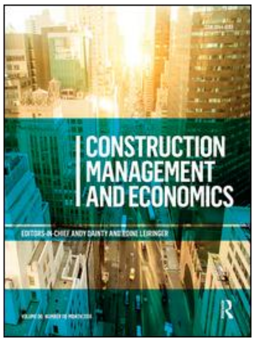

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Off-site construction in highways projects: management, technical, and technology perspectives from the United Kingdom

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ABSTRACT

With a rich off-site construction (OSC) experience accumulated over the last two centuries, the United Kingdom (UK) is looking up to OSC to deliver its critical infrastructure projects in the next decade. Highway projects are good fits for OSC with their project characteristics. However, the extant OSC literature for highways is mostly about OSC elements' design performance. Also, the OSC literature is predominantly building sector focused. Addressing this gap, the paper presents the findings of a research project, sponsored by the UK's National Highways, which aims at understanding what needs to be done to improve the current OSC condition for highways projects in the UK from a management, technical and technological perspective. After a detailed literature review, 20 in-depth interviews with subject experts were conducted. The initial findings were validated through five highways projects as cases and then ranked by two focus groups using the Delphi method. Alongside revealing the current OSC condition, 95 suggestions (43 management-related, 23 technical opportunities, and 29 technology-related) were elicited and ranked by their impact potential. Some of the high-potential suggestions are developing a collaborative OSC decision making framework, a product design mindset, improving OSC digital product libraries, creating mobile OSC factories, and a design options repository. The findings revealed that many OSC challenges identified in the general or building sector focused OSC discussions exist also in the highways sector. It is recommended that the identified high and medium impact potential suggestions are prioritized by practitioners and policy makers to improve the current OSC condition.

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Off-site construction; highways; management; technology; technical

Introduction

Off-site construction (OSC) is an umbrella term referring to a spectrum of innovative construction techniques, where all or some components, elements, or modules of a built asset are manufactured, partially or wholly assembled in an off-site environment, and then transported to a construction site for final installation (Hu *et al*. 2019b). This approach to construction is sometimes referred to as modular integrated construction (MiC), or design for manufacture and assembly (DfMA) (Ehwi *et al.* 2022). Construction components-wise, OSC covers (Lusby-Taylor *et al*. 2004): (i) modular (volumetric) construction, (ii) panelized construction (e.g. flat-packs), (iii) hybrid (semi-volumetric) components (e.g. pods), and (iv) off-site manufactured sub-assemblies (e.g. roof cassettes). Research shows that the productivity in off-site production of construction components is generally higher in comparison to corresponding on-site activities (Eastman and Sacks 2008; Goodrum *et al*. 2009). Other claimed benefits of OSC systems include superior quality as well as safer and less physically demanding workload on-site (Goulding *et al*. 2015). Reduced wastes, shorter cycle times (Ahn *et al*. 2020; Martinez *et al*. 2020), reduced supervision, on-site costs, and number of delayed project completions (Nasirian *et al*. 2019) should be also noted as OSC benefits. Responding to the increasing complexity and demanding requirements of construction projects, policy makers see OSC as one of the key means of improving the construction industry's performance (Wuni and Shen 2019), earning it the term "modern method of construction (MMC)" since the 1990s (Gibb 1999). Despite the global interest in OSC, its successful uptake is still problematic (Goulding *et al*. 2015).

The use of OSC in the United Kingdom (UK) can be traced back to the early 19th century (Taylor 2010). Since then, it has been held high as a panacea to the inefficiencies, labour shortages, and environmental

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impact of the built environment in the country (Taylor 2020), with fluctuating attention patterns. There are also some persisting problems highlighted in OSC discussions, such as lack of transparency in OSC decision making, perceived higher costs, and lack of available multi-skilled labour to work in the offsite factories (Goodier and Gibb 2007). Uncertainty about what OSC actually entails and a lack of shared understanding between the industry and academia are noted (Nadim and Goulding 2009). An excessive focus on direct material and labour costs for OSC evaluation (Blismas *et al*. 2006), complex commercial interfaces and long lead-in times (Arif *et al*. 2012) pose challenges in OSC implementations. Tedious procedures and permits, and a lack of OSC guidance and leadership (Pan *et al*. 2007) can be also added to the problems. These problems aside, as explained in the background section of the paper, the general OSC benefits seem to outweigh the problems highlighted, creating a favourable narrative for OSC in the literature for improving project delivery performance. This is reflected in practice as a conscious support and incentivization for OSC at strategic level by policy makers and large service providers (e.g. contractors, consultants, suppliers, etc.) in the industry. Despite the attention spanning over two centuries and the generally favourable view, the OSC sector falls short in improving its overall market performance and contribution to the UK construction industry (Taylor 2020), indicating still a limited use of the concept in practice.

The UK government has recently set out to invest £650 billion in the infrastructure across the country over the next decade (HMT 2020). Against this backdrop, and a growing pipeline of mega-infrastructure projects (e.g. High Speed 2 (HS2)—a new high-speed railway, Smart Motorways, Transpennine Route Upgrade, Lower Thames Crossing), it is hoped that adopting more of OSC will help to deliver this critical national infrastructure. To facilitate this, the UK's Budget 2017 announced the adoption of a presumption in favour of greater use of OSC for infrastructure projects by five central government departments—the Ministry of Justice, Department of Health and Social Care, Department for Education, Department for Transport and Ministry of Defence (IPA 2018). The government also sees OSC as a key means to modernize the construction industry (HMG 2018).

Despite the fact that infrastructure projects offer good fits for OSC with their relatively few number of components in larger sizes used in repetition in a project (Hällmark *et al*. 2012), much of the available academic literature on OSC is either framed in the context of buildings and the building sector (Boyd *et al*. 2013; Abanda *et al*. 2017; Dowsett *et al*. 2019; Iuorio *et al*. 2019) or holds a general tone (Mao *et al*. 2015; Wang *et al*. 2020b), lacking a clear OSC management for infrastructure perspective (Larsson *et al*. 2014). An apparent bias in the OSC literature (Hosseini *et al*. 2018) is also present towards technical product research over operations and management research. There is also a relative scarcity of explorative research of qualitative nature in the general OSC research literature (Ehwi *et al*. 2022). Therefore, there is a need to better understand the current OSC condition and priorities as to what can be done to improve the overall impact of OSC in the face of a growing number of infrastructure projects in the UK, beyond technical components, and scarcities of the literature focusing on this particular OSC domain from a qualitative lens.

Aiming to address this gap, the paper presents the findings of a research project on the OSC condition in highways projects in the UK from the perspective of construction project management, technical OSC components, and facilitating digital and automation technologies. The research touches on the manufacturing side of OSC to a limited extent. The research aim is therefore understanding and ranking by their value potential what measures and initiatives should be taken to improve the current OSC condition for highways projects in the UK from those perspectives. This is realized by first exploring the current condition, and then eliciting and ranking the future suggestions through an extensive literature review, 20 semi-structured interviews with subject experts, studying five highways projects with National Highways (used to be Highways England) as the client, and two focus groups. The rest of the article is organized as follows. Following the research background, the research method of the study is explained. The findings from the interviews, highways project cases, and focus groups are presented and discussed. The paper concludes with key points regarding the current OSC condition and future directions for highways projects.

Research background

Research trends

The use of manufactured buildings is not a new phenomenon. In the 1830s, John Manning created a portable cottage and there were several other examples of off-site production of building components throughout the 19th century. Prefabricated construction components started to be used in the post-World War II conditions to meet housing requirements. Those early generation projects often suffered problems and performed poorly due to lack of appropriate technology, materials, and coordination among professionals (Razkenari *et al*. 2020). With the development of new technologies and management concepts, the term OSC has emerged in recent decades as a popular umbrella term referring to the systematic planning, design, fabrication, logistics, and assembly of prefabricated construction components (Mao *et al*. 2015; Hosseini *et al*. 2018; Jin *et al*. 2018). The term OSC is also adopted in this study as it is frequently used in the academic and practice focused literature to generally refer to efforts associated with both technical and management sides of using prefabricated components in project delivery.

The main research trends in the field are (Jin *et al*. 2018) (i) integration with Building Information Modeling (BIM), DfMA, lean construction, and sustainability; (ii) project delivery process with a life cycle assessment perspective; (iii) stakeholder readiness for OSC investigations in different contexts; (iv) frameworks or models for prefabricated production; (v) holistic performance evaluation systems for OSC; and (vi) technical standards and tests for the application of new materials. The fabrication and construction (on-site assembly) stages rather than the design and maintenance have mostly been the focus of these works, and the emphasis has been on optimization (Hussein *et al*. 2021). Hosseini *et al*. (2018, p. 235), after a bibliometric investigation of 501 articles on OSC from top-ranked construction journals, conclude that "there is a bias (in the OSC literature) towards product research over operations and management, and a sharp compartmentalization of sub-fields, with little or no cross-fertilization between researcher areas, the researchers themselves, nor the research institutions". According to Jin *et al*. (2018), the future research in the field should focus on process improvement, technology applications, and performance evaluation.

OSC benefits, disadvantages, and barriers

The boundary between the conventional and offsite is blurring due to the gradual increase of prefabricated materials and components in conventional projects, indicating an appreciation of the benefits of OSC (Sutrisna and Goulding 2019). Indeed, the literature discusses many OSC benefits and drivers (Wuni and Shen 2019). The benefits mainly stem from relocating the in-situ activities to a controlled environment. Some of those benefits include shortened project schedule (Ahn *et al*. 2020) and improved safety and quality performance (Kamali and Hewage 2016, 2017). Higher efficiency, economies of scale through repetition (Martinez *et al*. 2020), reduced wastes (Boyd *et al*. 2013), and increased predictability of project cost and schedule (Razkenari *et al*. 2020) are also underlined. Numerous factors influence the on-site productivity of a construction project, but buildability is among the most significant (Abdulaziz 2016). It has been known that the adoption of DfMA and off-site components facilitates physically building, on-site assembling, or renovating the asset concerned (Choi *et al*. 2019; Gbadamosi *et al*. 2019; Gao *et al*. 2020). In Singapore for instance, as part of their construction productivity roadmap, the adoption of DfMA is mandated in the building codes regarding permissions for government projects (Gao *et al*. 2018). There is also a scoring system for buildability in the most recent code of practice where bonus points are allocated based on the use of a number of DfMA technologies, thus enabling designers to reassess and redesign by the buildability scores (Gao *et al*. 2020). There is a growing move toward adopting OSC in project delivery on a global scale. In China, the government has recognized the OSC benefits and actively supported the adoption of OSC as a facilitator for the industrialization of the Chinese construction industry (Gan *et al*. 2018). OSC is expected to account for 30% of the total construction in China in the near future (Gan *et al*. 2018). In the United States of America (USA), OSC is recommended by the National Institute of Standards and Technology (NIST) as one of the top five opportunities for breakthroughs in the construction industry (Razkenari *et al*. 2020). In 2013, the National Institute of Building Sciences (NIBS) founded the Offsite Construction Council (OSCC) to promote OSC research and implementation (Razkenari *et al*. 2020). OSC popularity has also been widely reported in Australia (Hu *et al*. 2019a), Canada (Kamali and Hewage 2016), Germany, and the Netherlands (Wang *et al*. 2020b).

