriers, challenges and benefits from the digitalisation of the construction supply chain traceability, producing novel insights to the field.

The methodological design consisted of three main steps: (*i*) definition of selection criteria; (*ii*) interviews with experts; and (*iii*) content analysis and propositions. These steps are detailed next (see Figure 1).

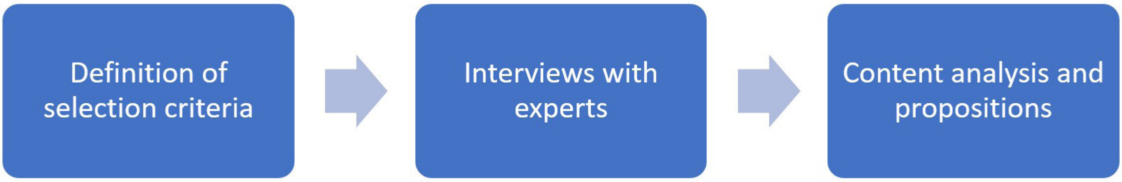

Figure 1. Methodological steps of this research.

3.1. 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 three 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 were composed by 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 utilizing the ones that were clearly associated with the context in which the expert is inserted. Two of the authors individually analysed interviews' transcripts to increase the reliability and mitigate biased findings, as performed by Tortorella et al. (2021).

Finally, 26 experts were identified and invited to participate in the research. Their profiles are summarized in Table 1. 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, as recommended by Shetty (2020).

The data collection method that helped to achieve the shape of interviewees in Table 1 was also based on theoretical sampling. According to Corbin & Strauss (2008, p. 143), its purpose is to "collect data from places, people, and events that will maximize opportunities to develop concepts in terms of their properties and dimensions, uncover variations, and identify relationship between concepts". The difference of theoretical sampling from conventional methods of sampling is that it 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 [e.g., Guest et al. (2006), Fugard & Potts (2015), Braun & Clarke (2016), Boddy (2016)] have recommended a minimum sample size of at least twelve 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 (Vasileiou et al., 2018). 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.

Table 1. Interviewees' profiles.

Category		Interviewee	Work experience (years)	Role	Organization size
Academics	Construction Management	A1	12	Senior Lecturer	>15,000 Students
		A2	18	Senior Lecturer	>15,000 Students
		A3	17	Associate Professor	>15,000 Students
		A4	9	Senior Lecturer	>15,000 Students
	Engineering, Design & Built Environment	A5	15	Dean	>15,000 Students
		A6	19	Professor	>15,000 Students
	Virtual Design and Construction	A7	28	Professor	>15,000 Students
Practitioners	Contractors	P1	15	Business Developing Manager	>500 Employees
		P2	10	Sustainability Manager	>500 Employees
		P3	13	Supply Chain Management	>500 Employees
		P4	12	General Manager	>500 Employees
		P5	11	Procurement Manager	<500 Employees
		P6	22	Procurement Manager	>500 Employee
		P7	25	General Manager	<500 Employees
		P8	10	Senior Project Manager	>500 Employees
	Sub-Contractors	P9	25	Director, State Manager	<500 Employees
		P10	17	Engineering Manager	<500 Employees
		P11	28	Operations Manager	<500 Employees
	Material suppliers	P12	17	Contracts and Procurement General Manager	>500 Employees
		P13	15	Innovation Manager	>500 Employees
Stakeholders	Technology providers	S1	12	Solutions Consultant	>500 Employees
		S2	19	Co-founder	<500 Employees
		S3	16	CEO	<500 Employees
		S4	13	National Business Developer	>500 Employees
	Regulatory Agencies	S5	21	Senior Research Advisor	<500 Employees
		S6	17	Sustainable Building Advisor	<500 Employees

3.2. 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 A) that allowed open answers. Questions were grouped into four parts. The first part comprised the professional background of interviewees. The second part sought information on their current traceability practices and technologies. The third part aimed at identifying the barriers and challenges for further digitalization of traceability in the construction supply chain, while the fourth part involved the assessment of the drivers and benefits for that.

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 subsequent ones, as recommended by Guest et al. (2017). Interviews were attended by at least two of the authors, thus increasing the ability to handle contextual information confidently (Dubé & Paré, 2003).

Information was transcribed and subsequently analyzed and discussed by the authors; summaries were then merged after reaching consensus on the main findings (Miles & Huberman, 1994). 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.

