MANAGING INTERFACES BETWEEN OFFSITE AND ONSITE CONSTRUCTION

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Discrepancies such as tolerance mismatches during the incorporation of offsite components into onsite construction can give rise to buildability problems. This results in considerable rework and subsequently causes delays and cost increases. Improving current knowledge of these discrepancies could help reduce buildability problems. One important challenge in this regard is related to effective knowledge exchange across structural and organisational boundaries in construction projects. This study explores how knowledge in these boundaries is activated and exchanged. Distributed Situation Awareness (DSA) theory, as a sociotechnical tool, was used to focus on knowledge distribution between project parties. Semi-structured interviews with construction participants managing offsite construction projects in the UK were carried out. The preliminary findings show that different trade specific standards from suppliers can give rise to tolerance mismatches. The expected contribution of the study is on practical project management insights into ways of designing and managing interfaces in offsite construction to facilitate knowledge exchange related to discrepancies.

Keywords: offsite; tolerance mismatch; buildability; distributed situation awareness

INTRODUCTION

Offsite construction (OSC) offers a sustainable approach in solving time, cost and waste challenges and leads to improvement in quality and productivity (Goulding *et al.,* 2015). However, there is slow uptake of OSC and one of the contributing factors is argued to be buildability problems arising from discrepancies (such as tolerance mismatches). The challenges of fitting offsite components with each other and/or with in-situ construction cause delay and rework (Arashpour *et al.,* 2020).

Buildability problems may also in turn negatively impact on building performance in-use relating to, for example, the ongoing robustness of joints between the physical components to ensure aspects such as watertightness, fire safety, airtightness and a range of other performance aspects throughout the building life cycle (Tang *et al.,* 2020). While buildability and long-term building performance are related, the particular focus here is on how well offsite components fit together with onsite construction during the construction process.

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Improving current knowledge of organisational and technical interfaces between offsite and onsite construction can help reduce discrepancies that cause delays and cost increases. One key area is by exploring how distributed and embedded knowledge can play a critical role across project teams (Bosch-Sijtsema and Henriksson, 2014; Liu *et al.,* 2022), when offsite products are being incorporated into onsite construction. Drawing on Distributed Situation Awareness (DSA) theory, the study explores how knowledge related to discrepancies that effect buildability problems is activated and exchanged between the designers, manufacturer, main contractor, and subcontractors. DSA is used to allow for the mobilisation of a sociotechnical approach and focuses on knowledge distribution and interaction or coordination between the different parties involved. Considering practitioners' lived experiences in projects as knowledge, its exchange to turn into distributed awareness has been examined.

LITERATURE REVIEW

Buildability is mainly concerned with the dynamics of the building works and solutions to putting together a complex of building materials, elements, and sub-assemblies. Ferguson (1989) defines buildability as the capacity to construct a building efficiently, economically and to agreed quality levels from its constituent materials, elements, and sub-assemblies. He highlighted that special attention should be given to interfaces because of the connection challenges which could result in project delays and high costs.

Referring to Ferguson’s point, interfaces in offsite construction (OSC) are problematic and less forgiving in comparison to traditional construction because of the associated tolerances (Shahtaheri *et al.,* 2017). Construction tolerances are described as the allowable variations of materials and components from nominal values/design specifications (Ballast, 2007). Tolerances ensure that the interfacing physical components fit together reasonably well taking into consideration buildability aspect (minimising the need for costly remedial work and quality issues) and future building performance (water tightness, air tightness and fire safety). In traditional construction, tolerance issues are handled element by element, and there is the opportunity to control and correct the tolerances as building progresses. OSC products/elements have highly restrictive construction tolerances and the points where tolerances can be controlled are fewer.

If tolerances are not properly understood and coordinated in OSC, tolerance problems can rapidly accumulate (Shahtaheri *et al.,* 2017). Arashpour *et al.,* (2016) through a simulation of two construction projects argued that the integration of offsite and on-site construction can cause deviations from plans and delays. The authors’ research was derived by a study of Australian house building projects. These authors, based on the Australian Bureau of Statistics (2015), indicated that the average house completion time had not been shortened, despite using offsite manufactured elements. Arashpour *et al.,* (2016) claim that one of the main contributing factors in this is related to tolerance management between offsite elements/products and onsite construction.