It has been also noted that OSC could assist in improving the sustainability performance of the construction industry (Razkenari *et al*. 2020). This includes reduction in construction dust, noise, and waste (Jaillon and Poon 2008), lower carbon and water footprint (Wong *et al*. 2017) as well as embodied carbon and emissions (Yunus and Yang 2012), improved energy performance and efficiency (Chen *et al*. 2010), reduction in site and community disturbance (Yunus and Yang 2012), and improved sustainability competence including circular construction (Pan *et al*. 2007; Mao *et al*. 2018).

On the other hand, preplanning efforts, site logistics, and transportation requirements increase in OSC (Zhai *et al*. 2014; Sundquist *et al*. 2018). Flexibility of OSC components for late design changes is constrained (Kamali and Hewage 2016), as well as the ability of interfaces between factory-made OSC components and those made in on-site assembly to absorb dimensional deviations (Zhai *et al*. 2014). The need for extensive collaboration and communication between OSC stakeholders (Rahman 2014) and OSC factory overhead costs (Razkenari *et al*. 2020) can be noted as the OSC disadvantages. Also, unnecessary (e.g. overdesigning) or some specific processes (e.g. extensive logistics requirements) in relation to OSC (Jin *et al*. 2018) as well as poorly designed components (Fifield *et al*. 2018) may have negative effects from a sustainability perspective.

The perception of OSC having a high initial cost is a key barrier (Pan and Sidwell 2011; Rahman 2014). However, when extended cost parameters, such as material waste and shortened schedule are considered, the perception may not hold true (Tam *et al*. 2015). Assessing the environmental impact and cost of an asset over its lifetime requires assessment of all its elements and life cycle stages. Life cycle assessment (LCA) and life cycle costing (LCC) approaches evaluate the lifecycle environmental impacts and life cycle costs, respectively (Islam *et al*. 2015). Although further justification is needed, on average, OSC methods show better lifecycle performance, for example energy and waste performance, and value (Pan *et al*. 2007; Blismas and Wakefield 2009; Kamali and Hewage 2016).

Inadequate policies and regulations, insufficient OSC knowledge and expertise in manufacturing, design, and on-site assembly (Arif and Egbu 2010) are further barriers for OSC. Alongside these, dominant traditional project management processes and procurement, reluctance of stakeholders to adopt and experiment with OSC components (Gan *et al*. 2018) are also highlighted for the barriers. Unsuccessful past experiences associated with OSC (Nadim and Goulding 2011), low standardization (Nasirian *et al*. 2019), and a lack of systems approach in OSC implementations involving different stakeholders (Warszawski 2003) are some of the other important barriers. Over-modularization—the unjustified application of OSC—is also a rising concern that may result in sacrificing the economic value of OSC for construction projects (Wong *et al*. 2017). Nevertheless, the overall conclusions in the literature have been that the potential advantages of implementing OSC typically outweigh the disadvantages (Sutrisna and Goulding 2019).

Technology supporting OSC

The current technology supporting OSC is broad and diverse. With parametric objects containing components' geometric and attribute data, BIM is used as a design development, information exchange, communication, and manipulation tool for 3-dimensional (3D) design (Cao *et al*. 2014). It is also used for project planning (4D), cost planning (5D), code compliance, clash detection, and sustainability analyses (Cao *et al*. 2014). Yin *et al*. (2019) summarized the research on BIM application in OSC in five categories through a bibliometric analysis: (i) interoperability and data management, (ii) sustainability, (iii) facility management, (iv) as-built BIM, and (v) BIM collaboration and implementation. Lack of codes, policies, and the organizational change required are the barriers to the BIM in OSC.

In parallel with this, the DfMA concept—designing OSC components considering their manufacturability, logistics, and assembly constraints—is gaining prominence (Tan *et al*. 2020). To support DfMA, semantic web-based platforms that link component manufacturing specification and physical descriptions to BIM object libraries were proposed (Costa and Madrazo 2015). This will facilitate the integration of models with computer numerical control (CNC) and 3D printing systems. Using cloud BIM models with the Internet of Things (IoT) to control the end-to-end process, radio frequency identification (RFID) systems developed for project control and real-time monitoring of progress, transportation, and assembly, integrating BIM with laser scanning and photogrammetry to check assembly quality and automatically create as-built BIM models are some of the other major technology areas in OSC (Wang *et al*. 2020b).

Immersive virtual reality (VR) technologies were proposed for OSC training (Goulding *et al*. 2012). Alongside this, robotics has been a key technology element since the 1960s for off-site production systems. Robotics applications include additive manufacturing (3D printing), on-site factories, automated inspection with drones (UAVs) and site operations with autonomous vehicles, and exoskeletons—wearable devices that work together with the user to reduce fatigue and injuries while increasing productivity (Delgado *et al*. 2019). Digital ledgers and blockchain in particular have been increasingly discussed as transparent and secure platforms for automated (smart) contracts and key data recording for ownership, provenance, permission, and quality data (Tezel *et al*. 2021).

As outlined in this section, a plethora of technologies (e.g. BIM, VR, 3D printing, IoT, RFID, laser scanning and photogrammetry, UAVs, exoskeletons, blockchain, etc.) supporting OSC adoptions is frequently reported in the literature and fast developing. They constitute an important part of OSC efforts. It should be recognized however that the degree to which those technologies have been used in practice and the technologies' value potential may depend on the OSC adoption context (e.g. highways).

OSC in highways projects

Across Europe, the current aging highway infrastructure is being used by increasing volumes of road traffic, which turns the attention to OSC components for less traffic disruptions during construction and maintenance (Tomek 2017). In the UK, the Strategic Road Network (SRN) comprises ∼4300 miles of motorways (Hawksworth 2014). The length of the SRN represents only around 2% of the total length of the UK's road network, but it carries approximately a third of all road traffic and two-thirds of freight (Hawksworth 2014). With increasing traffic, ∼95 billion miles are travelled on the SRN every year (NH 2020). Recognizing the mounting pressure and the need for modernizing the SRN, the UK government launched in 2015 its first Road Investment Strategy (RIS1) for the period 2015–2020, where it committed to investing over £15 billion in the SRN (DfT 2015). The RIS1 resulted in the completion of 36 enhancement schemes for traffic, 31 started schemes with added 370 lane miles of capacity, and achieved efficiencies of £1.4 billion in 2020 (NH 2020). The second Road Investment Strategy (RIS2) for the period 2020–2025 was subsequently announced in 2020 with a budget of £27.4 billion (DfT 2020). The RIS2 is more challenging and describes plans that include opening of 52 schemes, starting works on 12 new major road projects, and delivering £2.23 billion of savings with an emphasis on digital technologies and OSC for the delivery of the strategy (NH 2020).

OSC is of particular relevance to the highways sector, with companies often working on large projects in remote locations or constrained sites (Chris *et al*. 2019). Also, the relatively fewer number of large-sized component types used in repetition in a typical highway project renders those projects suitable for OSC (Hällmark *et al*. 2012). With increasing use and standardization of OSC components in key highway structures (e.g. bridges) (Antoniou and Marinelli 2020), it will be possible to seamlessly integrate smart asset monitoring systems with data-driven decision making and component supply chains (Hussein *et al*. 2021; Wu *et al*. 2022). This will lead to a timely flow of required components for repairs, upgrades and refitting, less re-work, work on-site, and process and material waste (Wu *et al*. 2022) in highways asset operations and maintenance. Traffic disruptions will also be reduced (Larsson and Simonsson 2012). This is in line with the client requirements of easier and more economic operation and maintenance as well as compliance with sustainability targets (Sutrisna and Goulding 2019).

The OSC supply structure and components used in highways still need extended standardization though (Antoniou and Marinelli 2020). Moreover, in infrastructure projects, early decisions concerning a project are often made without full knowledge of all options and direct involvement of some of the relevant parties (Fellows and Liu 2012). Similarly, an unwillingness to commit to a single point supplier, limited choice of supply chain, and supplier capacities should be noted (Blismas *et al*. 2005). There are also significant operational and legislative constraints associated with the logistics of large components, necessitating modularization for size reduction (Ahmadian *et al*. 2016; Sutrisna and Goulding 2019).

To counter these, preliminary transportation evaluations, alignment of project stakeholders for OSC decisions, and OSC decision support systems are needed (O'Connor *et al*. 2014). Timely staged design freezes for modularization to proceed as planned, choice of an appropriate modularization strategy, and contractors with experience are also important (Gosling *et al*. 2016). Benchmarking practices against modular-intensive sectors, such as the industrial construction sector could be also considered (O'Connor *et al*. 2015). The implementation of OSC in infrastructure project requires specific attention with tightly focused governance at the outset and profound changes to established attitudes, norms, and regulations (Larsson *et al*. 2014).

Despite the rising interest in OSC for infrastructure projects, the dominant scope of research and discussions in this domain is in OSC components' (e.g. bridge decks, underground chambers, concrete road slabs) design performance (Canning and Luke 2010; Hällmark *et al*. 2012; Gunawardena *et al*. 2019; Fang *et al*. 2021). There is a need to go beyond technical component-focused research, including the management of and technology supporting OSC in a specific sector context (Wrigley *et al.* 2021). In engineering management research, it is typical to conceptualize and analyze concepts in an integrated manner from a management, technical (engineered components) and technology perspectives in their contexts (Kotnour and Farr 2005; Elia *et al.* 2021). That is, the content and focus of the current OSC related research for infrastructure projects should be expanded and cover the project management, off-site construction components, and technology (i.e. digital, automation, and robotics) dimensions to better understand the current OSC condition and high-potential future actions (Jin *et al.* 2018; Hou *et al.* 2020; Assaad *et al.* 2022). Also, it can be noted from the OSC literature that the tone of the current OSC discussions is directed toward buildings, the building sector, and its supply characteristics. With increasing demand, expectations, and challenges, there is therefore a need for a distinct focus on understanding the current OSC condition and future directions from an infrastructural construction and particularly highways construction perspective, addressing the gaps in the literature.