3.3. Content analysis and propositions

In this step, we performed a content analysis of information gathered in interviews to develop a chain of evidence (Carter et al., 2014) that supported the formulation and categorisation of our findings. Information was grouped into two main categories: (*i*) drivers and benefits, (*ii*) challenges and barriers. Further, those categories were stressed according to five innovation attributes (Rogers, 1995) that may affect the digitalisation of the construction supply chain traceability, namely:

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 (Scott et al., 2008);

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 (Kaminski, 2011);

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 (Greenhalgh et al., 2004);

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; and

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 (Straub, 2009).

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 (qualitative analysis) of those items within each type of interviewee. Following Pagliosa et al. (2019) indications, items that were mentioned by 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 two of the researchers and, whenever a disagreement on one item was found, 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. Highly critical items were denoted for situations in which both frequency of citation and emphasis in the arguments were high. The criticality analysis enabled the prioritisation of the drivers/benefits and barriers/challenges in each innovation attribute.

The highly critical items had then their frequency of mentioning compared 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 allowed the identification of trends in drivers/benefits and barriers/challenges for the digitalisation of traceability across the construction supply chain. Having described the research methods and procedures, attention is turned to the core results provided at the following section.

4. Results

We now present the results from the semi-structured interviews. The main comments made by interviewees (Appendix B) were transcribed, coded, and analysed, leading to the consolidation of a total of 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 2. 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 2.

For relative advantage, five drivers/benefits stood out; they are: (*i*) *greater efficiency and productivity*, (*ii*) *improved sustainability*, (*iii*) *value gained*, (*iv*) *enhanced quality*, and (*v*) *more accessible product information.*

Table 2. 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 small and medium enterprises)	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
		Not Every Material is Worth Tracking	LOW	LOW			HIGH	LOW

Items mentioned by ≤ 33.3% of interviewees were considered lowly frequent, while items whose frequencies were > 33.3 were denoted as highly frequent; Emphasis level was qualitatively based on the strength of arguments or examples provided during the interviews; Gray cells indicate highly critical driver/benefits and barriers/challenges.

Table 2. Continued...

DIT's attributes		Elements	Academics		Practitioners		Stakeholders	
			Emphasis	Frequency	Emphasis	Frequency	Emphasis	Frequency
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
		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
	Barriers and challenges	Improve Response to Trade War Issues			HIGH	LOW		
		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		

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Table 2. Continued...

DIT's attributes		Elements	Academics		Practitioners		Stakeholders	
			Emphasis	Frequency	Emphasis	Frequency	Emphasis	Frequency
		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		
	Drivers and benefits	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		
Complexity		Distinctions in Traceability Processes			HIGH	LOW		
		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		
	Barriers and challenges	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

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Table 2. Continued...

DIT's attributes		Elements	Academics		Practitioners		Stakeholders	
			Emphasis	Frequency	Emphasis	Frequency	Emphasis	Frequency
Trialability	Drivers and benefits	Growing Interest in Trialling Technology			LOW	LOW		
		Positive Experiences Fostering More Trials			HIGH	LOW	HIGH	LOW
	Barriers and challenges	Workers Will Trial Engaging Products	HIGH	LOW				
		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	

Items mentioned by ≤ 33.3% of interviewees were considered lowly frequent, while items whose frequencies were > 33.3 were denoted as highly frequent; Emphasis level was qualitatively based on the strength of arguments or examples provided during the interviews; Gray cells indicate highly critical driver/benefits and barriers/challenges.

