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The Construction Materials Conundrum: Practical Solutions to Address Integrated Supply Chain Complexities

Article

The construction materials conundrum - Practical solutions to address integrated supply chain complexities

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Abstract

As projects evolve into complex and specialised temporary initiatives, accountability shortfalls in material flow is a major reason for schedule and cost overruns in construction. To date, researchers and practitioners are unresolved regarding the causes of material handling challenges and eminent solutions to improve material flow accountability. Consequently, inefficient supply chain management practices persist, leading to ineffective handling methods. This research, thereby, focuses on identifying critical material challenges encountered by contractors and presents solutions to alleviate schedule and cost overrun failures. The fuzzy Delphi approach was used to refine opinions and achieved group consensus from fifteen specialists' on the ranking of material handling problems and potential solutions associated with design-build projects. The research revealed that complexity, material flow, and lack of information sharing are the top three main causes of on-site material problems. Potential solutions identified are a faster response mechanism (as an alternative to a slower build schedule), increasing material handlers' manpower, subcontractors' involvement in the procurement process, and prefabrication. The research highlight subcontracting as a material handling paradox as apart from being a solution, it creates non-value-added costs in the supply chain and often inappropriately transfers risk. The findings showcased the potential to improve on-site material handling praxis by considering decision-making uncertainties in material flow and recognizing the importance of procurement methods in construction supply chain solutions in resolving scheduling and cost inefficiencies.

Keywords: Supply chains, materials, Fuzzy, Delphi, procurement, project delivery, design-build

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Introduction

The construction industry is the UK's least efficient sector. Low productivity levels and site disruption results from the ineffective material management systems used at construction sites (Naoum 2016; Thomas et al. 2005). The inefficacious use and management of materials throughout the construction lifecycle is ever increasing in criticality because in coordinating resources, material management practices should reflect global sensitivity towards sustainable and green practices (Egan 1998; Hasan et al. 2018; Spillane et al. 2011). From a built environment perspective, material management entails storage, handling, transportation, and distribution of resources, as well as the planning and active strategic undertaking to manage on- and off-site construction processes and progress (Whitlock et al. 2021). Essentially, effective material management ensures that the right quantity and quality of materials are specified correctly, at a reasonable cost, and readily available at the point of use (Georgy and Basily 2008). Proper materials handling is critical because materials can account for 50% - 60% of a project's cost (Kasim 2011; Ramya and Viswanathan 2019). The management of material flow in the supply chain and its transformation into a value-added product is thus a key component in meeting the expected time, cost and quality performance objectives for construction projects (Tedla and Patel 2018; Thomas et al. 2005). Cost and time overruns and quality failures are, thus, the consequence of the fragility and uncertainty of poor material management in the supply chain.

Logistic chains in construction are becoming increasingly complex (Whitlock et al. 2021) because existing solutions disregard the understanding that the material supplied according to a predefined schedule is non-uniformly consumed (Jaśkowski et al. 2018) and that there is an unresolved information asymmetry between suppliers and contractors. Consequently, site material management inefficiencies persist because research continues to ignore that such complexities and emerging solutions should not only focus on the construction site but should also incorporate the transition between construction and supply chain processes (Hu 2008). Early recommendations by Briscoe and Dainty (2005) necessitates team integration, which involves the supplier dedicating personnel to the main contractor to cater to their needs. Unfortunately, existing organisational and behavioural barriers must be overcome to achieve improvements in material management and consequent project performance (Baiden et al. 2006). Practitioners have also translated just in time (JIT) manufacturing methods to elicit guidelines for efficient management and improved handling practices in the construction supply chain (Jaśkowski et al. 2018; Kong et al. 2018). However, project managers leading projects must be competent as the necessary coordination skills are sometimes lacking as, more often than not, the delivery of materials varies from planned quantities, quality, and cost (Balakrishnan et al. 2008; Thunberg et al. 2017), resulting in early or late material arrival, causing detrimental effects on construction processes and the environment (Kong et al. 2018). It is, for this reason, Georgy and Basily (2008) used genetic algorithms to investigate material ordering and delivery optimisation based on construction schedules and material needs. Said and El-Rayes (2013) presented a construction logistics planning model that optimises material purchase and storage choices. Later research by Xu et al. (2016) studied the connection between the (off-site) material supply chain and the (on-site) project activity network. The lack of a centralised material management style and the associated inventory allocation issue in current conceptions is attributable to a paucity of awareness of procurement techniques and their link to supply chain activities. A framework identifying the critical factors for connecting the project timeline, supplier selection, and material planning is required to improve practical decision making and inform future research (Lu et al. 2018).

Abeysinghe et al. (2018) believed that these problems are amplified on large-scale construction projects, while Spillane and Oyedele (2017) view was that confined urban construction sites presented the greatest challenge. For this reason, Deng et al. (2019) provided an integrated framework for effective coordination between construction project sites and other project-related organisations based on 4D BIM and GIS. In their work, mathematical modelling proved the necessity of locating consolidation centres in congested regions with long delivery distances. However, their analysis does not address uncertainties in the building supply chain, such as the rates of change in material consumption as well as the price of commodities which leads to fluctuations in construction progress and price rates. Due to contractual risk allocations, these intertemporal changes vary between project delivery methods, but such peculiarities remain unaccounted in materials planning. As a result, despite theoretical and practical proposals, material handling problems persist because of the lack of understanding of the relationship between the supply chain and the fragmented nature of projects brought on by a failure to acknowledge the inherent difficulties of managing resources specific to each project delivery method

(Spillane and Oyedele 2017). Further, the myriad of previous works does not agree on the underlying causes to provide the generalisation required to plan future material needs and management.