Research method

OSC is a complex phenomenon related to interactions between interlinked stakeholders, project, supply chain, and sector conditions (Hosseini *et al.* 2018). Therefore, the study sets off from a constructivist ontology. Additionally, given that the research is focused on "what should be done" by studying a small sample of practitioners' construction of meaning and real-life highways projects for OSC realization, an interpretivist epistemology (Goldkuhl 2012) is adopted. The study, being of explorative nature, is therefore based on qualitative data. Data was collected over four stages: (i) literature review to understand the research gap and background, (ii) 20 semi-structured interviews with practitioners to expand on the current OSC condition and future OSC suggestions for highways projects in the UK, (iii) case study of five highways projects in the UK to validate the current OSC condition, and (iv) two focus groups to rank the OSC suggestions for value.

Interviews

In the first stage, the literature was reviewed for OSC in general and OSC in highways projects. After establishing a conceptual understanding of the topic, 20 construction practitioners from the UK were interviewed using semi-structured and open-ended questions by asking questions orally to interviewees. Semi-structured interviews are suitable for gaining an initial understanding when a complex socio-technical topic, such as OSC is explored in detail (Green *et al.* 2005). The interviews were used for that purpose in this study as the current OSC condition and future actions for highways projects had not recently been studied. To allow for researchers' freedom and the emergence of patterns in the data, the interviews were formulated as semi-structured (El-Razek *et al.* 2008). This flexibility enabled the researchers to adjust the pace and the interview content to topics that the interviewees were better-versed in. The interviewees were identified and contacted with the help of National Highways from senior practitioners managing and delivering infrastructure projects with OSC components. They were selected by their experience, variety of project management roles, interest, and active involvement in OSC efforts with their roles, and the OSC community (e.g. *Buildoffsite UK*—https://www.buildoffsite.com/) through purposeful sampling (see Table 1 for interviewee details). This kind of purposive selections are not uncommon when rich insights into a specific topic requiring a certain experience and background are sought in research (Robinson 2014). The selected practitioners for the interviews, as senior managers delivering large-scale highways projects, were deemed to be better suited to provide an overview of the current OSC condition and future requirements in an under-researched context.

The interview protocol included a briefing of the interviewees about the research aims, important keywords related to the study, and the nature of the interview questions. There were eight questions and the interviews lasted from ∼35 to 60 min, depending on the replying pace of the interviewees. The questions were about the professional background and experience of the interviewee, the current realization of OSC in highways projects in the UK, and future suggestions to improve the current condition of OSC (see Appendix 1 for the interview questions). Following the study's ethical considerations and confidentiality policy, all interviewees were informed that they and their organizations would be pseudonymized. All interviews were audio recorded with the express consent of the interviewees and then transcribed. Details of the interviews and interviewees can be seen in Table 1. Qualitative Content Analysis (QCA) was used to systematically analyze the qualitative data (Bazeley 2013). The interview transcripts were coded into themes using both inductive (emerging from

Table 1. Interview details.

No	Manager role	Sector	Supply chain role	Experience	Interview type/duration
1	Civil Design/BIM Manager	Highways	Tier 1 service provider	>20 years	Face-to-face/50 min
2	Structures and Temporary Works Coordinator	Highways	Tier 1 service provider	>20 years	Face-to-face/45 min
3	Civil Design Manager	Highways	Tier 1 service provider	>20 years	Face-to-face/60 min
4	Project Manager	Highways	Tier 1 service provider	>20 years	Face-to-face/50 min
5	Project Manager	Highways	Tier 1 service provider	>20 years	Face-to-face/45 min
6	Structural Designer	Highways	Tier 1 service provider	>20 years	Face-to-face/40 min
7	Production Engineering Lead	Highways	Tier 1 service provider	>20 years	Face-to-face/35 min
8	Senior Process Improvement Consultant	Highways	Consultant	>20 years	Face-to-face/50 min
9	Innovation Manager	Highways/Building	Tier 1 service provider	>15 years; <20 years	Face-to-face/40 min
10	Lighting/Technology Manager	Highways	Tier 1 service provider	>20 years	Face-to-face/45 min
11	Engineering Manager	Highways	Tier 1 service provider	>20 years	Face-to-face/65 min
12	Managing Director	Water/Highways	Client	>20 years	Face-to-face/60 min
13	Engineering Manager	Water/Highways	Client	>15 years; <20 years	Face-to-face/55 min
14	Performance Manager	Highways/Water	Tier 1 service provider	>15 years; <20 years	Face-to-face/50 min
15	Project Director (Mechanical/Electrical/Plumbing)	Highways/Building	Tier 1 service provider	>20 years	Face-to-face/40 min
16	Project Manager (Mechanical/Electrical/Plumbing)	Industrial/Building/Highways	Tier 1 service provider	>15 years; <20 years	Face-to-face/45 min
17	Managing Director	Infrastructure/Industrial/Highways	Material supplier	>20 years	Face-to-face/50 min
18	Managing Director	Highways/Industrial/Building	Consultant	>20 years	Online/60 min
19	Head of Industrialization	Highways/Industrial/Building	Tier 1 service provider	>20 years	Online/50 min
20	Head of Innovation and Technology	Highways	Tier 1 service provider	>20 years	Online/45 min

Table 2. Case project details.

No	Name	Sector	Site location	Project stage/duration	Project description
1	Project 1	Highways	Lancashire, UK	Construction/21 months	Motorway expansion and upgrade project involving an additional lane and road widening, capacity increase, a new bridge and underground structure, a link road, and electro-mechanical expansions for smart motorways. Estimated project cost is £140 million.
2	Project 2	Highways	Cheshire, UK	Construction/26 months	Motorway expansion and upgrade project involving an additional lane and capacity increase, two new junctions, two new bridges and underground structures, and electro-mechanical expansions for smart motorways. Estimated project cost is £192 million.
3	Project 3	Highways	Lincolnshire, UK	Handover to Operations/16 months	Motorway expansion and upgrade project involving road widening, capacity increase, a new pedestrian overbridge and electro-mechanical expansions. Estimated project cost is £89 million.
4	Project 4	Highways	Northamptonshire, UK	Handover to Operations/18 months	Motorway expansion and upgrade project involving road widening, capacity increase, a new junction, diversion, and overbridge, and electro-mechanical expansions. Estimated project cost is £100 million.
5	Project 5	Highways	Lancashire, UK	Construction/19 months	Motorway expansion and upgrade project involving road widening, capacity increase, two new pedestrian overbridges, a link road, and electro-mechanical expansions. Estimated project cost is £112 million.

the data) and deductive (emerging from the theoretical background) or *a priori* codes (Saldanā 2009). References to the management of OSC were classified under the management themes. References to off-site construction components were classified under the technical themes. References to digital, automation, or robotics technologies were classified under the technology themes. Those themes formed the content presented in Tables 3–5, respectively.

Case studies

The interview findings contained many references to the current OSC condition in highways projects in the UK. Those references were then validated by studying five large-scale highways construction projects as cases. The studied projects were identified with the help of National Highways by their size and adoption of OSC components for relevance with the study. Case studies

Table 3. Management-related suggestions for OSC in highways.

Theme	Suggestion
Decision making	Developing an available OSC systems catalogue with their usability matrices showing which components could be used together (MDM1)
	Developing a collaborative OSC decision-making framework with supply chain actors for component options, manufacturing, lifting and temporary works (MDM2)
	Reviewing the existing OSC systems in other sectors and in military construction (MDM3)
	Focusing first on critical path items for OSC priorities (MDM4)
	Expanding the definition of value in OSC systems beyond the initial cost element (MDM5)
	Understanding the repeatability of components for OSC with asset managers (MDM6)
Design	Earlier involvement of contractors and manufacturers (MD1)
	Developing a product design mindset (MD2)
	Developing the understanding on tolerances and interfaces between in-situ and off-site (MD3)
	A complete system thinking (i.e. bridges) in design for OSC (MD4)
	Third party design reviews for constructability and OSC (MD5)
	Clear OSC specifications, requirements, and targets from the main client (MD6)
	Standardized design for OSC systems (MD7)
	Promoting innovative design—changing the conventional design mindset through client leadership (MD8)
Commercial	Early contractor and supplier involvement/Design-Build or Framework type of contracts (MCm1)
	Developing a preferred suppliers/manufacturers list to enable earlier involvement (MCm2)
	Large works (i.e. all underground works) to a single contractor (MCm3)
	KPIs in contracts for OSC and DfMA (MCm4)
	OSC quotas and targets linked with commercial success (MCm5)
Construction	Pushing different OSC manufacturers to working together on-site to create modules for OSC components (MCns1)
	Developing prototypes for site trials with manufacturers (MCns2)
	Better temporary works and lifting planning for OSC components (MCns3)
	Employing OSC managers supervising the whole process (design, manufacturing, logistics, assembly) (MCns4)
	Contractors developing their own manufacturing facilities and supply chains (MCns5)
	Tighter on-site and off-site quality control (end-to-end) (MCns6)
	End of project reviews for OSC lessons learned (MCns7)
	Revising and standardizing the method statements for OSC (Cns8)
	Streamlining the current OSC approval process from the client's side (Cns9)
	Manual of Contract Documents for Highway Works (MCHW) in the UK should be reviewed for OSC (Cns10)
	Less prescriptive client and design specifications (Cns11)
	Having an idea capturing template for OSC systems for the supply chain (MCns12)
	Pushing value-adding technologies for OSC, such as on-site automation and robotics, additive construction (MCns13)
Project governance	Clearly defining OSC ownership for subsystems for better system integration (MPG1)
	Engaging more with OSC organizations, such as *Buildoffsite* (MPG2)
	Supplier and manufacturer schools for OSC development and management (MPG3)
	Partnering and team-building workshops for OSC (MPG4)
	Single point of contact for OSC (MPG51)
	Health and safety benefits of using OSC systems should be more emphasized (MPG6)
	A clear definition of DfMA (MPG7)
	Promoting OSC know-how sharing among service providers (MPG8)
	Publication of case studies and best practices by the client (MPG9)

are suitable when a phenomenon is studied in its context, out of the researcher's control (Yin 2011).