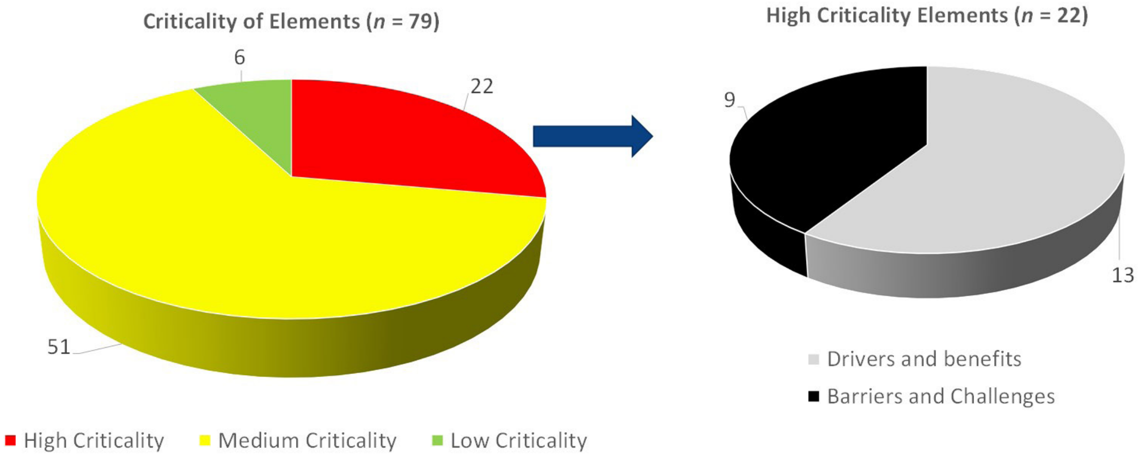

Figure 2. Distribution of criticality levels among all driver/benefits and barriers/challenges.

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 the incorporation of digital technologies into the 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.

From a compatibility standpoint, three drivers/benefits (i.e., *introduce government mandate*, *enhance supply chain collaboration*, and *educated local workforce*) were considered highly critical, while two barriers/challenges (i.e., *limited data accessibility/sharing*, and *end-to-end supply chain requirements*) were deemed as highly critical. It is worth mentioning that out of those five highly critical elements, academics pointed four of them, and practitioners and stakeholders indicated three 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, being the first two raised by academics and the third one suggested by stakeholders. In turn, from the ten barriers/challenges consolidated only the *existence of many different systems (software interoperability)* was pointed as highly critical by 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, three drivers/benefits and two 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 drive/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 attributed presented the largest number of highly critical barriers/challenges, suggesting a particular concern with the visibility of the results implied by the digitalisation of the traceability in the construction supply chain. Four barriers/challenges were both emphatically and frequently mentioned; they are: (*i*) *reactive responsiveness*, (*ii*) *short term relationships*, (*iii*) *unbalanced risk across the supply chain*, and (*iv*) *unbalanced bargaining power*.

Then, the thirteen highly critical drivers/benefits had their frequency of mentioning compared between early and late adopters of digital technologies in the construction supply chain. As displayed in Figure 3, 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 only cited them in 39% of the cases. Two of the highly critical drivers/benefits were only claimed by early adopters, they are: support premanufacturing strategies, and provide a visualisation system of data/models. A similar trend was observed for the nine barriers/challenges denoted as highly critical (see Figure 4). Early adopters commented about these barriers/challenges in 63% of the cases, whereas late adopters suggested them in only 37% of the time. Further, two barriers/challenges – *end-to-end supply chain requirements* and *existence of many different systems (interoperability)* – were only mentioned by early adopters.

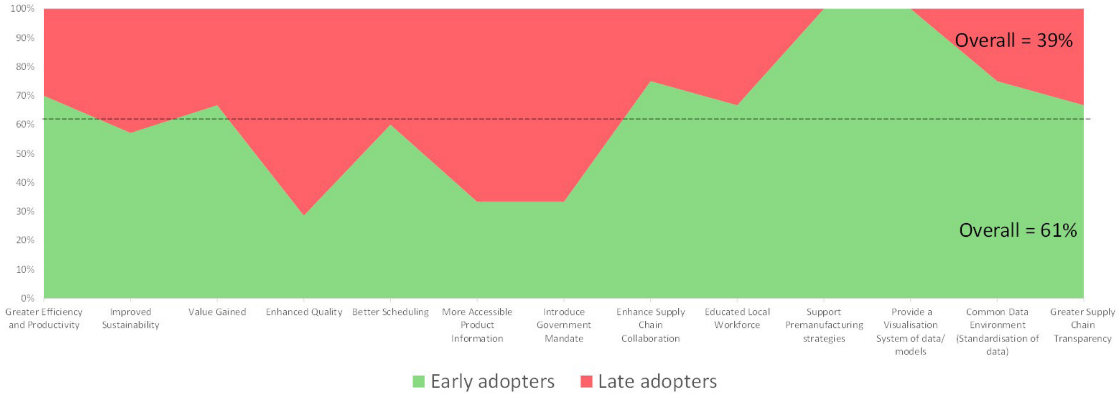

Figure 3. Frequency of mentioning of highly critical drivers and benefits between early and late adopters.