Solutions to curtail these eminent problems are lacking, and to date, no authority has addressed the complications inherent in material handling problems in the supply chain for design-build projects or attempted to account for the uncertainties associated with production. Design-build (DB) entails integrated design and construction activities (Xia and Chan 2010), in which the contractor assumes complete responsibility for design and construction processes (Chappell 2008). More importantly, design-build projects provide end-to-end supply chain integration of design and construction activities. While clients frequently prefer DB because of its single point of contact, cost, quality and delivery time (Egan 1998), it also offers increased buildability and reduced risk (Chappell 2008). However, the transfer of more risk to the contractor results in inherent problems (Liu et al. 2017; Tsai and Yang 2010). The original scope document or employers' requirements that elicit design and construction services must be carefully drafted (Xia et al. 2015), as the specifications should be more descriptive than prescriptive. Prescriptive specifications are such that the client can explicitly identify the required materials and workmanship. Comparatively, descriptive specifications or performance specifications state the code or standard by which the designer should abide. The degree of elucidation defines the various DB categories forming a contract (Martin and Ramjarrie 2021). As design-build projects can still be in the design stage when construction occurs, and the programming of materials becomes more complicated because the quantity and quality are not defined by the client before a contractor is engaged.

This study examines the sources of material handling problems and develops solutions for design-build projects to improve supply chain and production efficiencies. Therefore, the objectives are to determine, categorise, and rank on- and off-site material handling problems and solutions affecting construction projects. The results will facilitate an understanding of material handling practices that contribute to ineffective management for design-build projects. Comprehending supply chain failure is critical for construction businesses because construction projects are especially vulnerable to upstream supply chain inadequacies due to their limited and costly inventories to protect projects in the event of material shortages or management inefficiencies. Accounting for the uncertainty in practitioners' views provides a realistic platform for developing a proactive material handling and management system that can significantly impact the project's economic and workflow outcomes (Jaśkowski et al. 2018). The remainder of this paper will include a systematic literature review of the primary factors influencing on-and off-site material handling problems and possible solutions. The review findings inform the methodological basis for a fuzzy Delphi ordering of the material handling problems and solutions. Finally, a discussion of the factors is presented.

Material handling problems

Existing supply chain management research for process-based industries is useful to enhance client and stakeholder value while saving money substantially (Papadopoulos et al. 2016), but it does not readily translate to the construction environment; because of the transient nature of production in construction as relatively little is known about construction site management (O'brien 1999). Buildings, unlike process-based manufacturing, are unique and are allocated to a distinct client. The clients, like the key actors, are a diverse assortment of fragmented self-protective companies with distrusting tendencies of other construction supply chain management (CSCM) stakeholders, including architects and engineers, general contractors, specialised subcontractors, and material suppliers, all working toward the client delivery (Behera et al. 2015). Because CSCM knowledge is still considered embryonic, many unresolved questions arise in ignorance and misunderstanding. Notably, few studies have used supply chain management to deal with the ever-changing flow of interacting events in the construction industry, particularly addressing procurement differences. While many studies have been conducted on inappropriate material handling (Briscoe and Dainty 2005; Egan 1998; San Cristóbal et al. 2018; Thunberg et al. 2017), little is known about the relevance of underlying reasons or possible solutions to address the shortcomings of selected project delivery options. Consequently, several issues have still confused construction managers in their efforts to identify, analyse, and design material supply networks. Poor site handling, inadequate material supply, transportation issues, specification misuse, insufficient work planning, and excessive paperwork affect material management (Zakeri et al. 1996). Kasim et al. (2005) attempted to classify these problems based on the material flow on- and off-site. Such a classification condenses responsibilities and functions while ignoring current industry collaborations. The underlying problems highlighted in Table 1 require inexpensive and brisk solutions; moreover, questions regarding planning and procurement, information sharing, and strategic complexities in materials handling remain unanswered.

Table 1. Materials handling problem (**Insert here**)

Planning and procurement

Poor material planning is a problematic area of material management (Pande and Sabihuddin 2015), which often results in on- and off-site problems (Hittle and Leonard 2011; Pande and Sabihuddin 2015; Thunberg et al. 2014). The primary objective of planning the procurement of materials is to ensure that the materials are where, when, and how they need to be moved when required, at an agreed-upon price; so that records and target inventory levels can be set up, and the delivery frequency can be determined (Payne et al. 1996). However, consideration must be given to planning the transportation and access of materials to the construction site (Faniran et al. 1998) to develop an effective material management strategy that increases profitability and facilitate early project completion.

Pande and Sabihuddin (2015) indicate that material planning and knowledge of lead times before project initiation are vital to minimise disruption, but such information is usually not disseminated through the supply chain. The concurrent design and construction process in design-build projects prevent such quantities from being less evident at the start compared to traditional procurement approaches. Similarly, from a supply chain perspective, Hittle and Leonard (2011) argue that another example of poor planning is when the material is supplied earlier or later than planned. Materials that arrive at the site earlier than anticipated require additional storage spaces or double handling and are subject to damage, loss, or theft (Navon and Berkovich 2006), whereas materials that come late cause production delays. In extreme cases, increased double-handling interactions increase the risk of injury and casualties (Anil Kumar et al. 2015).

The relationship between material handling, procurement route, and planning is evident in the frequency and magnitude of delays experienced within the project schedule due to material mismanagement or emanating from change orders. These change orders are more frequent in some procurement routes than others. Thomas et al. (2005) identified the need to plan a work sequence and integrate it with the storage plan. This amalgamation will allow project managers to plan material laydown areas in detail away from the construction tasks, lowering the probability of material damage or loss and increasing the profit margin. Uncertainties in planning processes, or project uncertainty, may be minimised when all supply chain participants engage in the planning process and contribute their expertise in detecting uncertainties. Finally, better coordination and integration achieved by implementing supply chain planning procedures may solve material flow problems such as delivery dependability because information reliability increases when suppliers and contractors collaborate on material delivery schedules.