The focus and unit of analysis of the case studies in this study are the execution of OSC in highways projects in the UK based on the managerial, technical, and technological parameters identified from the interviews and the literature review. Those parameters were consciously probed within the studied cases. A variety of data collection methods for multiple sources of evidence, such as direct observations, interviews, and informal discussions with the project managers, construction managers, and project design leads, project archive, and record reviews were used. A case protocol defining information gathering for the case studies' reliability was produced and followed (Choudhari *et al*. 2012). The observations were used to complement and verify the interviews and informal discussions, project archive, and record reviews. The focus of the observations included the main OSC component types used on-site and included in the project design specifications, and the technology used to support OSC in on-site construction and design development. The observations were made on the construction sites and construction site offices.

The case protocol sets (Yin 2011) (i) the unit of analysis (i.e. OSC execution and methods in the studied highways projects), (ii) the sources of evidence (i.e. interviews, site observation, document review, and discussions), (iii) parameters to be investigated (i.e. OSC management practices and sub-themes identified in Table 3, technical components identified in Table 4 and technology elements supporting OSC identified in Table 5, and (iv) the measures for construct validity through multiple source of evidence, internal validity through pattern matching the case findings with the literature findings, external validity through data

Table 4. Technical suggestions for OSC in highways.

Theme		Suggestion
New and emerging OSC opportunities to be supported and prioritized	Pre-cast structures	Free-standing vehicle restraint systems (TNPr1)
	Pre-cast structures	Slot drain blocks (TNPr2)
	Pre-cast structures	Polymer reinforced pedestrian bridges (TNPr3)
	Pre-cast structures	Cruciform support structures and slabs (TNPr4)
	Pre-cast structures	Close-circuit television (CCTV) bases (TNPr5)
	Pre-cast structures	Creating interchangeable and interlocking parts (i.e. Headwalls) (TNPr6)
	Gantries	Fitted electric duct with signalling, cabling, lighting units, sockets and plugs (TNG1)
	Gantries	Signs and cameras fitted on gantries (TNG2)
	Gantries	Gantry base templates with cable entrances (TNG3)
	Pavement	Prefabricated bridge deck sections (structure + asphalt) (TNP1)
	Pavement	Prefabricated plastic slabs (TNP2)
	Pavement	Prefabricated bituminous slab designs (TNP3)
	Underground components	Modular and retractable (telescopic) chambers (TNU1)
	Underground components	Communication control bases allowing plug-and-play cable entry (TNU2)
	Underground components	Sealed manholes with modular verge details (TNU3)
More established OSC opportunities to be disseminated	Pre-cast structures	Bridge and wall structures (panels, abutments, decks, wingwalls, sill beams, piers, crossheads, W-beams) (TEPr1)
	Pre-cast structures	Stairs (TEPr2)
	Pre-cast structures	Drainage chambers (TEPr3)
	Pre-cast structures	Underground service protectors (TEPr4)
	Underground components	Flat pile caps (TEU1)
	Underground components	Modularized A-chambers (TEU2)

Table 5. Technology-related suggestions to support OSC in highways.

Theme	Suggestion
BIM	Encouraging 4D simulation for OSC installations for better logistics, temporary works, and space planning (TnBIM1)
	Encouraging BIM integration with computer numerical control (CNC) machines in OSC manufacturing (TnBIM2)
	Rapid prototyping for OSC using BIM (TnBIM3)
	Improving BIM product libraries for OSC (TnBIM4)
	Cloud-BIM based information exchange for OSC across supply chain (TnBIM5)
	RFID enabled logistics tracking (TnBIM6)
	BIM/GIS supported OSC assembly and logistics tracking (TnBIM7)
	BIM/VR supported OSC sequencing and assembly on-site (TnBIM8)
Additive construction	Concrete and asphalt printing (TnAC1)
	Plastic chamber printing (TnAC2)
Remote sensing	Experimenting with remote sensing (e.g. laser scanning or photogrammetry) for OSC construction progress tracking (TnRS1)
	Experimenting with remote sensing (e.g. laser scanning or photogrammetry) for OSC on-site quality control (TnRS2)
Internet of Things (IoT)	Sensor based component tracking for asset management (TnIoT1)
	Near-real time site data collection (TnIoT2)
Plant	Using numerically controlled plant (e.g. excavators, slip forming) as standards (TnP1)
	Driverless and remote-controlled plant (TnP2)
	Plant fitted with augmented reality systems (e.g. overlaying UG utilities) (TnP3)
Robotics	Improved UAV use for site progress tracking and control in OSC operations (TnR1)
	Remote controlled robotic arms for OSC assembly (TnR2)
Data analytics	Creating a design options repository for data analytics (TnDA1)
	Creating an OSC experience database for end-to-end process for decision making support (TnDA2)

triangulation, and reliability through adopting a case protocol, and (v) the data recording and sharing practices.

Multiple case studies allow better generalizability with cross-case comparisons and can be used as complementary research validation tools (Yin 2011). Case studies are often used in research for validating and understanding the current condition of a phenomenon (Yin 2011). The similarities identified through pattern matching across the investigated multiple cases enabled a validation, methodological triangulation of the interview findings, and insights into the current practice (Tellis 1997). The case studies also assisted the researchers in putting the comments and suggestions of the interviewees and focus groups participants into a real-life context.

The case projects were identified with the help of National Highways to represent the current condition of OSC in highways projects in the UK on the following common criteria: (i) accessibility of the project—the project must have been ongoing or recently completed with people involved being accessible and willing to share information, (ii) the project must have been delivered under National Highways' (main client) brief and expectation about the extensive use of OSC components with clear OSC delivery strategies and methods included in the project's execution plans, (iii) the project must have been large, and (iv) a certain amount of OSC components/elements must have been used in the project as highways projects may have varying degrees of OSC adoption in terms of component types and component numbers by their scope, project size, and specifications. All studied projects are highway expansion and upgrade projects in line with the UK's "smart motorways" plans. They, therefore, involve many large and small OSC components (structural and electro-mechanical) enabling studying OSC from a management, technical and technological perspective. Those commonalities across the studied cases ensured representativeness of the current manifestation of OSC in highways projects in the UK. Details of the case projects can be seen in Table 2.

Focus groups

In the last stage, two online focus group studies were organized involving six participants (two senior design managers, two senior academics, and two senior construction project managers) and five participants (three senior designers and two innovation leads), respectively. The participants were identified by their experience and interest in both OSC and infrastructure construction projects. Focus groups are suitable for rapidly collecting large amount of data from group interactions with high data validity (Dai *et al*. 2009). They can also be used for research validation and further exploration purposes following an initial understanding (Hijazi *et al*. 2021). In this study, the focus groups were used to discuss, group, and rank the findings from the interviews and case studies for impact from the UK highways sector's perspective.

The first focus group participants ranked the management related suggestions while the second focus group ranked the technical and technological opportunities by their value following the Delphi method (Chan *et al*. 2001). The focus groups were executed dynamically allowing the participants to add new suggestions to the initial set of OSC suggestions. Notes were taken and an online audience interaction system was used to capture the ranks. After each round of the ranking, the ranks were shared with the participants to enable further discussions. The participants then were allowed to rank the suggestions again until a consensus is reached. When a consensus could not be reached for a suggestion, the average of the values for the suggestion was rounded to the nearest ranking system point to identify its rank. A three-category numerical ranking system (1 = lower impact, 3 = average impact, and 5 = higher impact) was used to streamline the ranking process for the participants as 95 suggestions in total were ranked (43 management-related, 23 technical opportunities, 29 technology-related). This practically helped with the timing and pacing of the focus groups, which is necessary when iterative and consensus-based data collection techniques, such as the Delphi method are involved. Moreover, the primary aim of the ranking is determining the group of a particular suggestion rather than sorting the suggestions by the order of their ranks. Hence, the three-category ranking system.

Findings from the interviews

The analysis of the interviews covers three main groups: (i) management-related suggestions to improve the OSC condition for highways projects in the UK (Table 3) (ii) technical OSC opportunities to be supported, prioritized, and disseminated (Table 4), and (iii) enabling and high-potential technologies for the OSC in highways (Table 5). The management related suggestions were grouped under five themes: (i) decision making, (ii) design, (iii) commercial, (iv) construction, and (v) project governance. The technical OSC opportunities were grouped under two main themes, (i) new and emerging OSC opportunities to be supported and prioritized and (ii) more established OSC opportunities to be further disseminated in highways projects. The latter were then sub-grouped into (i) pre-cast structures, (ii) gantries, (iii) additive construction, (iv) pavement, and (v) underground (UG) components. The enabling technologies for OSC were grouped under seven themes: (i) BIM, (ii) additive construction, (iii) remote sensing, (iv) IoT, (v) plant, (vi) robotics, and (vii) data analytics.

Management-related suggestions

Decision making

The first thematic group in the management-related suggestions is decision making (see Table 3). In this category, developing an OSC systems catalogue with their usability matrices comes to the fore. Producing such a catalogue will support the decision-making process and help with combining the available OSC components to create modules, according to the interviewees. Also, a collaborative OSC decision making framework was suggested to improve the current, ad-hoc and central OSC decision-making mechanism executed by a few—mainly senior—designers and project managers. In line with this, involving asset managers into the decision making and technical development process was highlighted. Asset managers' input into what components should be manufactured off-site will be useful. This will also support collaborative value engineering. Systematically prioritizing activities on the critical path for OSC adoption was recommended. Benchmarking OSC practices and systems against other sectors (e.g. likening modularized skid designs in the water sector for the u-chambers and technology components in highways) and the military construction is another key point. Some interviewees complained about the narrow and excessively cost-centric value definition and decision-making criteria for OSC, suggesting expanding this definition more towards other key OSC benefits, health and safety, and well-being in particular.