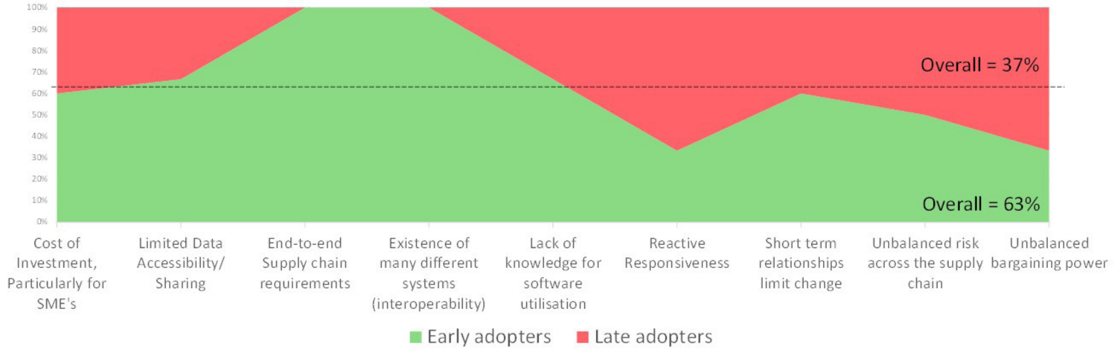

Figure 4. Frequency of mentioning of highly critical barriers and challenges between early and late adopters.

5. Discussion

Now we discuss our results in light of the existing body of knowledge. The predominance of early adopters' perceptions in the frequency of mentioning of highly critical drivers/benefits and barriers/challenges suggests a higher awareness related to the digitalisation of traceability systems in the construction supply chain. Following the concepts from hierarchy of competences proposed May & Kruger (1988), whose ideas about were later extrapolated to the organizational context (Thompson & Martin, 2010), this outcome may be associated with the existence of four competency levels: (*i*) unconsciously incompetent, (*ii*) consciously incompetent, (*iii*) consciously competent, and (*iv*) unconsciously competent. In our case, late adopters are expected to lack of proficiency and be unaware of the necessary skills to digitalise the traceability in the construction supply chain. This might explain the lower awareness level and, hence, frequency of mentioning, of the highly critical driver/benefits and barriers/challenges related to the traceability digitalisation. In this sense, late adopters could be positioned in the very 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 in the construction supply chain, which make 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 that early adopters are likely to be consciously incompetent when considering the digital traceability in the construction supply chain. This finding is also somewhat aligned with the indications from Adel et al. (2022) and Gharaibeh et al. (2022), which suggested that the digitalization of the construction supply chain is still at early stages when compared to other industry sectors.

Nevertheless, it is worth highlighting that 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 for the digitalisation of the construction supply chain traceability is equally acknowledged regardless the company's stage in the hierarchy of competences. In other words, may be even more prominent and, hence, should be firstly addressed in the traceability digitalisation. Such outcome complements the work from Wang et al. (2020) and Filippo et al. (2022), as we provide the clear indications of which drivers/benefits and barriers/challenges are more likely to be observed in the traceability digitalization of the construction supply chain.

6. Conclusions and future opportunities

In this study, we aimed at identifying the drivers/benefits and barriers/challenges for the digitalisation of the construction supply chain traceability. Based on data collected through semi-structured interviews with experts (academics, practitioners, and stakeholders), we consolidated 79 elements, being 44 of them drivers/benefits and 35 barriers/challenges. Out of those, 22 elements (13 drivers/benefits and 9 barriers/challenges) were assessed as highly critical for a successful digitalisation of the traceability systems.

Experts apparently deem more prominently the drivers/benefits that promote real advantages in relation 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 the digitalisation of the construction supply chain. It is worth mentioning that some highly critical drivers/benefits (e.g., *enhance supply chain collaboration*, and *greater supply chain transparency*) may only be fully achieved if the entire construction supply chain really engages in the 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.

Furthermore, companies that already have some initiatives towards the digitalisation of the construction supply chain traceability (early adopters) may be able to understand and visualise the drivers/benefits and barriers/challenges than others that have not started yet (late adopters). This suggests that the more companies advance in the traceability digitalisation, the more aware they will become regarding 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 for such digitalisation.