Information sharing

Communication is defined as a two-way exchange of information, ideas, and analysis that is often accompanied by an attempt to convey meaning and understanding (Martin et al. 2014). The ease and quality of the interaction, which is a measure of the effectiveness of information exchange, is important because inadequate communication is a significant cause of errors and omissions, resulting in design adjustments and reworks during construction (Ye et al. 2015) and consequent reordering and extra pressure on delivery quantity and quality to meet the new requirements. Consequently, communication is a frequent source of on-site material handling issues, as it requires the sharing of relevant, timely, and assumed information (Martin et al. 2014). Compared to traditional procurement methods, the connection between the designer and builder during design-build projects better facilitates the flow of information and, consequently, the effective exchange of material specifications and quantities for a more buildable construction solution (Songer and Molenaar 1997). Conversely, information discord is more likely to occur when subcontractors are not nominated by the client, leaving contractors to pursue profit maximising switching of suppliers across the supply chain. The burdensome responsibilities of the contractor often result in a failure to communicate critical project information to new supply chain partners, such as specifications and site logistics (Briscoe and Dainty 2005), causing worries about product quality and material supply delays. Xie et al. (2010) assert that integrating specialised knowledge throughout the supply chain and the construction project team has grown into a vital component of the material management process. The role of a third person as a mediator demonstrates the critical need for effective communication and information sharing. Larger construction projects are more prone to lack information exchange about material placement, and in the absence of a specified process, more supplies may be acquired while already on-site (Navon and Berkovich 2006), incurring extra expenses and waste. Despite benefiting from a more integrated built process, current design-build project delivery, like other procurement options, suffers from information constriction because of the temporal nature of construction. The lack of material management information sharing and flow between projects is magnified by the absence of subcontractors and other key stakeholders from the planning process. Lack of information sharing between construction firms and suppliers was confirmed by Ojo et al. (2014) as a critical barrier to implementing green supply chain management in construction.

Strategic complexity

The separation of construction and supply chain processes implies that coordination is necessary to cope with the complexity arising within projects. However, further challenges arise because material supply chains are complicated and characterised by hostile short-term interactions driven by competitive bidding processes, very little information exchange among participants, and little incentive for continuous learning. Many identified problems arguably originate from a lack of supply chain integration with construction project processes, in line with Bäckstrand and Fredriksson (2020) claims. Bäckstrand and Fredriksson (2020) suggested that problems perceived on-site or in the supply chain often arise from mistakes made in earlier phases of the construction project, for example, in the design phase. Bäckstrand and Fredriksson (2020) elaborate on this, arguing that decisions in either construction (e.g. type of materials) or supply chain processes will affect each other. The material flow characteristics imply that the material flow issues can be linked to the supply chain as it affects all parts of the supply chain, including on-site construction.

Given the confinement and complexity of construction sites, it is critical to develop a well-planned material handling strategy. Because construction projects are frequently assumed to be similar, their complexity is often underestimated (San Cristóbal et al. 2018). Modig (2007) characterises a construction project as a temporary organisation and argues that construction projects are complex and require prior planning. They argue that projects are frequently designed and developed with the knowledge and management systems of previously completed similar projects under the grave assumption that these directly apply. According to Spillane et al. (2011) and Chan et al. (2004), the complex nature of construction projects necessitates the use of numerous materials and meticulous planning to ensure that they are delivered at the appropriate stage. This convolution presents a challenge for project managers working on small projects because they must ensure that materials are on-site while working under severe time constraints. Additionally, Thomas et al. (2005) assert that effective material management is becoming more challenging owing to the confined space on construction sites. Test runs of the logistics flow of materials are often required to identify impediments and constraints on transportation routes. Suppliers' on-site visits enable them to identify issues with delivery routes, site access, entry, traffic, laydown areas, lifting equipment required for space, as well as the necessary safety precautions. Weather conditions can also harm the conditions of materials on-site. Due to the geographical dispersion of construction projects, inclement weather can cause significant damage to materials in transit or during on-site storage; adequate storage must be provided (Chan and Au 2007).

Modern approaches to resolving material handling problems

Supplier development and performance measurement are among the critical elements of supply chain improvement, as recommended by Egan (1998). Further recommendations include the acquisition of new suppliers through value-based sourcing, the organisation and management of the supply chain to maximise innovation, learning, efficiency, the management of workload to match capacity and the incentivisation of suppliers to improve performance, and the capture of suppliers' innovations in components and systems. Although not explicit, Egan (1998) recommendations are underpinned by a more sophisticated ICT management system, which Kasim et al. (2005) and Lindblad et al. (2018) later recommended as beneficial to improving productivity and enhancing materials handling planning implementation processes. With digital technology, construction supply chain data collection and analysis, automation to build self-contained systems, synchronisation, connectivity, and linking operations and activities across supply chains are all possible (Chakuu et al. 2020).

Materials management solutions in construction have sought to improve material identification, tracking, tracing, information sharing, and payment. The earliest of the approaches, since 1987, is the bar-code and QR code system, which provides up-to-date material quantities by scanning codes located on the materials (Chen et al. 2002). Shehab et al. (2009) claim that the bar-code system enhances collaboration between multi-project teams and is up to 9 times faster than manual material recording systems. However, software unavailability, as well as traceability, limits their widespread use at construction sites. These limitations were overcome by radio frequency identification (RFID), which benefits wireless real-time tracking and identification with an increase in productivity of 8-10% (Lindblad et al. 2018). Construction applications have focused on combining radio and ultrasonic signals to track material and equipment assets (Jang and Skibniewski 2009) and monitoring tools on construction sites (Goodrum et al. 2006). Chin et al. (2008) integrated RFID with 4D CAD to develop a logistics and progress management information system in which the material tags communicate with a BIM model or a computer through bluetooth or general packet radio service (GPRS). Despite these advantages, information asymmetry and data security remain crucial problems as traditional systems rely on central databases. Recent proposals by Tezel et al. (2021) and Wang et al. (2020) on blockchain technology suggest that it can improve production and delivery timelines by providing project teams and supply chain stakeholders with readily available information such as traceability and monitoring of goods. Accordingly, blockchain is likely to decrease on-site material handling by limiting the need for on-site storage. Blockchain technology can be considered a shared database across a peer-to-peer network where transactions are gathered together in blocks and then added to a permanent chain. Once these blocks are put into a chain, they cannot be changed, making the transaction chain public. The popular cryptocurrency Bitcoin pioneered blockchain technology, allowing digital information to be disseminated without being copied or altered (Tian 2016).