Similarly, Killingsworth *et al.,* (2020) studied one construction project in the USA and found that practitioners’ unfamiliarity with the specifics of offsite manufactured structural frames led to tolerance mismatches between the frames and the in-situ concrete podium. The connection between manufactured structural system to the concrete slab required the slab to be perfectly flat, which, according to the practitioners on site, was difficult to achieve. This led to delays in the project programme due to the remedial work to the concrete podium to accommodate the manufactured structural system. Tolerance mismatches have long existed in construction with various causes. Talebi *et al.,* (2021, p.10) studied two UK construction projects to identify the causes of tolerance mismatches and found factors such as fragmentation of tolerance information in the specifications, inadequate tolerance information for interfacing components in the reference documents and poor communication and coordination of tolerance information between project participants.

The construction process in offsite-onsite interface typically involves a variety of project participants i.e., manufacturer, main-contractor, and subcontractors, etc who need to coordinate tolerances by exchanging appropriate knowledge (Arashpour *et al.,* 2020). Rausch *et al.,* (2020) argue that the complexities of tolerance specification and uncertainties during project delivery triggers the onsite team to use reactive measures to manage tolerance issues. Mainly, this is because the burden of meeting designer-specified tolerances is passed down to the construction team, who are tasked to correct tolerance mismatch issues (Milberg and Tommelein, 2020). This implies that project participants exchange buildability knowledge as they interact or coordinate to exercise their problem-solving measures. However, the actual interaction or coordination of project participants in OSC remains to be explored as much focus is on adaptation to industrialisation and strategies concerning business, production, and products (Lessing *et al.,* 2015).

Interestingly, Goulding *et al.,* (2015) argues that problems in OSC can be reduced by focusing on people, process, and technology as one to understand project team interaction and how knowledge is exchanged. Liu *et al.,* (2022) further develops these ideas, arguing that maintaining strong informal relationships and increasing task dependence among project team members could facilitate knowledge exchange connections in OSC.

What the current debate demonstrates is that effective interaction or coordination between project participants in OSC is required to exchange knowledge for problem solving when discrepancies arise on site. However, how knowledge related to these discrepancies such as tolerance mismatches in OSC is activated and exchanged between project team members is yet to be explored. Exploring how knowledge is activated and exchanged between the designers, manufacturer, main contractor, and subcontractors will shed light on buildability problems in offsite construction and what actually happens in the offsite/onsite interface. Such research calls for an analytical framework in which knowledge related to discrepancies being exchanged and coordinated across project teams can be analysed. Distributed Situation Awareness (DSA) theory offers a potential platform to examine this phenomenon of interest as it focuses on how information and knowledge is distributed across sociotechnical systems.

Distributed Situation Awareness (DSA) Theory as a Theoretical Background

Distributed situation Awareness (DSA) is described as activated knowledge for a specific task, at a specific time within a sociotechnical system (Stanton *et al.,* 2006). In other words, DSA model is focused on the awareness that is distributed across human and nonhuman agents of a system. Examples of nonhuman agents would be artifacts such as tools, documents, and displays. In the present study, two elements of DSA namely compatible SA and SA transactions were mobilized in the analysis of the data.

Compatible SA deals with the content of awareness. More specifically, it acknowledges that although team members may access the same information in a system, they hold different perspectives of the situation. This is mainly because of the factors such as individual roles, goals, tasks, experience, training, and schema are different for every individual (Stanton *et al.,* 2006). The team members may have the awareness of their tasks within each situation for their specific task but are also cognisant of what other team members need to know.

SA transactions explain how agents within a system can facilitate and enhance the awareness of each other through SA transactions. Team members exchange information with one another (i.e., through requests, orders, and situation reports) leading to knowledge being developed and maintained (Stanton *et al.,* 2009). DSA theory emphasizes that SA transactions are mediums for coordinating teamwork, and such transactions lead to improved task performance (Stanton *et al.,* 2009).

Reflecting on the aim of the study using the lens of DSA and considering the incorporation of offsite products into onsite construction as a sociotechnical system, this research is an attempt to answer how roles and tasks of project team members are related to reduce discrepancies effecting buildability problems during offsite and onsite construction integration. The approach to answer the question is explained in the method section.