Some limitations of this study must be highlighted. 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 statistically generalizable findings. Thus, future studies should enlarge the sample size and diversity, enabling the utilisation of more sophisticated multivariate data analysis techniques whose results can complement the ones presented here. Second, larger samples would allow to empirically verify how companies' contextual characteristics may influence the adoption likelihood of digital technologies in the construction supply chain traceability. Further, operational performance could also be included as one of the studied variables, leading to the identification of the relationship between the traceability digitalisation and performance improvement. Finally, the proposition of an implementation roadmap that could guide the construction supply chain agents towards the digital transformation of the traceability systems could be another opportunity for future studies. This roadmap would help to systematize and articulate the digital transformation in an organised way, minimising useless efforts and increasing the odds of a successful implementation. In the same vein, future studies could also approach the implementation of digitization and the monitoring of the construction supply chain raising the inherent benefits.

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Appendix A. Semi-structured interview protocols.

A.1 Protocol for practitioners

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

2. Please, tell us more about your organisation.

a) Where is the organisation located and who do you provide for?
b) How large is the organisation?
c) Where are your suppliers located/ where do you source your materials?
d) 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.

a) What are the main benefits and drivers you observed to digitalise traceability in the construction supply chain?
b) What are the main benefits and drivers you observed to digitalise traceability in the construction supply chain?
c) What are the current gaps and opportunities in the digitalisation of your supply chain traceability? Please, provide some examples.

A.2 Protocol for academics and stakeholders

1. What is your professional background? Please, provide a brief description of your professional experience.
2. Please, tell us more about your organisation and how it is related to the construction supply chain.
3. What are the main benefits and drivers for the digitalisation of construction supply chain traceability? Please, give examples to justify your answer.
4. What are the main challenges and barriers for the digitalisation of construction supply chain traceability? Please, give examples to justify your answer.
5. What are the future opportunities for construction supply chain traceability?

Appendix B. Main comments from interviewees.

DIT's attributes		Academics	Practitioners	Stakeholders
Relative advantage	Drivers and benefits	(...) *Industry quite rightly actually needs to be making a profit in order to stay in business and we need to understand how we can actually number one help industry to increase their productivity and profit through new technologies, we have to actually demonstrate that to them and support them in the process.* (...)	(...) *If we embark on circularity and suddenly tracking and tracing is begging again. It is actually high importance because this is the only way you can actually guarantee circularity.* (...)	(...) *There is there is a cost involved (in digitalisation), but let's say an asset is a is $1,000,000... even if there's a 5 or 10% cost overrun... And also the risk of delay. So, by digitizing that process and making it more efficient, you can save a part of that. Then the cost is only a small fraction of the amount of money saved.* (...)
		(...) *During the operation and maintenance you actually can get the data about the condition of the asset itself...* *They have sensors inside the concrete, to test the vibration and the loading and all these things and they have access to the data from these sensors inside this building.* (...)	(...) *What does radio frequency identification (RFID) enable straight off the bat? You do not actually need to read it with line of sight, it can actually be automated. So, something like a fixed dead reader on a crane or on a forklift time or a gantry, but it also enables a lot of other things like Geo location, real time tracking, stock control.* (...)	(...) *You are getting all these inefficiencies because it is a combination of paper-based stuff, stuff in emails, stuff in drawings, and you know you can't put them all together as in a true database because there's simply not compatible.* (...)
	Barriers and challenges	(...) *The entry point for technology can be quite expensive for some companies in particular in the SME sector... and because the government has not really taken an active role in that part, it's a combination of all of those which I think is keeping the sector behind.* (...)	(...) *The price point of each individual product is not as high in revenue. It doesn't really justify those (digital traceability) initial costs* (...)	(...) *How we can ensure that there are cost effective ways and, you know, technologies that are accessible for the smaller players* (...)*?*
		(...) *We have a 60% adoption of building information management (BIM) tools, so we have 40% of companies, probably very small companies that cannot afford or they are not interested and that creates a lot of troubles.* (...)	(...) *It takes a significant amount of investment. in technology, both in people and then and putting the solutions in place and some of them (other organisations), will be just getting by on our day-to-day basis.* (...)	(...) *It is not as if every single thing is worth tracking.* (...)
Compatibility	Drivers and benefits	(...) *It should be a given that they can readily access their mobile phone or tablets to scan the code, get the necessary (material) information. If there is a non-conformance, they can easily you know.* (...)	(...) *It (near-real time tracking) builds customer confidence. the customer doesn't have to make that phone call and ask 'where is my product'? They can see it without actually interacting with you. And at any time they can actually adjust their plans based on where a product is so you know it's really delivering on the customer.* (...)	(...) *If you can make it cheaper and easier for them to demonstrate compliance (through technological solutions), then they'll jump on board with that and will address things like your flammable cladding.* (...)
		(...) *Government, it is to be acting as the as the expert client, the heavy responsibility in in that role. And if they as clients are not introducing processes that would increase quality and increase uptake of some of those technologies, the sector is not interested.* (...)	(...) *To have that as a 4D model, it just makes it so much easier for everyone to understand. What happened quicker or slower and where it happened and where the hole points were... without having intimate detail of that project physically, go oh OK, this is what happened. This is where the hole point. So, I think it can help you plan for the next one. Much better even in that sort of rough digital format.* (...)	(...) *If construction is going to change, it means that those existing relationships need to dissolve more design needs to be a collective in needs to be the responsibility of whoever builds. ...there might be 50 trades on a certain package, like how do you get all those guys to agree and to be doing things that collectively and holistically or benefiting?* (...)
	Barriers and challenges	(...) *Even though we've seen people coming up from trades doing really well with modern technology, but still proportion of them who are very hesitant to use all these modern technologies* (...)	(...) *They have lot of data in the front end which is in the digital design in the BIM drawings and other things. But it does not flow from there into their procurement, into their sourcing, into material procurement and then coming back into the site. There is no data. It's all sitting in siloed Excel sheets.* (...)	(...) *Trace ability requires the entire supply chain be interested, up to the end user.* (...) (...) *This is the problem with the industry. Everyone says they're using standards, but they're all different. And then people go and modify them and add new attributes to it. And the software from all the different vendors are all slightly different.* (...)
		(...) *Vertical integration in the sector is just not happening. You know, we have been talking about it for 20 years and it's just not happening and the reason for that is because nobody wants to move away from this flexible resource model.* (...)	(...) *Any of the original market's or suppliers of a product they normally have good systems of tracking their products right? The hard part is how those materials then land up into a subcontractor's hand and then how that transforms into a product that comes to the site.* (...)	(...) *There is no standardization and so you would end up for every single manufacturing of building management systems having different connectors so to speak with different capabilities.* (...)