The current point of departure

The uptake of the discussed approaches has been comparatively slow for supply chain management applications at construction sites despite some being in existence for more than 30 years. The rationale for the resistance in uptake could be the lack of understanding of the causes, the lack of literature, methodology, popularity, or misdirected analysis. This research addresses these concerns by updating the literature and adopting an empirical approach to uncover much-needed explanations in this area of research for further reflections, inquiries and critical analysis. The research, therefore, adds to the practical suitability of adopting existing material handling solutions on design-build construction projects of various sizes. Mishra et al. (2018) conclude that establishing a materials strategy and then executing it without input from the environment is not viable; neither is the continued exclusion of uncertainty or neglect of the impact of project delivery methods on the materials management problems encountered or derived solutions. Therefore, a consensus from the analysis of factors causing materials problems is needed with site data to ensure future solutions will reflect the feasibility of the underlying interventions.

Research Methodology

Design

This research design is anchored by pragmatism theory, which allows for an in-depth analysis of the subject area. Pragmatism is a problem-oriented theory that claims that to address each research goal effectively, the researcher must use the best research methods (Pansiri 2005). Therefore, a mix of qualitative and quantitative methods is needed to investigate different aspects of the research problem and for accurate sequential interpretation in this research topic.

The traditional Delphi method is justifiable for formulating solutions by leveraging the expertise, experience, and knowledge of subject matter experts in their chosen field when quantifiable data are unavailable (Habibi et al. 2015). However, the Delphi technique has several drawbacks (Hasson et al. 2000); it necessitates repetitive surveys, which can be time-consuming for both the participant and the researcher and is costly (Hsu et al. 2010). Ishikawa proposed the fuzzy-Delphi method (FDM) (Hsu et al. 2010), which is a technique that modifies the traditional Delphi by accounting for the uncertainty associated with experts judgement (McKenna 1994). Experts' current knowledge is converted to triangular data statistics to produce more concise results than the original Delphi method or a literature review. Fuzzy theory avoids distorting expert views, captures the semantic structure of anticipated objects, and analyses the ambiguity of acquired data (Padilla-Rivera et al. 2021). In other words, FDM is resilient because it considers and integrates expert opinions, decreasing inquiry periods and decision-making costs (Lee et al. 2018).

The application of fuzzy concepts is important to material handling because product and handling quality, delivery efficiency, and time are all fuzzy concepts (Pattanayak et al. 2021; Perçin 2018). They are fuzzy because the boundary, if any, in the cognition of different decision-makers is vague. Such uncertainty, fuzziness or vagueness results from the absence of distinctness (Ocampo et al. 2018). In the way humans perceive the world, vagueness, the opposite of exactness, cannot be avoided (Martin and Ramjarrie 2021). When making real-world decisions, it is preferable to use fuzzy numbers because linguistic preferences reflect perceptions (Bui et al. 2020).

Data collection method

Participant's selection

Manakandan et al. (2017) describe a panel of experts as a group of skilful people in a particular study topic. According to Cantrill et al. (1996) and Mullen (2003), there are no hard and fast guidelines regarding panel sizes. Linstone (1978) stated that a reasonable minimum panel size for the conventional Delphi is seven, although panel sizes vary from four to three thousand. FDM needs fewer samples and provides a more thorough depiction of expert knowledge (Padilla-Rivera et al. 2021). As a result, panel size is determined empirically and pragmatically, taking into account issues such as time and money. Potential participants were considered based on their job title, knowledge and experience in the construction industry (McKenna 1994). The FDM is based on the knowledge and opinions of experts; thus, Adler and Ziglio (1996) suggested four criteria were used to confirm experts inclusion:

1. Knowledge and experience with the issue under investigation
2. Capacity and willingness of the experts to participate
3. Sufficient time to participate
4. Effective communication skills

As questions are only sensible and pertinent within a panellist knowledge realm (Rowe et al. 1991), site managers, buyers, construction directors, buying managers, and material controllers were the most suitable candidates for this research. They all deal with the daily on-site material handling problems.

Questionnaire development and validation

The Fuzzy Delphi is a mixed-methods approach with a sequential qualitative, quantitative design consisting of 3 stages (Ocampo et al. 2018); see figure 1. In the first phase, a literature review, limited between 2001-2021, was used to gather data about the suitability of material handling factors and solutions. On-site material handling problems are the subject of Questionnaire #1. The responses were closed-ended, requiring a response to validate or delete the suggestions. The questionnaire had three sections. Section one gathered background information on the participant, section two analysed on-site material handling issues, and section three included on-site material handling solutions. Participants were encouraged to submit as many suggestions as possible to maximise the chances of inclusion (Schmidt 1997). The addition or removal of suggested factors was based on their vagueness or redundancy. Acceptance and validation of each factor were based on 67% of the participants agreeing (Sinha et al. 2011). The survey was completed and administered using the Bristol Online Survey. A hard copy was provided to participants requesting such a format.

Figure 1: 3 stage process to the Fuzzy Delphi Method (**Insert here**)

The results from the first round of questionnaire #1 were used to create questionnaire #2. Chang (1994) suggested that larger Likert point scales such as 7, 9, and 11 promote confusion and laziness in the answers, often described as the ‘’laziness’’ phenomenon. Therefore, a 5-point Likert scale was used as recommended by Zhao et al. (2013) as they described this rating system as being easy for users to understand linguistic terms. The instrument was presented to the original participants using a five-point Likert scale to rank the factors. The material handling problems and possible solutions were rated from 1 to 5, 1 being very unimportant to 5 being very important. The same questionnaire administration format was used for questionnaire #2 as questionnaire #1. The expert participants ranked each variable in order of their contribution to on-site material handlings problems and solutions. The close-ended nature of round 2 of the fuzzy Delphi questions ensures they were easy to answer and improve the researcher’s consistency in the derived ranked quantitative outcome. Each participant's feedback in questionnaire #2 was assessed, and a consensus was achieved when 70% or more of the responses to each statement were within one standard deviation of the average triangular fuzzy number (Henderson and Rubin 2012). The distance between the participant's triangular fuzzy number (TFN) and the average TFN was calculated for each statement, followed by the average distance. After computing the standard deviation of the responses, the lower and upper limits to meet the acceptance criteria were determined. The final results were defuzzified by converting the aggregated TFN for each factor to a crisp value.

