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From Construction to Production: Enablers, Barriers and Opportunities for the Highways Supply Chain

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# From Construction to Production: Enablers, Barriers and Opportunities for the Highways Supply Chain



## Innovative Design Lab



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## Innovative Design Lab Research Centre – University of Huddersfield

IDL is a new interdisciplinary research centre/ laboratory at the University of Huddersfield.

The lab conducts theory based and applied research generally into product design, and especially in the built environment, pushing the impact of design thinking and practice to new areas. It cuts across the areas of architectural design, construction management, interior design, new product development, engineering, social sciences and healthcare.

Our research focuses on solving real world problems through design innovation, mobilising the underlying theories as well as the enabling processes and technologies needed to deliver value to users and the society at large. Our research is developed closely with diverse public and private sector organisations to propose novel solutions to design challenges and project based problems.

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## Executive summary

The report presents the initial findings of a project part of the Lean Collaborative Research at Highways England with academia that aims at understanding enablers, barriers and opportunities to transform the current highways construction supply chain into a more manufacturing-like environment, where the benefits of production thinking can be achieved. The focus of the project is mostly on the adoption of off-site/modular (O/M) construction systems and advanced technologies, under a greater vision called “manufacturisation” of the highways supply chain

From the initial findings, the research identifies several opportunities to decrease the waste in the delivery and maintenance of highways projects (i.e. 71% potential reduction in project times by using O/M systems). The adoption of O/M construction systems and advanced technologies will have a greater impact on Highways England’s delivery of the Road Investment Strategy (RIS) targets by:

- Improving the current quality of construction
- Promoting the Design for Manufacturing and Assembly (DfMA), and maintainability
- Reducing whole life-cycle costs
- Promoting a culture of engagement across the supply chain
- Improving safety by reducing staff exposure
- Improving user satisfaction by reducing the impact of construction and maintenance on road users and ensuring the smooth flow of traffic (supporting the network capability)

By pursuing a standard approach to the manufacturisation across the supply chain, Highways England will be able to demonstrate a clear path to improving the delivery of construction and maintenance activities.

The manufacturisation vision will also support BIM implementation and add value to the current BIM deployment.

There are barriers within Highways England and its supply chain, which need to be addressed to create an environment that will allow manufacturisation practices. A number of opportunities are also identified and discussed in the body of this report.

A summary of some of the key findings are as follows:

*Enablers and barriers associated with off-site/modular systems:*

- 1) Early design focus on modular offsite, with supporting BIM models.
- 2) Developing the product design and DfMA mindset.
- 3) Appropriate decision support structures to facilitate modular offsite approaches
- 4) Construction processes that promote modular offsite
- 5) Commercial systems that incentivise modular offsite.
- 6) Appropriate project governance to allow modular offsite to flourish
- 7) Short term relationships with suppliers

*Opportunities for advanced automation and further pre-fabrication/ modularisation in the supply chain:*

- 1) Greater use of onsite robotics
- 2) Greater use of additive construction
- 3) Greater use of numerically controlled plant
- 4) Adoption of innovative technologies and off-site/modular construction in specific product areas: pre-cast structures, gantries, underground components, and pavements
- 5) Improved site logistics



## Construction to production

The “Manufacturization” of construction - the act of likening construction products, materials/components, processes and project governance/management practices to the ones in manufacturing or emulating the characteristics of the production management elements in manufacturing - has been a popular theme for construction management researchers and practitioners. The “manufacturization” idea has generally been investigated under a broad spectrum of terms such as production thinking, construction or project production management, and manufacturing thinking, and has also included discussion of offsite manufacture using modular approaches and on-site assembly.

The move towards manufacturization of construction industry is motivated by an ambition to get the design right first time and make the whole construction process faster, cheaper, safer, and more environmentally friendly to build. This has led construction industry to borrow range of good practices from manufacturing industries, particularly automotive and aerospace industries, including lean manufacturing principles, modular design, additive manufacturing concepts including 3D printing, and more advanced technologies including robotics and internet of things.