METHOD

Using the lens of DSA theory, the focus of the study is on how knowledge related to buildability is distributed and embedded across the agents (designers, manufacturer, main contractors, subcontractors, and nonhumans). Data from semi-structured interviews were used to capture participants' experiences of buildability problems relating to onsite/offsite integration. By using active interviewing (Cicmil *et al.,* 2006), the participants were encouraged to share their reflection and accounts of the discrepancies they encountered while performing project tasks. The human agents of the study were selected based on their position in the project or contractual responsibilities and duties. In addition, they were required to have more than 2 years of work experience in offsite construction. Table 1 outlines the profile of the selected participants (anonymised).

Table 1: Profile of participants

Interviewee Position	Organization	ID
Product Manager	Main Contractor	K1
Director	Modular Manufacturer and Installer	M1
Assistant Site Manager	Main Contractor	Z1
Technical Leader – Structures	Manufacturer and Contractor	P1
Structural Engineer	Manufacturer and Contractor	D1
Senior Design Manager	Steel Manufacturer and Installer	V1

Interviews with 6 participants (average duration 35 minutes) were recorded and transcribed verbatim. To examine the data through the theoretical lens, reflexive thematic analysis (Braun and Clarke, 2006), was carried out in NVivo 12 Pro. The coding of the transcripts of the interviews was developed based on several elements of the DSA theory. Importantly, the coding scheme focused on the DSA elements defining the SA transaction dimensions including coordination, communication, and interaction. It also focused on compatible SA dimensions, including roles and tasks. An extra layer of coding for the sources of interaction used by the human agents for each transaction dimensions was included to cover artefacts and interactions with other members of the project team (either manufacturer, designer, or contractor). An important limitation of this study is the small number of informants - however, this was a scoping exercise, and the intention is to explore individual’s experiences and perspectives (Creswell, 2014) rather than to generalise the findings.

FINDINGS

In the interviews, two incidents of buildability problems in the integration of offsite and onsite construction were identified. These two incidents were based on the information provided by the product manager working in a main contractor organisation and the senior design manager working in the steel manufacturer and installer organisation. (K1 and V1). The first incident happens in a housing project completed in 2021, which involved the interfacing of the in-situ concrete roof slab and a glass reinforced plastic (GRP) tank. The second incident is of a commercial building and involves a manufactured framing system.

These incidents involved multiple 'agents' engaged in undertaking interdependent tasks. The analysis focuses on SA transactions and compatible SA. SA transactions centre on interaction, communication, and coordination between human and nonhuman agents to capture collective knowledge regarding buildability problems and how knowledge was developed and changed. Compatible SA focuses on the relations between roles, and tasks of the human agents and how knowledge of the situation is activated and managed on the same piece of information.

Incident 1: Product Manager's (K1) perception

The Product Manager (PM) working for the main contractor explained that they had a project which involved installing a very large offsite manufactured GRP tank on the in-situ concrete slab flat roof. The main contractor subcontracted the works to two companies: 1) subcontractor for in-situ concrete slab roof; and 2) Mechanical, electrical and Plumbing (MEP) subcontractor for the water tank installation works. The MEP subcontractor subcontracted the tank installation to a tank manufacturer. This meant that the main contractor had no direct relationship with the tank manufacturer. After the tank was put into position, filled with water and the building was commissioned, the tank cracked and eventually failed, leaking all its water throughout the building. This resulted in considerable physical damages, including time delays and addition remediation costs of the associated reworks. The project team established that the reason for this was the tolerance mismatches between the GRP tank and the concrete slab. From the PM's perspective, the slab wasn't flat and well levelled, and this caused distortion and cracking in the tank structure, and eventual failure. The tank manufacturer has specific tolerances that are very precise requiring the tank to sit on a base that is very flat. The tank manufacturer had not communicated this piece of information either to the MEP subcontractor nor to the main contractor. Hence, the concrete slab subcontractor was not aware of the precise tolerance information required for the tank installation, the PM explained:

> “What we got was what we got because no one communicated anything. It also wasn't checked on site. The tank supplier should have been on site to do the survey of the slab before erecting the tank and say this is not acceptable for us. But ultimately, it's not their responsibility to make sure that the slab is within their tolerance, but they assumed that someone else had checked that for them”.

The PM suggested that to avoid such incident in future, there should be effective coordination between the parties to accommodate different trades standards for the specific tolerances.