Fuzzy set Theory

Definition 1

For real numbers between 0 and 1, each element of a fuzzy set is mapped to [0, 1] by membership function as shown in equation 1:

$$\mu_{\bar{A}}(x): X \rightarrow [0, 1] \qquad (1)$$

Definition 2

$\forall\, x_1, x_2 \in X, \lambda \in [0, 1]$, a fuzzy set $\bar{A}$ of the universe of discourse X is convex if and only if as defined by equation 2.

$$\mu_{\bar{A}}(\lambda x_1 + (1 - \lambda)x_2) \geq \min(\mu_{\bar{A}}(x_1), \mu_{\bar{A}}(x_2)) \qquad (2)$$

Where: min denotes minimum operators.

Definition 3

A fuzzy $\bar{A}$ of the universe of discourse X is called a normal fuzzy set, implying that $\exists x_i \in X, \mu_{\bar{A}}(x_i) = 1$.

Definition 4

If a fuzzy set is convex and normalized, and its membership function is defined in $\Re$ and piecewise continuous, it is called a fuzzy number.

Definition 5

Triangular fuzzy membership functions were used for each linguistic option due to their computational benefits over other membership functions, as they are often employed for subjective description (Balin 2011). See table 2.

Table 2: Triangular fuzzy numbers for 5-point Likert scale (**Insert here**)

For a fuzzy number represented with three points, its membership function can be interpreted and holds the conditions, such that a to b is an increasing function; b to c is a decreasing function; and a ≤ b ≤ c (Latpate 2015). For triangular fuzzy, F(x) is the grade of membership. F(x) > 0 when a < x < c; F(x) = 0 when x ≤ a or x ≥ c; and F(x) = 1 when x = b. "b" is the highest grade of membership at the modal value, "a" is the minimum grade at the lowest value, and "c" represents the maximum grade of membership at the highest values. The arithmetic operations of the interaction of triangular fuzzy numbers are available from Ocampo et al. (2018).

Triangulation of fuzzy numbers

The average fuzzy number is calculated using equation 3.

$$TFN_{average} = \frac{\sum Fuzzy\ values}{Number\ of\ experts} \qquad (3)$$

Equation 4 shows the Euclidean distance between two fuzzy numbers, m and n, using the vertex method (Abdulkareem et al. 2021; Manakandan et al. 2017)

$$d(\tilde{m},\tilde{n}) = \sqrt{\frac{1}{3}\left[(m_1 - n_1)^2 + (m_2 - n_2)^2 + (m_3 - n_3)^2\right]} \quad (4)$$

The standard deviation is calculated using equation (5).

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2} \qquad (5)$$

Where *N = number of experts; x = distance between the average response and the respective expert's response; and μ = average distance for the factor.*

For factors of questionnaire 2 that achieved consensus, the group opinion of (i = n) experts for each factor (j) was aggregated using the geometric mean adopted from Hsu et al. (2010) and Chen (2014), see equation (6).

$$\tilde{w_j} = (a_j, b_j, c_j) \qquad (6)$$

Defuzzification

The graded mean integration representation method, proposed by Chen and Hsieh (1999) and described in equation (7), is used for the defuzzification as fuzzy numbers cannot be ranked if they are not crisp. Finally, (S_j) is ranked for each factor from highest to lowest.

$$S_j(expert\ group\ opinion) = \frac{a_j + 4b_j + c_j}{6} \qquad (7)$$

Bias

Bias can be described as any factor which prevents unprejudiced consideration (Pannucci and Wilkins 2010). According to Hallowell and Gambatese (2010), participants are most likely to be affected by eight types of bias during the FDM (see table 3). To prevent collective bias, a selection of participants chosen for the questionnaire is from the site team and supply chain, as well as directors with considerable experience in procurement and site processes. Using a scale of validate and delete lessened the effects of contrast bias. The only outcome of the event was poor on-site material handling and possible solutions; therefore, neglect of probability was not affected in this process. No pressure was put on participants to complete the survey; due to the anonymity of those taking part, participants could not influence other participants whilst completing their responses, which reduced the effects of dominance. Von Restorff effect, Myside bias, Recency effect, and Primary effect bias were lowered by having a consensus threshold in both questionnaires #1 and #2.

Table 3: Eight types of Bias in the fuzzy Delphi process (**Insert here**)

Ethical approval

Ethical clearance strengthens the results' validity and safeguards participants' data. Ethics training was completed before research commenced and granting of approval number PGT/20/113.

Results

Panel of experts

All fifteen persons invited participated in the study, achieving a satisfactory sample size and response rate (Roy and Garai 2012). See table 4 for the participant's classification by job title, experience and attained education.

Table 4: Demographic characteristic of expert (**Insert here**)

Validate and Delete

From a comprehensive literature review, twenty-eight of the twenty-nine variables contributing to poor material handling met the consensus of 67 per cent or higher, with only "No prior relationship between the contractor and the supplier of goods" failing to meet consensus and thus was deleted. Three factors marginally met the selection criteria to be included in questionnaire #2: "the site team fails to communicate delivery dates to suppliers", "insufficient laydown areas provided due to budget", and "the geographical location of sites". This moderate level of agreement indicates that experts' opinions on these variables were somewhat divided. In contrast, all experts agreed that "delivery of the materials before a specified date" and "poor on-site access/conditions" should be included. Table 5 also summarises potential solutions to on-site material handling identified in the literature review. One of the twelve factors (Radio Frequency Identification) was deleted during the process and was not included in questionnaire #2. Interestingly, 7 of the 15 experts have 16+ years of construction industry experience, which may have influenced the removal of this factor, as they are unfamiliar with this process.