Appendix B. Continued...

DIT's attributes		Academics	Practitioners	Stakeholders
Complexity	Drivers and benefits	(...) *When it comes to prefabrication, I think that is the next step in the sector already. I think that is happening to certain to create through RFID, others as part of these kind of smart cities agenda. It is very important that that is taking place. So, I think the change is coming from the product supplies perspective and end of things and still manufacturing effectively they had to do that because there is very little variation inside that you can do with that product as opposed to anything else.* (...)	(...) *The beauty of a prefabricated element is that we actually are then in control of the trace ability that goes along with that, and we can actually apply a tag or a label to the finished product that actually identifies that product... it does give you more control and it is a really good path and I think you know prefab is certainly one way of improving robustness of trace ability.* (...)	*If offsite manufacturing of more and more things and modularization can come in. It almost solves that (traceability) problem automatically because now you've got a bunch of different people manufacturing things in a in an environment where they control it and, therefore, they are able to enforce it.*
		(...) *Every company in the future will have to have a (digitised) model of their product. They could just be picked up and be incorporated into design (BIM model).* (...)	(...) *This whole submission (project handover) that we have to make at the end is usually pretty significant and we were ringing round suppliers and sort contracts. Get all this information of you know what's this? What's this product here? What is it made of? What's the? What is the part number? And God knows what else but you must think there's an electronic solution or electronic solution to that.* (...)	*We are trying to get all of those things of different standards into one common data environment.*
	Barriers and challenges	(...) *Within our industry there are lots of different software providers, and they're all trying to lock their customers in and they're not really interested interoperability, because they do not want them to escape. So, the problem we have is that there are that many different providers, that many different software platforms, that a single supplier needs to understand how to use half a dozen different systems.* (...)	(...) *We can trace who it was sent too, and then that is sort of where, and when it was delivered to them and how it was delivered to. And then that sort of stops and that goes into a separate system.... there's no connecting back with those two systems at all.* (...)	(...) *It takes a huge amount of work to create a IoT industrialized platform.*
			(...) *As all these suppliers have their own app, how do you bring that together?* (...)	(...) *All these formats or the files are in general different because they're stored in different formats and then there's different engineering and architectural kind of. Things which may need to be combined and they they are done. There are some software's which do it in a limited way. But there is no one single source of truth where you can actually construct a true database.* (...)
		(...) *Many of the components are large and heavy... So, if you stack them up three in a sandwich horizontally, an RFID tag that's in the middle piece signal will not be able to get out.* (...)	(...) *We are attaching RFID to a product that's not really conducive to RFID. RFID is all about signal and attenuation, and we're trying to attach it to steel. So that's actually you know, shielding or scattering. It's wreaking havoc with the ability to read RFID.* (...)	
Trialability	Drivers and benefits	(...) *This process of code development of things is super useful in organisations when you make them (trades) power off. 'OK guys, we're doing this. Do you want to help us to see how this work?' Develop pilots, trials, engagement workshops, and all these... the buy in of workers can be excellent if the if there's a well design process to implement this thing that consider there.* (...)	(...) *We are just starting up the trial (to see how) those Technologies of the next generation of a full model can be utilized to increase the efficiency of our daily operations.* (...)	(...) *which software they should they be using? Is it going to be the same one in a year's time? What system should we be using to develop the model in so we know that it will be usable in 10 years for the next 50 years?* (...)
	Barriers and challenges		(...) *We have had a go at with a package to be able to use that BIM model to track the extent of the installation... we probably had the bleeding edge project for about two years, but we couldn't get it done on a reliable, consistent way.* (...)	(...) *There is more and more experimentation, but there's also more and more offerings.* (...)
				(...) *which software they should they be using? Is it going to be the same one in a year's time? What system should we be using to develop the model in so we know that it will be usable in 10 years, for the next 50 years?* (...)