Design

Design was frequently mentioned as the key project stage for OSC in highways. Commercial arrangements and contracts permitting, earlier involvement of contractors and manufacturers in the design and decision-making process was suggested. Moving from the traditional design approach and developing a product-design mindset and system thinking (e.g. designing a bridge and its components as a whole rather than designing subunits separately) were seen as imperative. Excessive reliance on design software and past data/design templates hampers innovation and constructability. Lack of design standardization (e.g. many types of gantry bases) hampers the OSC efforts. Insufficient interface design between OSC and existing components for highways maintenance and upgrade projects was mentioned. According to some interviewees, third-party design reviews for OSC and constructability will be useful. Overdesigning with rigid specifications in highways projects was also mentioned as a barrier for experimentation and innovation for OSC. An insufficient understanding of the interfaces and tolerances between in-situ and off-site systems was highlighted. The main client of the highways supply chain was advised to be clearer in its OSC specifications, expectations, requirements, and targets, supporting and awarding experimentation and innovative designs in OSC.

Commercial

Proper commercial arrangements facilitate of most of the suggestions outlined for decision making and design. In that regard, for OSC, the interviewees recommend integrated procurement systems with large chunks of works given to a single contractor with design responsibility. Lack of coherent work packages that will support OSC creates problems related to ownership. Work package decisions should consider OSC arrangements as well. Developing a preferred suppliers/manufacturers list to enable earlier involvement for OSC is advised. OSC suppliers should be included in the integrated procurement teams. Including OSC and DfMA key performance indicators (KPIs), targets or quotas as part of the bid evaluation, and project success criteria are recommended.

Construction

The largest set of suggestions was collected for the construction phase. Pushing different off-site manufacturers to joint-working and site-testing for prototypes comes to the fore for construction. Components already manufactured off-site should be systematically reviewed and combined to produce modules. Some interviewees find the current logistics, lifting, and temporary works planning ineffective for off-site components. Another distinctive suggestion is creating an off-site manager role to supervise the end-to-end process. This also links with the comment regarding tighter on-site supervision and quality control for OSC, which can be associated with the design related comment of insufficient understanding of the in-situ/-off-site interfaces and tolerances. Some interviewees complained about difficulties for the main contractors to control the OSC quality in factories, stemming mainly from the fragmented procurement models. According to some, over-modularization of components leads to tightened tolerances and leaves no room for site arrangements during construction, reflecting the disconnection between contractors, designers, and suppliers. Large off-site systems pose their own installation challenges. Parapet and longitudinal elements require significant temporary installation systems (supports) and pose logistic challenges. They also have different lifting requirements, space and storing issues, reduced capability to absorb dimensional deviations, and tight design tolerances. Including OSC as a topic for the end of project reviews for continuous learning is suggested. Idea capturing for OSC is currently performed ad-hoc. Some client-related expectations, such as standardizing the method statements for OSC, streamlining the OSC approval process, and revising the UK's Manual of Contract Documents for Highway Works (MCHW) (UK Highways Agency 2009) were noted. Less prescriptive specifications, introducing an idea capturing template for OSC systems for the supply chain, and supporting value-adding technologies for OSC were also suggested.

Project governance

Project governance is the last thematic category for the management related suggestions. These suggestions are mainly for the policy makers and the sector leadership. More engagement with OSC championing organizations in the UK, such as *Buildoffsite* at the national level is recommended. Setting up supplier and manufacturer schools for OSC development and management is deemed useful. In line with this, efforts for team building and knowledge sharing activities across the supply chain for OSC, and a better dissemination of case studies and best practices by the client are required. A clear definition, scope, and target for DfMA in the highways sector is expected. The health and safety benefits OSC systems should be emphasized more across the supply chain. Also, the practices for creating a single point of contact for OSC to prevent creating many points of contacts for different systems during project execution and establishing clarity for the ownership and responsibilities for highways sub-systems for system integration should be promoted. Some feel that the OSC expectations and priorities of the client are not clear for the supply chain to develop on. Lack of objective OSC evaluation and performance criteria with a positive bias for OSC leads to over-modularization and OSC just for the sake OSC.

Technical suggestions

The suggestions in this category are related to some of the technical subsystems or components of a modern highway and their potential in being manufactured off-site or modularized for the sector (see Table 4). According to the interviewees, the new and emerging OSC opportunities to be supported and prioritized include interchangeable and interlocking parts (i.e. headwalls), and polymer reinforced pedestrian bridges. Modularization of gantries with fitted electric ducts, cabling, signalling/lighting units, sockets and plugs, prefabricated bridge deck sections (structure and asphalt), and modular and retractable (telescopic) underground chambers are also among those opportunities. The other group of OSC opportunities mentioned by the interviewees are those that are more established but need further dissemination in use, such as bridge and wall structures (e.g. abutments, decks, wingwalls, sill beams, piers, crossheads, W-beams) and pre-cast drainage chambers.

Technology-related suggestions

As the backbone of digital construction, many of the technology-related suggestions are linked with BIM (see Table 5). These include BIM/RFID enabled logistics tracking, BIM/geographic information system (GIS) supported OSC assembly and logistics tracking on large highways sites and BIM/VR supported OSC sequencing and assembly for on-site teams. Improving and expanding OSC product libraries for BIM are requested. The interviewees think that some of the fundamental BIM features, such as 4D simulation for OSC logistics, temporary works, and space planning, creating rapid design prototypes, and BIM and CNC integration are underutilized. One of the key suggestions to dissolve the silos across different supply chain actors is moving to cloud-BIM for information sharing.

Despite still being in their infancy for highways, additive construction (3D printing) of concrete and asphalt was mentioned. Another opportunity lies in printing plastic underground chambers. The remote sensing technologies of laser scanning and photogrammetry were mentioned as underutilized for on-site progress tracking and quality control. Interconnected sensor networks (IoT) are seen as an opportunity to provide near-real time data from manufacturing, logistics, and site operations for project control and component tracking for asset management purposes. Plant-wise, using numerical controlled plant as standards in highways projects, driverless and remote-controlled plant, and plant fitted with augmented reality technologies as visual aids for operators are seen as value-adding for OSC. According to the interviewees, to be able to effectively utilize artificial intelligence (AI) and data mining (DM) techniques in the sector for OSC decision making, a design options repository should be created. This links with the management-related suggestion of creating an OSC catalogue with usability matrices. Some interviewees required a shared platform where practitioners can record their OSC experience containing personal insights/verbal information on which natural language processing (NLP) techniques could be employed to support decision-making.

Findings from the case studies

To validate the current OSC practices in highways projects elicited from the interviews, the OSC condition of the case projects were analyzed through the management-related, technical, and technology-related perspectives (see Table 6). Some patterns emerged across the cases in the analysis as explained below. The case study findings were also linked and cross-referenced to the interview and focus group findings and abbreviations in Tables 3–5 and 7 with the codes in parenthesis.

Management-related case study findings

Decision making

The OSC decisions are centrally made by designers and project managers (MDM2, MDM6), who lack a comprehensive OSC components catalogue (MDM1). Currently, the main decision criterion and driver for OSC is initial cost without due consideration of LCC (MDM5). However, OSC's programme/schedule, quality, and logistic benefits are acknowledged. Activities on the critical path in the projects' schedules/programmes are prioritized for OSC decisions (MDM4).

Design

The design is executed and managed conventionally by dividing a highways asset into components and disciplines, and designing those components individually, lacking a product design mindset and a complete systems thinking (MD2, MD4). In some cases, OSC suppliers would lead and execute the design process of specific OSC components; however, early involvement of manufacturers and contractors in design should be ensured (MD1). No asset management involvement in the designs or third-party design reviews was identified (MD5). According to the project managers, in expansion and upgrade projects in particular, *in-situ* and off-site component interfaces cause issues in design and, consequently, in site installation (MD3). No clear OSC targets and requirements (MD6), or innovative OSC design promotions (MD8) were identified.

Commercial

Commercially, the case projects are similar: a large consortium of Tier 1 contractors executes the project under a framework agreement. In some cases, long-term relations exist between the Tier 1 contractor/consortium and some key OSC suppliers. This enables the suppliers' earlier involvement and further engagement (MCm1), for example, on-site trials. For certain works, preferred supplier lists exist (MCm2). However, those long-term arrangements are often at the discretion of the Tier 1 contractor/consortium and the OSC suppliers are rarely part of a framework. There are no specific OSC KPIs (MCm4) or OSC quotes/targets (MCm5) for commercial arrangements.

Construction

For the assembly and construction, no evidence of different OSC suppliers working together on site was found (MCns1). Some key suppliers would be included in the collaborative planning meetings requested by the main client, however. In two cases (Case 2 and Case 4), the Tier 1 consortium were working together with a few long-term supplier partners to jointly develop new off-site components, such as slot-drains (MCns2). It was also found that lifting and logistics are two of the key challenges for OSC components in the construction phase, requiring specific attention to site logistics, lifting plans, and temporary works (MCns3). The OSC components are mainly controlled and supervised by the quality and construction managers on site. There is no separate OSC responsible or manager monitoring the end-to-end process (MCns4). This management role will also enable tighter OSC on/off-site control and supervision (MCns6). The long OSC component approval procedure was mentioned as a barrier to new developments and experimentation in the field (Cns9). Some construction managers confirmed the need for simplification and flexibility in specifications to facilitate OSC trials (Cns11). There is no specific OSC focus for idea capturing (MCns12). However, the end project reviews cover OSC lessons-learned (MCns7).

Project governance

For project governance, there are many similarities across the cases due to the fact that the highways sector in the UK is driven by a few, large public clients, and a tiered (Tier 1, 2, 3 …), hierarchical supply chain structure, leading to the formation of more homogenous sector-wide practices. The case project managers were aware of the existence and mission of the OSC organizations, such as *Buildoffsite* (MPG2). However, they stated that they had not engaged with them closely aside from subscribing to their electronic newsletters or having brief discussions with practitioners actively involved in those organizations. Case 2 and Case4's design managers mentioned they had attended a few of *Buildoffsite* events. No supplier and manufacturer schools for OSC development and management (MPG3) or partnering and team-building

Table 6. Cross case comparison.