Table 5: Possible contributory factors and solutions to on-site material handlings problems

(**Insert here**)

Most of the responses supplied were already covered in questionnaire #1, including the variables contributing to on-site material handling concerns and remedies proposed by specialists. However, three variables, two potential contributors, and one potential solution were extracted from the experts' opinions and added to questionnaire #2. "Part deliveries with missing items marked to follow" and "over-ordering to compensate for climate/shortages" were among the contributors. "Training and awareness courses dedicated to material handling, storage, and control" was also suggested as a solution. The results of Questionnaire #2 were then "fuzzified" and "defuzzified" to find the crisp value, allowing the factors to be "ranked" in order of importance (see tables 6 & 7).

Table 6: Crisp value and the rank causes of material handling (**Insert here**)

Table 7: Crisp value and the rank solutions of material handling (**Insert here**)

Discussion

Based on the research's methodological trajectory investigating material handling, a deeper forensic on the "cause-solution" causal chain is pursued by evaluating the top three ranked causes and top four solutions voiced by fifteen experts. To further draw meaningful context-specific insights from the results, the least ranked factors and solutions were also discussed to determine their lack of fitness for use in the current debate.

Causes of on-site material handling problems

Delivery of materials after the specified date

The late delivery of ordered material is the most important cause of supplier-related delays (Aibinu and Odeyinka 2006). There was consensus among the experts that the top-ranked cause of material handling problems was the shortfall in achieving scheduled delivery of materials since materials were usually received after a specified date. While the material logistics processes encompass sourcing materials, agreeing on a delivery date, placing orders, payment, and delivery, the various interaction and coordination nuances highlight potential areas where issues can arise and delay occurrences even before the materials are delivered to the site. The travelling distance of the deliveries is recognized as the most typical factor impacting delivery time to the extent that materials arrive after the specified date (Buzoianu 2020). Acknowledged by Hittle and Leonard (2011) as an unplanned risk to contractors, the failure to manage late materials arrival can lead to financial losses and damage. Further, time, effort and resources are consumed when project managers have to subsequently reprioritise their time to have a contingent material supply chain to mitigate the non-arrival of materials by the specified date. This inefficient and duplicating use of resources has further negative effects on project workflow, such as quality control and critical path management. Further, communication clarity and specificity between contractors and suppliers could ensure readily available stock for products, especially for materials with longer lead times. The contractor can prepay for scarce materials and provide a delivery schedule upon contract commencement. This provision allows a supplier to stock the required materials. However, such payment mechanisms are only practical if adequate legislation to recover funds exists to remedy contractual obligations (Peters et al. 2019). Also, enforcing the duties require the contract between the buyer and the supplier to specify the point of late delivery, which cannot be changed without resigning the contract (Ngniatedema et al. 2015).

A streamlined approach to material delivery through collaborative working ensures that the materials are delivered as requested. When ordering materials, accurate and better information sharing practices among project teams are improved with ICT involvement (Ahmed 2017; Kasim 2011). Although the panel placed a lower preference for this method, the research trend in construction management suggests that a blockchain-based framework enables easy and controlled access to information. Improved information availability and control access allow for improved delivery times, resulting in enhanced production levels (Wang et al. 2020). However, blockchain technology is a new and emerging field in the construction industry, and even fewer practical examples are known.

Materials ordered late

This study confirms Rahman et al. (2017) findings that late materials procurement is an important cause of material delivery delays. There are many implications associated with the late ordering of materials. Contractors lose their competitive advantage as the last option materials are not the most suitable. A wider implication is the loss of the benefit of reduced prices and economies of scale when material drawdown planning has not been accounted for within the construction phase. Contractors directly restrict the flexibility of their ability to purchase and explore a wider market for pricing opportunities. By limiting their ordering practices to be "on-demand" in an attempt to meet stipulated deadlines, they withdraw themselves from optimising on potential negotiations to hedge material commitment drawdowns and discounted pricing from vendors. This, in turn, can have potential limitations in the material flow process and the consequential late delivery of materials to sites.

One of the reasons for the persistent nature of this problem in design-build is the late completion of designs, which is concurrently executed with construction activities. Additionally, the high-pressure environment and the demanding workload of a project manager are major contributors (Leung et al. 2008). The dynamic nature of a project and the typical shortfall of managerial resources on-site places additional responsibilities on the project manager, who, for smaller projects, also acts as the procurement manager. Another issue encountered is the non-availability of materials when required, leading to a slowdown in site activities or re-prioritization of tasks. Relief can be sorted if some suppliers have inventory stock, but this aid often occurs by chance. Materials being ordered too late have the same lasting effects as the factors listed previously; material delay influences the critical path. Any potential float assigned for unforeseen events is absorbed by late ordering, which increases the risk of exceeding the critical path, which in turn increases the potential for delays or building out of sequence - cost overruns and potentially huge financial implications results (Assaf et al. 1995). Improving awareness of these simple issues through direct formal training or indirect through planning meetings to address call-off procedures, maintain the supply chain, and notify them of material lead times are immediate solutions that can be implemented that eventually save on cost implications for the project. Also, additional procurement staff to assist the project manager could be another option; however, an extra budget will be needed to accommodate the expense.

Confined spaces on-site limits offloading on-site

Construction projects are well known for their complexity, especially in built-up areas with little space for material delivery on- or off-site. Confined spaces provided limiting loading and offloading areas on-site and were ranked third by expert participants. Thomas et al. (2005) also agreed with this, claiming that effective material management is becoming increasingly difficult due to confined spaces on construction sites. Material delivery and laydown areas must not be overlooked and should be meticulously planned during the design phase of a job. If there are no suitable spaces identified on-site to unload materials, delivery drivers can potentially offload materials at rationalized points of convenience, which are often areas of heavy traffic prone to damage by moving plants (Spillane et al. 2011). Accordingly, this can result in materials being delivered without management knowledge, leading to improper storage and exposure to deterioration and theft.