Relationships between roles and tasks of different agents in the system
The tank and concrete installation describe the requirements of different agents in the system. The concrete slab required specific tolerances to accommodate the tank. However, the transaction of knowledge on specific tolerances did not take place. In this incident, the main contractor, MEP subcontractor and roof subcontractor were not knowledgeable of the requirements for specific tolerances to successfully interface the slab and the tank. This information on tank tolerances was with the tank manufacturer whose task was to install the tank. Indeed, the tank manufacturer was aware of the specific tolerance for the tank but not of the slab. The manufacturer's knowledge of this interfacing tolerances had not activated as there was missing SA transactions on specific tolerances between the tank manufacturer and the roof subcontractor. Although the main contractor, MEP subcontractor, roof subcontractor and tank manufacturer were using the same information (drawings of the roof and tank), their awareness was different based on their own requirements and tasks.

Role of nonhuman agents in SA transactions and compactible SA
The interaction between the tank and the slab led to the awareness of the main contractor, MEP subcontractor and roof subcontractor about incompatible issues. The failure of the tank resulting in water spillage was a form of non-verbal communication that enabled SA transactions (i.e., knowledge on specific tolerances) between human agents. Had the tank not cracked and failed, the non-verbal communication signal to the human agents would have been 'everything is perfectly fit'.

The explanation of the PM on the Building standards highlights their importance on facilitating SA transactions (specific tolerances) for the right information to be passed to the right agent at the right time. Building standards are important to achieving compatibility among different trades involved (Product Manager K1). In this aspect building standards are storage and provider of information, which enables the construction system to perform. However, from the explanation of the PM, there are different standards of specific trades, which requires coordination to avoid the adverse effects of tolerance mismatches onsite. This suggests that the differences in trades tolerance specifications may lead to inappropriate SA transactions (i.e., inadequate, missing, and incomplete information) and SA incompatibilities causing buildability problems on site.

The experience of the PM indicates how SA transactions and compatible SA plays an important part in accommodating tolerances. The missing communication link between the main contractor, MEP subcontractor, roof subcontractor and tank manufacturer demonstrate erroneous assumptions about responsibilities for coordination in this interface.

Incident 2: Senior Design Manager's (V1) Perception

A Senior Design Manager (SDM) working for the Steel Manufacturer and installer explained the situation in this incident. His role involved studying 3D models and coordinate between the manufacture and the project team to ensure that there is no liability with the manufacturer due to any discrepancies in the drawings. In one instance, he sent two emails to the architect and project engineer explaining that there were several clashes based on the clash detection. In his perspective, the high number of clashes was because certain manufacturers and subcontractors had been exempted from the use of BIM by the main contractor because of the costs involved in having BIM.

SDM noted that despite the checks, discrepancies typically arise in the project because of the complex offsite products being installed by different subcontractors and the exemption of the other parties from the use of BIM. An important issue is that every manufacturer or subcontractor will have a set of tolerances unique to their products. These tolerances are typically included in contracts requiring the specialist subcontractor to build within those limits, or to rectify their work to the set tolerances. The SDM explained, "during the execution of the tasks in this project more than 7 different subcontractors are in a single area, all trying to prioritize their own tasks. Later, when there are connection problems, the manufacturers and subcontractors involved point fingers at each other in the meeting for delaying one another and incurring costs".

Relationships between roles and tasks of different agents in the system
This incident describes that the agents (architect and engineer) despite using the same model, had different perspective on the model based on their goals, roles and tasks that they were required to undertake. The Senior Design Manager was provided with SA by the system to plan, check and coordinate the two 3D models, whilst the architect and project engineer who undertook the works depended on the communication (about drawings not matching) from the Senior Design Manager to have adequate levels of knowledge to undertake their required tasks efficiently. Upon receiving the two models from the architect and project engineer, the Senior Design Manager checks and communicates for any discrepancies within the models. Since the roles were clearly defined at this stage, when SA-related knowledge was required, the agents involved knew what was going on and where to get the information.

Although at the factory level there could be adequate SA transactions and compatible SA, the findings suggest that this is not the same when the building elements from different manufacturers are interfacing onsite. The involvement of complex interfaces i.e., different manufactures' offsite products and subcontractors require that the agents involved understand specific information elements (i.e., tolerances) related to the subsequent tasks involved. Interestingly, after activating the SA related- knowledge (i.e., tolerances, connection problems), the agents (main contractor, manufacturer, and subcontractor) held meetings to solve the incidents which indicates the emergence of new project practices due to this formal interaction or coordination.