	Management					Technical		
Case name	Decision making	Design	Commercial	Construction	Project governance	New OSC	Established OSC	Technology
Project 1	• OSC decisions are mostly central by designers and project managers • Lack of available OSC systems catalogue • Cost is the dominant factor in decision making, other factors, such as programme, quality, and logistics are considered	• Conventional design approaches. • Design managed and executed in some cases by OSC supplier • OSC supplier and subcontractor involvement in general design decisions is limited • No asset management involvement • No 3rd party design reviews • In-situ and off-site component interfaces cause issues in design	• Framework type contracts with Tier 1 contractors • Difficulties in earlier engagement with suppliers • No specific KPIs for OSC	• Different OSC suppliers do not work together on-site • No OSC prototyping or trials • No specific OSC focus for idea capturing • Quality and construction managers are responsible for OSC elements, No specific OSC responsible • Long OSC component approval procedures • Collaborative planning with BIM	• Limited engagement with the OSC organizations • General team building efforts—not specifically focused on OSC • No single point of contact for OSC • No conscious distribution of the OSC system ownership • Initial cost, cost implications, and client priorities are the main OSC decision making drivers	• CCTV basis • Vehicle restraint systems	• Stairs • Bridge structures • Drainage chambers and manholes • Gantry structural components • Precast wall panels	• BIM models shared with project members including OSC suppliers • 4D BIM for progress control, lifting and site layout planning on site. • GIS for planning but not specific OSC focus • Cloud and mobile BIM for construction operations • RFID and barcode tracking for OSC components • Numerically controlled plant.
Project 2	• OSC decisions are mostly central by designers and project managers • Lack of available OSC systems catalogue • Cost is the dominant factor in decision making, other factors, such as programme, quality, and logistics are considered • Difficulties in executing value engineering	• Conventional design approaches • Design managed and executed in some cases by OSC supplier • OSC supplier and subcontractor involvement in general design decisions is limited • Manufacturer and subcontractor involvement is limited • No asset management involvement • No 3rd party design reviews • In-situ and off-site component interfaces cause issues in design	• Framework type contracts with Tier 1 contractors • Collaborative and long-term relations exist between Tier 1 contractors and some key OSC suppliers • Difficulties in earlier engagement with other suppliers • No specific KPIs for OSC	• Different OSC suppliers do not work together on-site • New OSC components developed in collaboration with suppliers • No specific OSC focus for idea capturing • Quality and construction managers are responsible for OSC elements, No specific OSC responsible • Long OSC component approval procedures • Collaborative planning with BIM	• Limited engagement with the OSC organizations • General team building efforts—not specifically focused on OSC • No single point of contact for OSC • No conscious distribution of the OSC system ownership • Expectation of better integration of the OSC efforts with their flying factories • Initial cost, cost implications, and client priorities are the main OSC decision making drivers	• Slot drain blocks • CCTV basis • Vehicle restraint systems	• Stairs • Bridge structures • Drainage chambers and manholes • Gantry structural components • Precast wall panels	• BIM models shared with project members including OSC suppliers • 4D BIM for progress control, lifting and site layout planning on site. • GIS for planning but no specific OSC focus • Cloud and mobile BIM for construction operations • RFID and sensor tracking for OSC components • Some laser scanning efforts on ground (no UAVs) • Numerically controlled plant • OSC BIM libraries should be expanded. • Tier 1 contractor working to build flying-factories for OSC (Mobile OSC production facilities)
Project 3	• OSC decisions are mostly central by designers and project managers • Lack of available OSC systems catalogue • Cost is the dominant factor in decision making, other factors, such as programme, quality, and logistics are considered	• Conventional design approaches • Design managed and executed in some cases by OSC supplier • OSC supplier and subcontractor involvement in general design decisions is limited • No asset management involvement • No 3rd party design reviews	• Framework type contracts with Tier 1 contractors • Difficulties in earlier engagement with suppliers • No specific KPIs for OSC	• Different OSC suppliers do not work together on-site • No OSC prototyping or trials • No specific OSC focus for idea capturing • Quality and construction managers are responsible for OSC elements, • No specific OSC responsible • Collaborative planning with BIM	• Limited engagement with the OSC organizations • General team building efforts—not specifically focused on OSC • No single point of contact for OSC • No conscious distribution of the OSC system ownership • Initial cost, cost implications and client priorities are the main OSC decision making drivers	• CCTV basis • Vehicle restraint systems	• Stairs • Bridge structures • Drainage chambers and manholes • Gantry structural components • Precast wall panels	• BIM models shared with project members including OSC suppliers • 4D BIM for progress control, lifting and site layout planning on site. • GIS for planning but not specific OSC focus • Cloud and mobile BIM for construction operations • RFID and barcode tracking for OSC components • Numerically controlled plant

(*continued*)

Table 6. Continued.

	Management					Technical		
Case name	Decision making	Design	Commercial	Construction	Project governance	New OSC	Established OSC	Technology
Project 4	• OSC decisions are mostly central by designers and project managers • Lack of available OSC systems catalogue • Cost is the dominant factor in decision making, other factors, such as programme, quality, and logistics are considered • Difficulties in executing value engineering	• Conventional design approaches • OSC supplier and subcontractor involvement in general design decisions is limited • No asset management involvement • No 3rd party design reviews • In-situ and off-site component interfaces cause issues in design	• Framework type contracts with Tier 1 contractors • Collaborative and long-term relations exist between Tier 1 contractors and some key OSC suppliers • Difficulties in earlier engagement with other OSC suppliers • No specific KPIs for OSC	• Different OSC suppliers do not work together on-site • New OSC components developed in collaboration with suppliers • No specific OSC focus for idea capturing • Quality and construction managers are responsible for OSC elements. No specific OSC responsible • Collaborative planning with BIM	• Limited engagement with the OSC organizations • General team building efforts—not specifically focused on OSC • No single point of contact for OSC • No conscious distribution of the OSC system ownership • Expectation of better integration of the OSC efforts with their flying factories • Initial cost, cost implications, and client priorities are the main OSC decision making drivers	• Slot drain blocks • CCTV basis • Vehicle restraint systems	• Stairs • Bridge structures • Drainage chambers and manholes • Gantry structural components • Precast wall panels	• BIM models shared with project members including OSC suppliers • 4D BIM for progress control, lifting and site layout planning on site. • GIS for planning but not specific OSC focus • Cloud and mobile BIM for construction operations • RFID and sensor tracking for OSC components • Some laser scanning efforts on ground (no UAVs) • Numerically controlled plant • OSC BIM libraries should be expanded. • Tier 1 contractor working to build flying-factories for OSC (Mobile OSC production facilities)
Project 5	• OSC decisions are mostly central by designers and project managers • Lack of available OSC systems catalogue • Cost is the dominant factor in decision making, other factors, such as programme, quality, and logistics are considered • Cost is the dominant factor in decision making	• Conventional design approaches • OSC supplier and subcontractor involvement in general design decisions is limited • No asset management involvement • No 3rd party design reviews	• Framework type contracts with Tier 1 contractors • Collaborative and long-term relations exist between Tier 1 contractors and some key OSC suppliers • Difficulties in earlier engagement with other suppliers • No specific KPIs for OSC	• Different OSC suppliers do not work together on-site • No OSC prototyping or trials • No specific OSC focus for idea capturing • Quality and construction managers are responsible for OSC elements, No specific OSC responsible • Long OSC component approval procedures • Collaborative planning with BIM	• Limited engagement with the OSC organizations • General team building efforts—not specifically focused on OSC • No single point of contact for OSC • No conscious distribution of the OSC system ownership • Initial cost, cost implications, and client priorities are the main OSC decision making drivers	• CCTV basis • Vehicle restraint systems	• Stairs • Bridge structures • Drainage chambers and manholes • Gantry structural components • Precast wall panels	• BIM models shared with project members including OSC suppliers • 4D BIM for progress control, lifting and site layout planning on site. • GIS for planning but not specific OSC focus • Cloud and mobile BIM for construction operations • RFID and sensor tracking for OSC components • Some laser scanning efforts on ground (no UAVs) • Numerically controlled plant • OSC BIM libraries should be expanded.

workshops specifically for OSC (MPG4) were identified. There are general partnering and team building efforts between the Tier 1 and 2 project supply chain members for a specific project, however. The main client also emphasized the importance of and focus on adopting OSC with the project teams during the tendering, design, and construction. No single point of contact for OSC (MPG51) was identified in the studied projects, but the construction, quality, design, and logistics/supply managers would engage with the management of OSC during different project delivery stages. It was observed that the Case 2 and 4 managers expected to be able to better integrate their OSC design, manufacturing, logistics, and construction efforts with the flying factories. In line with this, there was no conscious planning and distribution of the ownership of the OSC subsystems in the design and construction for better system integration (MPG1). There was an overall appreciation of the OSC benefits among the project teams including its health and safety benefits (MPG6). It was accepted however that the main decision making parameters for OSC were still initial cost, its associated cost and programme benefits, and the client's priorities.

Technical OSC components-related case study findings

Technical component-wise, some more established OSC components, such as stairs (TEPr2), bridge structures (TEPr1), drainage chambers and manholes (TEPr3, TEU3), gantry steel structural components and pre-cast wall panels were identified in all the five projects. As for the emerging OSC components, closed circuit television (CCTV) basis (TNPr5), vehicle restraint systems (TNPr1), and slot drain blocks (TNPr2) seemed to have diffused in the projects. The construction and project managers frequently called for an increase in the number of easy-to-assembly modular units for larger structural components.

Technology-related case study findings

The BIM models are shared between the project partners including the OSC suppliers for manufacturing purposes (CNC integration), if necessary (TnBIM2). They are also used to support the collaborative planning sessions in the construction phase. An expectation for the expansion of highways OSC components' BIM libraries was recorded (TnBIM4). Mobile and cloud-BIM applications are also commonly used (TnBIM5). 4D planning is executed with a focus on progress control, site layout, and lifting planning for large components (TnBIM1). Numerically controlled plant is commonly used on sites (TnP1), as well as RFID (TnBIM6) and sensor tracking (TnIoT1) of the OSC components. GIS was used for planning and coordination, but not specifically for OSC efforts (TnBIM7). Experimentation with ground laser scanning for quality checks was recorded (TnRS2). In two cases (Case 2 and Case 4), the Tier 1 consortium were working to build flying factories or field factories (MCns14)—temporary facilities used to manufacture prefabricated components.

Findings from the focus groups

In addition to the OSC suggestions from the interviewees, the focus group participants raised 12 suggestions for OSC design, construction, new and emerging OSC opportunities, more established OSC systems, BIM, additive construction, robotics, and blockchain, as can be seen in Table 7. These additional suggestions were also included in the ranking.

Table 7. OSC suggestions by focus group participants.