An onsite recommendation to counteract this problem would be to plan the build route starting from the innermost point of the site and then radially outwards. This sequencing would enable easy access and material loading areas at the front of the site for the remainder of the job. However, some contractors may not agree, as making the front of the project as attractive as possible could entice future customers. The offsite solution includes sourcing storage spaces close to the site, often renting off a landowner or using construction consolidation centres (CCC). A construction consolidation centre is a distribution facility that can manage project logistics and handle material deliveries to a big single construction site or several sites (Katsela et al. 2022). It improves material movement across the supply chain, decreasing waste and other problems like congestion (Guerlain et al. 2019). Until the CCC operator receives a call from the site, construction materials are kept at the CCC until a consolidated load can be delivered. This distribution is done 'just in time' for efficiency. The primary contractor usually decides to employ a CCC and bears the expense. Subcontractors, suppliers, and hauliers all see the advantage of not reordering damaged or lost materials; thus, expenses may be shared.

Factors that did not meet consensus

Traffic around the site and material laydown areas not being used to their full potential where the two of thirty factors participants disagreed were significant in poor on-site material handling. Site traffic flows are often agreed upon with external stakeholders. Consequently, they may not be as significant as previously noted by Mawdesley et al. (2002) because on- and off-site logistic separation of pedestrian, vehicular, and equipment traffic reduces the effects of traffic on poor material handling.

Thomas et al. (2005) emphasised the importance of adequate laydown areas with properly labelled materials to enable subcontractors to distinguish the materials they require readily. The inefficient use of material laydown areas accounts for a sizable portion of on-site material handling issues. This factor, however, was deemed unimportant in this study despite low productivity levels and wastage being directly correlated to poor material management in laydown areas (Katsela et al. 2022). This finding contradicts Spillane et al. (2011) assertion of material laydown area being a major contributor to material mismanagement on a construction site. Perhaps, project managers with great experience and knowledge have better administration and control of their material laydown areas (Mohamed and Anumba 2006; Soltani and Fernando 2004). Our analysis supported this explanation, where four of the six site managers had more than ten years of experience and did not view this as a significant factor.

Solutions to material handling problems

The results of the potential solutions in order of rank are shown in table 7.

Slower build program

A slower build program was ranked the number one solution for solving material handling problems. Slowing the built program affords the flexibility of fewer deliverables and enables the project manager to focus their attention on meeting the deadlines of intermittent project milestones. This, in turn, minimises stress emanating from material call-offs, planning material storage areas and tracking materials (Haynes and Love 2004). However, some construction companies would see this as a loss of production as less value is generated during a particular period. In addition, because of contractual penalties in exceeding the project's completion date, slowing the built program without compromising completion within the planned period is a difficult decision and trade-off (Bagaya and Song 2016). An alternative to the need for a slower build program is a faster response mechanism to the material demanded. However, delivery teams are pressured to meet the demand when material consumption rates exceed the supply rate. Provisions such as efficient and accurate material quantity and specifications takeoff, timely ordering, tracking, receipt verification, storage and payment can mitigate against material consumption and supply. Adding additional labour will improve material delivery rates, but it does not guarantee the accuracy or the timely exchange of information and value-added outputs. Therefore, the aim is to improve both predictability and visibility by streamlining the material procurement supply chain. This integration will offset fragmentation within existing processes and improve accountability within the supply chain. Such a system can improve predictability and drive product quality and services. With BIM, blockchain can provide a single source of truth for and trust between participants in the material supply chain by ensuring that the correct information is readily available (Wang et al. 2020).

Increase the number of material handlers on site

Material control is a time-consuming process that requires dedicated resources. The material controller's job function should not subsume a project manager's time. Material controllers would accept deliveries, inspect them for damage, ensure that the correct materials arrive, confirm that the quantity is met, and store materials in an orderly and safe manner (Donyavi and Flanagan 2009). More importantly, they can communicate with the project manager on inventory and usage. Larger construction firms can afford to invest in ICT to help streamline this system, whereas small and medium-sized builders may look to materials handlers for assistance.

Involvement of subcontractors in the procurement process

Subcontracting within material handling presents a paradoxical issue of both solution and problem. The practice of subcontracting portions of a project to specialised subcontractors is well-known in the construction industry (Eriksson et al. 2007). However, the resulting lack of integration across the supply chain manifests in tiered transactional interfaces, creating duplicate non-value-added costs and inappropriate risk transfer (Farmer 2016). Subcontracting can shift the focus of the supply chain, which is cost rather than value-focused. Consequently, the added participants do not always increase value and innovation (Eriksson et al. 2007). Nevertheless, subcontractors' early involvement in material planning and handling enables the site's limited storage space to be efficiently managed, limiting movements between locations, specification development and completeness and the need for additional costs for staffing and equipment needs (Pheng et al. 2015; Zeb et al. 2015). By increasing the influence of subcontractors on design-related innovations, the design-build process can fortify relationships between design consultants and subcontractors and influence innovation (Eriksson et al. 2007).

Frequently, the prime contractor hires subcontractors on a labour-only basis, which enables the prime contractor to procure and deliver materials to the job site, and the subcontractor risks managing labour costs. Occasionally, additional manual labour is needed due to limited space, machinery incapabilities, or ineffective management of site activities (Zeb et al. 2015). The constrained availability of space on a job site leads to conflicts among contracting and sub-contracting parties, resulting in disputes and delays (Zeb et al. 2015).

<u>Prefabrication</u>

Prefabricating elements of the project allows for improved quality in a controlled factory environment and then transported to the site for final assembly and installation (Wuni and Shen 2020). Volumetric, penalised, pod, hybrid, or sub-assembly and component systems are used to assemble three-dimensional units (modules) that can be used independently or combined with other modules to form a modular building (Waste and resource action Plan 2007). Prefabricated structures are ranked fourth most important in addressing material handling problems and are proposed to compensate for low productivity rates and waste generation (Forsythe and Sepasgozar 2019). Prefabrication is ideal for maintaining consistent quality and addressing numerous on-site material handling problems. While the need for logistics and transportation solutions increases with more prefabrication, the number of stakeholder interfaces, workers needed, and individual components arriving on-site are significantly reduced. Consequently, the number of labelling required is reduced without decreasing the significance of accurate labelling.