The push towards integrating the construction supply chain to deliver innovative solutions has led towards the adoption of good practices such as collaborative planning, Building Information Modeling (BIM), and Design for Manufacture and Assembly (DfMA). The successful application of each of the aforementioned concepts is contingent on joint collaboration between clients, main contractors, designers, and sub-contractors in the construction supply chain. This report will further investigate the application of such innovative ‘manufacturization’ concepts in construction industry and discuss some of its challenges, enablers, benefits, and opportunities using a case study based approach.

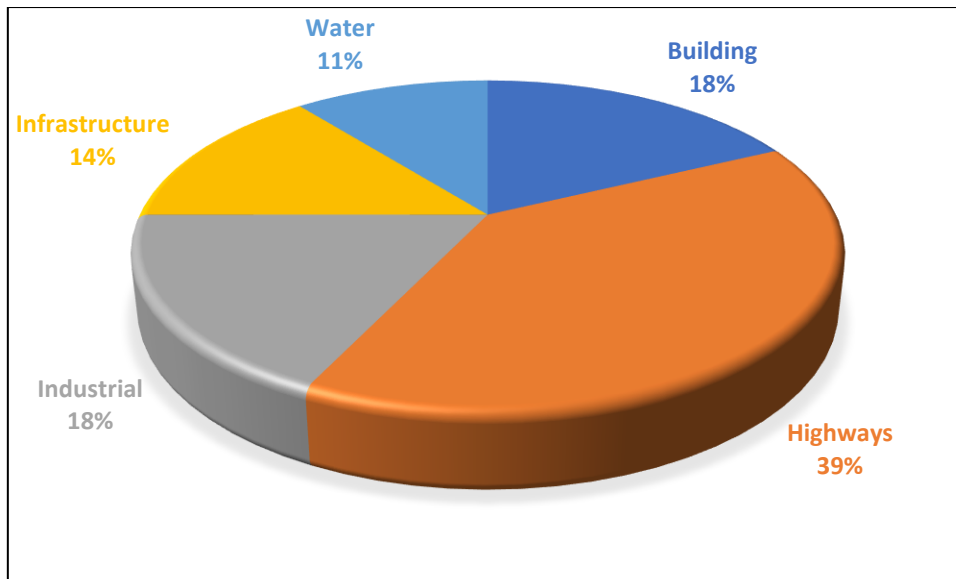
## Project activities

The primary data collection method includes 19 in depth-interviews with managers from different construction sectors (see Table 1, Figure 1 and Figure 2 for interview details and interviewee profiles) and literature review for best practices, opportunities and challenges. The interviewees were identified in collaboration with Highways England, Anglian Water and Buildoffsite, among managers that have been actively involved in efforts toward the “manufacturization” of their sectors. The detailed transcription of the interviews can be found in Appendix.

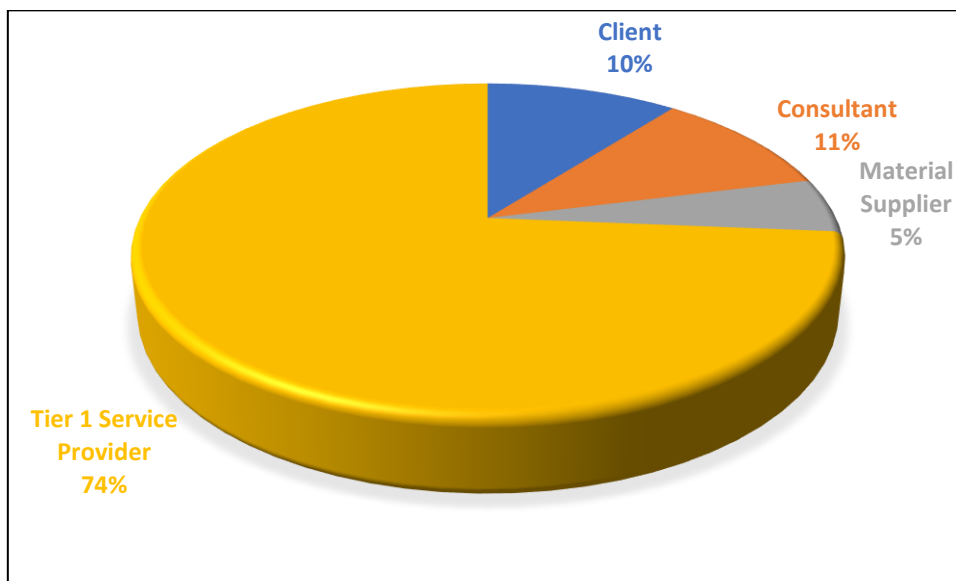
**Table 1: Interview details with managers from different construction sectors**