Management-related suggestions	Design	Experimenting with the platform design approach in elements, such as vehicle and pedestrian bridges, underground passes, drain channels (MD9)
	Construction	Adopting flying factories (mobile off-site manufacturing facilities) in highways projects for shorter supply links (MCns14)
Technical suggestions	New and emerging OSC opportunities	Scaling large pre-cast structures into smaller sections (TNPr7)
	More established OSC opportunities	Injection moulding for underground chambers (TEU3)
Technology-related suggestions	BIM	BIM/data analytics for generative design for optimum OSC configurations (TnBIM9)
		BIM enabled collaborative planning and control systems for OSC (TnBIM10)
	Additive construction	Experimenting with Contour Crafting (CC) (TnAC3)
		3D concrete mould printing and milling (TnAC4)
	Robotics	Employing robotic production units in flying factories or on-site production facilities (TnR3)
		Experimenting with wearable exoskeletons for OSC assembly on site (TnR4)
	Blockchain	Automatic contracts on blockchain for OSC elements (TnB1)
		Recording key OSC data (quality, source, ownership, approvals) on blockchain (TnB2)

Table 8. Ranking of the OSC suggestions for highways projects in the UK.

	Management		Technical	Technology
Higher	MDM1	MCm4	TNPr6	TnBIM4
	MDM2	MCns2	TNP1	TnBIM9
	MDM5	MCns4	TNP3	TnAC1
	MD2	MCns9		TnIoT2
	MD4	MCns13		TnP2
	MD6	MPG8		TnR3
	MCm1			TnDA1
Medium	MDM3	MCns7	TNPr3	TnBIM1
	MDM6	MCns10	TNPr4	TnBIM3
	MD1	MCns12	TNPr7	TnBIM5
	MD3	MCns14	TNG1	TnBIM7
	MD8	MPG1	TNG2	TnBIM10
	MD9	MPG3	TNP2	TnAC3
	MCm2	MPG5	TNU1	TnRS2
	MCm3	MPG6	TNU2	TnP3
	MCns1	MPG7	TEPr1	TnR1
	MCns3		TEPr3	TnR4
	MCns5		TEU2	TnDA2
	MCns6		TEU3	TnB2
Lower	MDM4		TNPr1	TnBIM2
	MD5		TNPr2	TnBIM6
	MD7		TNPr5	TnBIM8
	MCm5		TNG3	TnAC2
	MCns8		TNU3	TnAC4
	MCns11		TEPr2	TnRS1
	MPG2		TEPr4	TnIoT1
	MPG4		TEU1	TnP1
	MPG9			TnR2
				TnB1

During the focus group meetings, the identified OSC suggestions for highways projects in the UK were shown to the participants to discuss their potential impact and requirements as well as rankings in iterations as explained in the research method section. It should be noted that the ranking is relative in a group, not meaning a lower-ranked suggestion is not important but rather relatively not as important for impact for OSC in highways. This forms high, moderate, and low impact suggestion groups in a hierarchical order. By this, there are 23 high impacts (13 management-related, three technical, and seven technology-related), 45 moderate impact (21 management-related, 12 technical, and 12 technology-related), and 27 lower impact (nine management-related, eight technical, and 10 technology-related) suggestions. The groups are shown in Table 8.

Discussion

The discussions follow the management, technical, and technology categorization, addressing the gap identified in the literature for OSC in highways projects in the UK. The high/medium/low impact suggestions that are discussed subsequently in this section touch on the thematic areas under which the findings were grouped.

Higher impact suggestions

The higher impact suggestions should be prioritized as they hold the potential for major impact in improving the current OSC condition. The decision making for OSC in highways projects is central, top-down, and by few, which is a factor behind the problems related to transparency and innovation problems as highlighted previously in the literature from the perspective of buildings and more generic applications of OSC (Goodier and Gibb 2007). Therefore, a collaborative decision-making structure is suggested and ranked as higher impact (MDM2). Other collaborative frameworks, for instance, the Last Planner System (Ballard and Tommelein 2012; Lerche *et al*. 2020) from the lean construction domain could be mimicked or serve as a basis for such a structure. The highways sector in the UK is now familiar and well-versed with the lean construction concept (Tezel *et al*. 2018). To be able to realize the expected joint decision making and collaborative experimentation for new off-site modules, integrated commercial arrangements including the OSC suppliers are necessary (MCm1) (Hu and Chong 2020). This will also facilitate the much-needed modularization coordination and decision making for larger components (Gosling *et al*. 2016; Sutrisna and Goulding 2019). Currently, this integration is partially realized through framework agreements, but the inclusion of the OSC suppliers is at the discretion of the Tier 1 contractors/consortia. As suggested (MCns2), there is evidence of the benefits of this joint working and long-term relations which was documented in Case 2 and Case 4. Establishing long term relations and creating national and regional OSC knowledge-exchange hubs will promote know-how sharing among the service providers (MPG8) (Said 2015; Hairstans and Smith 2018) and will help to reduce the costs through a learning effect (Pan and Sidwell 2011).

Despite the long-term discussions on expanding the construction KPIs in the UK (Egan 2002), there is no OSC specific KPIs guiding the commercial decisions and project success evaluations (MCm4). It has become clear from the research that the highways supply chain looks up to the main public client for clear OSC specifications, requirements, and targets (MD6), supporting value adding technologies (MCns13) and streamlining the current OSC approval process (MCns9). This indicates a lack of guidance and the existence of tedious procedures, which have been long-term inhibitors for OSC (Pan *et al*. 2007). In this regard, the main client may consider empowering and consulting with its supply chain (Alazzaz and Whyte 2015). Widespread OSC use results from institutional pressures, leadership, and resources interacting (Oti-Sarpong *et al*. 2021). The initial cost-centric view is still prevalent and drives the decision making; this has been frequently discussed as a barrier for OSC (Goodier and Gibb 2007; Pan and Sidwell 2011; Razkenari *et al*. 2020). In line with this, to challenge the current mindset, expanding the definition of value of OSC systems beyond the initial cost element (MDM5) with more emphasis on health and safety, programme/schedule benefits, and whole-life cost should be considered and prioritized. The OSC benefits of time savings in project programmes/schedules and better health and safety performance will lead to project cost savings. Research should also be directed more to the environmental and social side of OSC (Hussein *et al*. 2021).

Experience of designers, their empowerment for developing OSC solutions, and extended collaboration with the supply chain is key (Wu *et al*. 2019). However, the warning about introducing off-site or modular into the projects for the sake of off-site/modular or for secondary reasons, such as impressing the client and policy makers should be noted. This introduces the practice of over-prefabrication or over-modularization. Producing an available OSC systems repository with their usability matrices (MDM1) will support the design decision making and future data analytics applications for automating design optimization (TnDA1) (Gbadamosi *et al*. 2020). Challenging the current design mindset reliant on past data, traditional practices, and software to develop a product design mindset (MD2) and complete system thinking (MD4) is needed. This need for shifting from the construction design mode to the product design mode has been previously highlighted in the literature (Luo *et al*. 2017). The current gap between the designers, contractors for constructability studies, and suppliers for off-site component development and site-testing should be bridged (Goulding *et al*. 2015). For this, employing OSC managers to supervise the end-to-end process (MCns4) can be considered.

In terms of OSC components (i.e. technical construction components), interchangeable and interlocking parts (TNPr6)—frequently likened to Lego blocks—such as prefabricated bridge deck sections (structure and bituminous top layers on one module) (TNP1) (Saleem *et al*. 2021) and prefabricated bituminous slab designs (TNP3) (Naus *et al*. 2010) were ranked as high impact opportunities. The additive construction technologies of concrete and asphalt printing (TnAC1) (Jackson *et al*. 2018) are also seen as priorities and strong drivers for OSC in the highways context. Practitioners' expectations of these technologies are recognized by the research community. Engineering and material-related research on these high-impact opportunities is ongoing for practical use. However, there are also commercial, logistics, and site assembly (e.g. specifications, lifting, and component joints) challenges associated with them (Razkenari *et al*. 2020), which should not be overlooked. Relevant highways/infrastructure codes and regulations should also keep up with and cover those emerging construction technologies as appropriate. In line with this, as seen in Singapore, OSC mandates in the codes and regulations for the infrastructure sector in the UK can be considered. This will require a broader discussion among stakeholders.

Propelled by the UK government's BIM mandate in the early 2010s to achieve level 2 BIM by 2016 in public projects (Ragab and Marzouk 2021), BIM has penetrated also in the highways projects with the umbrella term "infrastructure BIM". This has resulted in the need for creating and expanding the BIM object libraries for in-situ and off-site/modular components, containing life-cycle information (TnBIM4) (Aziz *et al*. 2017). This was also documented in the case projects. Coupled with a machine-readable design options repository (MDM1), the expanded BIM libraries will support generative design practices for optimum OSC configurations and component matching for modular systems (TnBIM9) (Salama *et al*. 2017), which is currently missing in the highways supply chain. Another high-impact potential is in using sensor networks (IoT) for near-real time data collection for OSC supply chain management, logistic planning, and site operations (TnIoT2) (Dave *et al*. 2018; Wang *et al*. 2020a). Some Tier 1 suppliers' initiative of on-site, mobile factories (flying factories) (Young *et al*. 2015) should be fitted with robotic production units (TnR3) to liken them to factories and to increase their effect.

Medium impact suggestions

The medium impact suggestions may not have the same impact as the higher impact suggestions but can be relatively easier to implement in shorter term. In line with the expected better supply chain integration outlined in the higher impact suggestions, preferred OSC supplier lists should be used in contract awarding and execution (MCm2). With that, the work packages should be carefully created to award related chunks of work to a single contractor (MCm3) for better system integration. It will be useful to review the current contract awarding practices in the industry involving OSC components from this viewpoint (Charlson and Dimka 2021).

For the design, earlier involvement of contractors and manufacturers (MD1), developing the understanding of tolerances and interfaces between in-situ and off-site (MD3), and promoting innovative design (MD8) by the main client are recommended as important suggestions. Similar recommendations have been recorded in the literature for different contexts (Pan *et al*. 2007; Mao *et al*. 2015; Razkenari *et al*. 2020), indicating these being persisting issues. Another notable suggestion is regarding experimenting with the platform customization design approach (Piroozfar *et al*. 2019) (MD9). This can be seen in the OSC components of recent public building projects (e.g. hospitals and prisons), in highways elements, such as vehicle and pedestrian bridges, underground passes, and drain channels. In line with this, reviewing the existing OSC systems in other sectors (MDM3) for benchmarking should be noted. Sectors, such as water and industrial are generally known to have advanced modularization practices.