Role of nonhuman agents in facilitating SA transactions and compatible SA
The interaction between the human agent (Senior Design Manager) and nonhuman (drawing models) enabled the Senior Design Manager’s knowledge to be activated resulting in SA transactions (i.e., information not matching) facilitated by emails (nonhuman) to achieve compatibility of the architect and engineers’ drawings. The role of the Senior Design Manager, after interacting with the models, was to ensure that there is a common understanding between the agents. Again, the contract has been explained as the place where information on specific tolerances resides. The role of the contract is to inform the interfacing agents (specialist subcontractors) to build within the specified tolerances or rectify the works to the set tolerances. However, according to the findings, there seem to be a shortfall of SA-related knowledge to check the different manufacturers' or subcontractors' tolerances. This leads to clashes or connection problems. This finding suggests that interface design intended to

support offsite and onsite integration needs to encourage usability, ease of use of the system and reduction in interaction time to search for information and tools required.

In this study, DSA theory which adopts a sociotechnical system perspective, was used as a lens to study how knowledge related to buildability problems in the integration of offsite and onsite construction is activated and exchanged among construction participants. Importantly, how knowledge is distributed between the 'agents' to identify and solve discrepancies effecting installation problems is the contribution of this paper to offsite construction project management. The research focused on DSA elements namely SA transactions and compatible SA to identify what information was needed, who needed it, how it was provided and when it was required (Salmon *et al.,* 2009). The nature of planning and execution of construction activities in OSC depends on different agents with different requirements and roles. These agents require different types of information, or they use the same set of information differently. Importantly, the agents are vital sources of knowledge for understanding the current situation and anticipating any installation problems. This displays a need for agents to pay close attention to their knowledge needs and the ways in which knowledge can be activated and exchanged at the interface of offsite and onsite construction.

The results illustrate that different manufacturers' offsite products require specific attention to interaction and coordination between the parties involved. This is to reduce the adverse effects of tolerance mismatches. In addition, there may be assumptions among the participants in the interface of offsite and onsite construction which contributes to inappropriate SA transactions (i.e., inadequate, missing, and incomplete information) and SA incompatibilities (i.e., unclear link between roles and subsequent tasks). These assumptions may arise because other important human agents are either exempted from the modes of information exchange adopted (e.g., in the use of BIM in incident 2), or are not integrated early (eg.in the case of the manufacturer in incident 1).

The incidents above highlight that knowledge gaps were only addressed when things went wrong during task performance. A clear understanding of the likely situations to cause installation problems may substantially improve the project participant's interaction to exchange the required information in OSC. This may prompt the project participants to actively seek and exchange knowledge from the project environment, rather than passively waiting for the knowledge to emerge.

The findings also show that the information exchange practices happening during the interaction or coordination methods (i.e., face to face meetings, emailing) resulted in the emergence of more formal practices. For instance, in the incidents, the meetings conducted to find solutions shows how interaction or coordination formalises such meetings into series of meetings to analyse and solve the incident. This is in line with Bygballe *et al.,* (2016) who argued that new project practices emerge as project participants coordinate in new ways. Thus, knowledge is subjected to both formal and informal coordination (Jacobsson, 2011). This explains that pre-specified construction management system design in OSC evolves as the agents give sociotechnical meaning to the project structures through interaction and coordination. More importantly, the finding suggest that unforeseen challenges may not be excluded altogether (Jacobsson, 2011). These unforeseen challenges may require effective knowledge exchange practices if OSC delivery is to be enhanced.

CONCLUSION

Interaction or coordination is important for knowledge exchange between offsite and onsite construction interfaces. To reduce discrepancies effecting buildability problems in OSC, various interaction or coordination methods are used. The effectiveness of these interactions can be improved by exploring how knowledge related to discrepancies is activated, exchanged, and managed. The DSA model shows that different manufacturers' offsite products and different trades standards in OSC demand that the human agents interact or coordinate to exchange knowledge to reduce buildability problems. The analysis showed that there were missing communication links between the project parties in the interface creating room for a lot of assumptions. This suggest that the information systems and interfaces that facilitate information and knowledge exchange between agents in OSC need to support SA transactions. More importantly, the preliminary findings highlight that the human agents may also need to be flexible in their interaction or coordination procedures.

Future work will extend the DSA three-part model of knowledge elicitation, extraction, and representation (Stanton *et al.,* 2006), by considering the social, task, and knowledge networks to illustrate how knowledge related to discrepancies is activated and exchanged between offsite and onsite interfaces.

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