| No | Manager Role                               | Sector   | Supply Chain Role |         |          |
|----|--------------------------------------------|----------|-------------------|---------|----------|
| 1  | Civil Design/ BIM Manager                  | Highways | Tier 1            | Service | Provider |
| 2  | Structures and Temporary Works Coordinator | Highways | Tier 1            | Service | Provider |

|           |                                                     |                                      |                                                                            |  |
|-----------|-----------------------------------------------------|--------------------------------------|----------------------------------------------------------------------------|--|
| <b>3</b>  | Civil Design Manager                                | Highways                             | Tier 1 Service Provider                                                    |  |
| <b>4</b>  | Project Manager                                     | Highways                             | Tier 1 Service Provider                                                    |  |
| <b>5</b>  | Project Manager                                     | Highways                             | Tier 1 Service Provider                                                    |  |
| <b>6</b>  | Structural Designer                                 | Highways                             | Tier 1 Service Provider                                                    |  |
| <b>7</b>  | Production Engineering Lead                         | Highways                             | Tier 1 Service Provider                                                    |  |
| <b>8</b>  | Senior Process Improvement Consultant               | Highways                             | Consultant                                                                 |  |
| <b>9</b>  | Innovation Manager                                  | Infrastructure/ Buildings            | Tier 1 Service Provider                                                    |  |
| <b>10</b> | Lighting/ Technology Manager                        | Highways                             | Tier 1 Service Provider                                                    |  |
| <b>11</b> | Engineering Manager                                 | Highways                             | Tier 1 Service Provider                                                    |  |
| <b>12</b> | Managing Director                                   | Water                                | Client                                                                     |  |
| <b>13</b> | Engineering Manager                                 | Water                                | Client                                                                     |  |
| <b>14</b> | Performance Manager                                 | Water/ Highways                      | Tier 1 Service Provider                                                    |  |
| <b>15</b> | Project Director (Mechanical/ Electrical/ Plumbing) | Industrial/ Building                 | Tier 1 Service Provider                                                    |  |
| <b>16</b> | Project Manager (Mechanical/ Electrical/ Plumbing)  | Industrial/ Building                 | Tier 1 Service Provider                                                    |  |
| <b>17</b> | Managing Director                                   | Infrastructure/ Industrial           | Material Supplier (Corrosion protection and monitoring management systems) |  |
| <b>18</b> | Managing Director                                   | Infrastructure/ Industrial/ Building | Management Consultant                                                      |  |
| <b>19</b> | Head of Industrialisation                           | Infrastructure/ Industrial/ Building | Tier 1 Service Provider                                                    |  |