Solutions that did not meet consensus

Of the twelve solutions listed, three did not meet consensus: better packaging, improved supplier's payment system, and a blockchain-based framework.

Better packaging

Despite the acknowledgement that materials on site are not always protected in a dry, controlled location and are susceptible to inclement weather, mould and poor ventilation (Johnston 2016), better packaging was not agreed as a leading solution, perhaps because it is an unbudgeted expense to acquire as well as to dispose of or extra bulk which reduces storage space. Further, extensive packaging can prevent materials from 'breathing' or increase susceptibility to humidity.

Improved system for supplier's payment

Payment is the lifeblood of construction projects and is a major source of disruption and conflict (Peters et al. 2019). Coordination and management of multiple subcontractors' materials are challenging when clients, contractors and subcontractors experience cash flow difficulties. Cheques, vouchers and cash systems are still very common at construction sites. Alternatively, advances in the financial sector through wire transfer, online banking, and cryptocurrency payments allow for immediate payments with low associated transaction costs. Online systems facilitate frequent contact between commercial managers, quantity surveyors, and subcontractors, thus allowing discussions, negotiations, and the resolution of payment challenges. The participants could not agree on whether an improved payment process would solve the supply chain's current material handling problems. Perhaps, such reservation is associated with the consideration of the risk associated with off-site materials payments giving rise to several questions about the ownership of materials, how to identify materials for specific clients/projects if off-site, payment of off-site materials bond, insurance and the contractor having the ability to inspect off-site materials for quality control and what happens in transit. Future studies should investigate the factors that hinder financial innovation in payment systems.

Blockchain-based framework

A blockchain-based framework is a relatively new and untested approach amongst most construction companies. Often, there can be hesitation with new processes, which could be a factor as to why it did not meet consensus. More so, the volatility of cryptocurrency prices as opposed to the robustness of the technology could be the reasons for disagreement. Further research understanding adaptability issues is needed to confirm these assertions for one of the most anticipated industry innovations.

General classification of materials handling problems on-site

This study identified complexity as the first material handling categorisation, which includes material laydown areas, inclement weather, confined spaces for offloading materials, and the site's geographical location. The randomized nature of these causes increases complexity leading to material handling problems (Wood and Ashton 2010). Complexity must be addressed in the design stages of every site and will need to be extensively planned to combat issues during a project (Thomas et al. 2005).

The second category is the flow of material. Material flow occurs between the supply chain - project team interface. A descriptive analysis of the research's primary and secondary data categorised material flow as the leading cause of material handling problems. Issues include materials arriving at unspecified times, partial deliveries, inadequate packaging and the absence of adequate material handlers on site. Material flow problems are usually associated with the supply chain based on the failure to pay suppliers on time for goods received (Briscoe and Dainty 2005). Better collaboration between the teams would ensure a streamlined approach to material flow.

Lack of real-time information sharing forms the final category of poor on-site material handling causes. This category includes the following variable: site team unaware of lead times, materials ordered too late, site teams failing to communicate delivery dates to suppliers, and lack of trust between suppliers and contractors. These factors can be split into two communication groups, hard and soft factors (Thunberg et al. 2017). Hard aspects include how information is shared between all parties involved in the construction process, and soft aspects include mindsets and relationships. Forming relationships is vital for information sharing and ensuring construction projects succeed.

Limitations and recommendations

For a macro-level knowledge of the UK's future building materials supply chain, an industry-wide research including delivery drivers and haulage contractors is required. Future research should address the individual treatments for fragmentation and poor adaptation of present technologies to rectify material handling problems. Future works should also investigate the factors that hinder financial innovation in payment systems and the blockchain-based material handling framework’s adaptability to prefabricated construction forms. Because the data is confined to design-build contracts, the study recognises that the results and conclusions cannot be generalised. Nevertheless, researchers may use the technique to comprehend different procurement choices, which is the first step to addressing industry-wide standards for materials management.

Conclusion

Poor material management at construction sites will remain unresolved without agreement on important contributing elements or potential solutions to existing and future challenges (Pande and Sabihuddin 2015). This study explores poor material handling industry practices within the context of design-build projects at the site level, categorises problems encountered within the supply chain and the crossover on-site, and offers solutions. It was argued that poor material handling occurs on-site due to the interaction of both project and supply chain management teams and the difficulty in accounting to single point ownership of this problem. Therefore, the traditional response has been representative of compartmentalisation, which is fragmented by the extent of subcontracting within the industry. By using a panel of experts in a fuzzy Delphi study, a consensus was then sought to rank problems contributing to and possible solutions to resolve on-site material handling. The research categorised three main problem areas: complexity, material flow, and lack of information sharing between the construction project team and the supply chain. The main factors in these categories were primarily caused by late deliveries to sites due to late ordering, as both factors were ranked first and second by construction experts, respectively. Confined spaces on-site that limit loading and offloading areas was also a major contributor, ranking third. These results have a wider implication, highlighting much-neglected issues on site that influence the direct relationship to stakeholders and the potentially negative effects on construction business with faulty material management. The main outcome of this consequential, often ignored, and expensive subfield in construction management is raising both situational awareness and institutional checks at the crossover interface between site and supply chain management. This importance is emphasized and may have wider public policy implications when sustainability and conservation are national policy criteria, yet contractors and sub-contractors are losing money due to poor practices, causing huge financial implications, wastages and mental stress. Highlighting the main dilemmas regarding on-site material handling problems will allow contractors to alleviate such difficulties in future projects. In remedying material handling challenges, the experts concur that a faster response mechanism to material demands is an alternative to the top choice of a slower build programme. Other salient solutions are increasing the number of material handlers and involving subcontractors in the materials planning and management process. Prefabricated structures were ranked fourth in importance for resolving material handling concerns and have been proposed to offset low productivity and waste generation in the supply chain. This study highlights the importance of considering the unique characteristics of procurement options, particularly the influence of design-build project delivery on construction supply chain challenges and possible solutions.

Data availability and conflict

Data for this research is provided within the manuscript. There is no conflict of interest to report.

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