Appendix B. Continued...

DIT's attributes		Academics	Practitioners	Stakeholders
Observability	Drivers and benefits	(...) *I always think that putting an RFID tag gives you more transparency. You can see where every single item is,* (...)	(...) *If the client was clear with what they want and all the tier ones are clear as what they want, then all the supply chain, subbies, suppliers, can then adapt to it. And they are keen to (adapt) but it's just when they're not sure what you want.* (...)	(...) *One of the requirements for buildings is to have their occupancy permit displayed, which means that if there is any variation from the building code you need to actually list it there. What are the variation and how would you justify those variations? From memory, more than half of these buildings don't even have those things displayed. Which means that you're sort of running blind half the time.* (...)
		(...) *Providing enhanced visibility and possibility to the whole supply change is very important to being able to track data and track the monitoring (of) the performance of different stages, tiers across the supply chain. That is super important because the industry is very fragmented... So, if we are able to make it apparent, that traceability of data across the supply chain, that's going to be super helpful to improve transparency and integration and start breaking down this this fragmentation of the industry.* (...)	(...) *We want full transparency or knowing where everything is and it's very hard for us to do that, just being one cog in the chain.* (...)	(...) *How do you make sure that what do you accept, it actually meets the requirements and specifications? Because right now it's probably emails right? A few days later someone sending email I got it, but I think this is missing on that spot and solve part of the problem. So how do you get that whole block chain up, which is clear visibility for all of those partners in the supply chain?* (...)
	Barriers and challenges	(...) *Our large contractors do not build. Everything is subcontracted out. So, if you're not doing any construction work, then what's the point of tracking materials?* (...)	(...) *we don't actually self-perform a lot of work, we really don't self-perform any work, it's all subcontracted.* *So that detailed kind of granular tracking and tracing of material and equipment is probably something that that we would be more expecting the subcontractor to take care of and then and then report up to us* (...)	(...) *Contractors are less concerned about trace ability in some ways because they manage that through risk of contracts... they're paid to manage that risk, and they do not really have an incentive to innovate or pass on any savings. So, it is not really a centralised, controlling system.* (...)
		(...) *that contractual relationship is created only for a particular project. It is not as strong as a subcontractor or supplier relationship in manufacturing. In manufacturing you work with the supplier or subcontractor over a longer term... We can never improve on our supply chains because we are a project-based organisation.* (...)	(...) *How do we actually ensure that the information on labels or RFID tags or QR codes, it is actually the right information?* (...) (...) *One of the problems that that the main contractors have is they don't really have any direct control. They sub everything out... You're not able to integrate all the systems, so you have one system for all materials.* (...)	(...) *A big part of the reason that you don't see more technology-based automation in this industry is the big guys go out and spend the money in the little guys will say I cannot afford to do that.* (...)