To shorten the OSC supply chain and to improve in-house OSC capabilities, the emerging flying factories or mobile production facilities close to sites for OSC components (Young *et al*. 2015) by the Tier 1 suppliers should be supported by the main client and policy makers (MCns14). Alongside demonstrating a commitment to OSC, the productivity gains induced by those flying factories may provide the suppliers with a competitive advantage during the project bidding and execution stage. In line with this, the large contractors should consider developing their own manufacturing facilities and supply chains (MCns5) for OSC components, which will help them to better control the end-to-end process (MCns6). Pushing different OSC manufacturers to work together on-site with the contractors (MCns1) is promising for developing new modules from the existing components; however, this requires better integrated procurement arrangements. OSC is part of the end of project reviews currently (MCns7) as documented in the case projects but there is no specific OSC focus in the continuous improvement efforts, which is essential for long-term OSC success (Meiling *et al*. 2012). For this, a standard idea capturing template for OSC systems (MCns12) could be introduced to the supply chain by the main client and large Tier1 suppliers.

Clarity as to the definition and scope of DfMA (MPG7) and OSC ownership (MPG1) mechanisms are expected from the policy makers across the supply chain. Establishing OSC schools (MPG3), single point of contact for OSC initiatives (MPG51), and increased emphasis on the health and safety benefits of OSC are seen as useful (MPG6) actions that can be realized without much effort. There is however a need for an integrated and holistic strategy at a higher level, capturing the gist of those requirements for a clear direction to improve the overall situation and project governance for OSC (Rahman 2014).

Supporting and further disseminating some of the more established technical OSC components, such as bridge structures (TEPr1) and drainage chambers (TEPr3) were advised. With the new and emerging technical components, communication control bases allowing plug-and-play cable entry (TNU2), modular and retractable (telescopic) chambers (TNU1), and modular gantries fitted with signs and cameras (TNG2) were found value-adding. Prefabricated plastic slabs (TNP2), on the other hand, stirred discussions with their potential cost, programme/schedule, and sustainability benefits as the slabs can be manufactured from recycled plastics. However, there are risks of fire and potential respiratory health hazards associated with them as plastic particles may be dispersed in the air from the surface with tear and abrasion.

Encouraging the use of 4D BIM (TnBIM1) and cloud-BIM based information exchange (TnBIM5) (Sacks *et al*. 2018) are seen as important and were also documented in use in the case projects. It is critical though to include the OSC suppliers in the 4D BIM process and increase the number of professionals capable of using these technologies across the project life cycle. 4D BIM should not serve merely as a visual representation of a project progress but a real planning tool for site logistics and for providing the on-site staff with virtual work instructions (Magill *et al*. 2020). However, no evidence of rapid prototyping for OSC using BIM (TnBIM3) or BIM/GIS supported OSC assembly and logistics tracking (TnBIM7) was found. Efforts towards integrating BIM models with the weekly collaborative planning and control sessions (TnBIM10)—the UK's version of the Last Planner System (Daniel *et al*. 2017)—were documented. Alongside this, work for ground-based laser scanning for construction quality control and tolerance analysis was identified in some cases (TnRS2). These efforts can be expanded with photogrammetry and UAVs (TnR1). However, the use of UAVs in highways projects is subject to specific permissions in the UK. The permission procedure should be reviewed and streamlined for specific uses.

Contour crafting (TnAC3) (Khoshnevis 2004) is a lesser known additive construction technique in the UK. It can be trialled with large highways structures (e.g. walls, bridge components, underground channel sections), and in mobile manufacturing facilities (flying factories) to be established around construction sites in particular. As the technique is suitable for entirely constructing a large-scale structure in an additive manner in a relatively short time period, the need for using sub-components for the structure will be eliminated and productivity gains will be achieved.

As for the remaining medium potential technology-related suggestions, wearable exoskeletons (TnR4) have been experimented within different countries to ease the strain on on-site workforce for some time (de Looze *et al*. 2016). However, they are not currently being used or trialled in real-life highways projects in the UK and can present an opportunity to support the OSC component assembly on site. They can also contribute to increasing on-site assembly productivity and health and safety performance of the OSC efforts.

Creating an OSC experience database from professionals' input (TnDA2) to support the decision-making and continuous improvement, and recording key OSC data (quality, source, ownership, logistics, approvals) on blockchain (TnB2) (Tezel *et al*. 2021) are the other notable technology-related suggestions that are yet to be implemented. The use of digital ledgers (blockchain) for key component data recording can be more straightforward in short term than smart contracts and automated payments as explained in the following section. The suitability of recording the OSC decision making database (TnDA2) in a blockchain (TnB2) environment can be also investigated.

Lower impact suggestions

The lower impact suggestions are seen as useful but having relatively limited or potentially unintended impacts. Some of those suggestions are better established and already adopted. Hence, relatively limited impact. Some were documented in the case projects, such as RFID enabled logistics tracking (TnBIM6), using sensors for component control and tracking for asset management (TnIoT1), and CNC and BIM integration (TnBIM2). Also, prefabricated stairs (TEPr2), underground service protectors (TEPr4), flat pile caps (TEU1), and plastic chamber printing (TnAC2) were identified in use. Using numerically controlled plant (TnP1), experimenting with remote sensing (TnRS1), and focusing first on critical path items for OSC priorities (MDM4) were also observed in practice. These should be maintained. Some of the suggestions require an integrated commercial structure and collaborative environment in the supply chain to be fully utilized, such as partnering and team-building workshops for OSC (MPG4). Some of the suggestions are seen as complementary to the higher or medium impact suggestions, such as the publication of case studies and best practices (MPG9), third party design reviews (MD5), and engaging more with OSC organizations and other related communities (MPG2).

Some of the suggestions may have unintended, and even detrimental consequences. If those risks are eliminated, they may be treated as a medium or higher impact suggestion. Using VR helmets for OSC sequencing and assembly on-site (TnBIM8) may be impractical and introduce serious health and safety risks (Delgado *et al*. 2020). Having OSC quotas and targets linked with commercial success (MCm5) could fuel the over-modularization concerns. Standardizing the design (MD7) and method statements (Cns8) for OSC systems could inhibit experimentation and innovation. Less prescriptive client and design specifications (Cns11) for flexibility are seen as important; however, as defining what is less or more descriptive is difficult with the specifications for the whole supply chain, this may pose the risk of misguidance or reduced value for taxpayers' money. Automatic contracts on blockchain for OSC elements (TnB1) can help to reduce the transparency concerns, automate the payment procedure, eliminate the gatekeepers, and increase trust (Tezel *et al*. 2021). However, the current contract regulations, legacy IT systems, and human resources should be aligned with the technology. If this readiness is not achieved before the implementation, serious conflicts may arise in payments.

Conclusion

OSC components have been used in the UK for nearly two centuries. Despite the experience and support from the policy makers, the OSC sector has remained short of the expectations. With a growing array of mega-infrastructure projects, the country is consciously prioritizing OSC for its expected benefits. The research presented in this paper bridges the gap in the literature by presenting a detailed OSC analysis of the highways infrastructure sector in the UK for the current OSC condition and future suggestions. The suggestions were ranked by their impact potential. The exploration of the current condition and suggestions for improving OSC from a management, technical and technological perspective led to the conclusion that many of the previously highlighted inhibiting conditions, which have been discussed often from a building sector perspective, still exist and are relevant also in the current OSC context of highways projects in the UK.

There are however many OSC related suggestions identified in this research, some of which have already been adopted (see the lower impact suggestions) in the highways projects, with impact potentials that can be prioritized to improve the current condition. Seemingly, some of those suggestions are more of long-term expectations, such as developing a design repository with associated BIM objects, driverless plant, or asphalt printing. There are also suggestions that can be adopted in shorter term. These include learning from other sectors (e.g. water or industrial), including off-site suppliers into integrated contracts for joint component development and site testing, developing a collaborative decision-making framework, or supporting the Tier 1 contractors' flying factory initiatives. In this regard, the research will be useful for policy makers and practitioners in understanding the current condition and future priorities for OSC in highways.

The research has several limitations. All of them pinpoint further research opportunities. The boundary of the work is set as construction project management, which leaves little room for the manufacturing, logistics, and maintenance side of OSC. Future research can expand on the research boundaries to focus more on the manufacturing, logistics, and maintenance side of OSC in infrastructure projects. Although the findings were validated through the case projects, the rankings and suggestions are mostly based on the views of a selected group of expert practitioners and a few academics. The findings, therefore, represent the views of management practitioners mostly. Data collection can be also diversified to capture more of the views of other key stakeholders including OSC suppliers, policy makers, representatives of OSC interest groups and communities, asset management and maintenance service providers, owners, clients, end-users, and academics. To widen the breadth of data in this field and improve the generalizability, the findings can be further investigated through a large-scale survey for one or more of the study dimensions (management, technical components, technology). Similarly, the suggestions identified in this research can be also ranked and sorted by the order of their impact potential through a large-scale survey study. It is necessary to study OSC components and efforts in-depth in the sector from a life cycle, environmental, and sustainability performance perspective, which is shallowly touched on in this research. This will also assist in broadening the current value perception and decision making for OSC in the sector. Validation of the future suggestions in practice is missing in this research. Action or design science research-based studies implementing and evaluating the suggestions outlined in practice are necessary.

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Appendix 1. *Interview questions*

1. Could you please introduce yourself (e.g. your background, your current role, your industry experience) and briefly talk about your experience/engagement with OSC (i.e. design, construction management, asset management)?
2. How do you see or evaluate the current condition of OSC in the infrastructure sector?
3. More specifically, how do you think OSC is currently managed in the highways construction context (i.e. project management perspective)?
4. In your view, what should be done to improve the current management of OSC for highways construction projects (i.e. project management suggestions)?
5. From your perspective, what highways construction components are good fits for OSC (i.e. technical component suggestions)?
6. In your experience, what technologies are being adopted to support the current OSC implementations in highways projects (i.e. digital, automation, and robotics)?
7. What are the other high potential technologies for OSC in highways projects (i.e. digital, automation, and robotics)?
8. Any final comments or suggestions related to the current condition or future suggestions for OSC?