**Figure 1: Sector distribution of the interviewees**



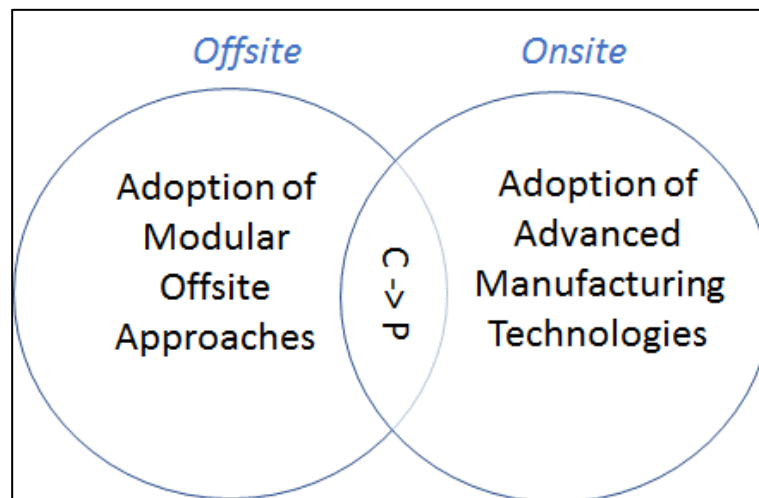
**Figure 2: Sector roles of the interviewees**

## Structure of the report

In moving from construction to production, and promoting the manufacturization of construction, this report makes the case for an integrated supply chain approach, exploiting the following:

- Adoption of modular offsite construction
- Adoption of advanced manufacturing technologies encourage production thinking for onsite activities

Figure 3 depicts the focus of this report, where we seek to assess the barriers, enablers and opportunities for the uptake across the infrastructure sector.



**Figure 3: Construction to Production**

## **Modular Offsite construction**

### ***What is modular offsite construction?***

Modularity involves breaking up a system into discrete chunks, which communicate with each other through standardised interfaces, rules and specifications (Baldwin and Clark 2000). Key challenges for a modular system are finding the appropriate number of modules, design elements, interactions and interfaces. Modularization is a broad concept though, with various interpretations and meanings across research disciplines and market sectors (Cigolini and Castellano 2002). The collective acronym PPMOF (Prefabrication, Preassembly, Modularization and Off site Fabrication (Pan et al. 2012) helps to describe the modern methods that can be considered in construction. To make sense of this topic, it does help to consider the distinction between a 'design view' and an 'operational view' of modularity (Salvador et al. 2002). The design view focuses on how designers consider the linkages and dependencies between different aspects of products they design. The operational view considers the physical manifestation of these products, and how they are managed in terms of deliveries and installation. Most of the current research on the deployment of modular offsite construction has focused primarily on housing or building construction projects (Pan et al. 2007; Gosling et al., 2016).

### ***The potential and pitfalls of modular offsite construction***

Early studies of modularization in the construction sector sought to demonstrate that the savings outweigh any extra design and engineering costs (e.g. Glaser et al. 1979). Using PPMOF has long been suggested to allay the industry's inherent problems. Alongside reducing the health and safety risk exposures, modular configurations and standard items can reduce costs and lead times (Blismas et al., 2006), and link with the broader move to apply operations management concepts and approaches in

construction. Summarising previous literature, it is possible to see that offsite approaches have the potential to offer the following benefits:

- Greater certainty of outcomes, as deliveries and costs can be controlled more effectively.
- Time compression of site activities and associated cost benefits.
- Improved site logistics, particularly in congested work areas.
- Quality benefits, since production/ fabrication, testing and checking can be undertaken in a controlled environment, reducing the potential for snagging and rework.
- Health and safety benefits, as more work can be undertaken in a controlled environment.
- More free road space which is not restricted by on-site construction activities.

Modular offsite construction is not without challenges, and the above benefits are subject to effective management of the approach. Summarising previous literature, the usual pitfalls are summarised below.

- Interfacing issues, resulting from different complex modules
- Understanding constraints, caused by site, project and supply chain factors.
- Attitudinal barriers, including co-operation and collaboration issues, as well as resistance to change.
- Understanding manufacturing capacity, and incorporating offsite manufacturers into the planning process.
- Design issues, particularly understanding design freeze and design impact on modular approaches
- Engagement issues associated with supply chain actors

### ***Modular offsite approaches and practices across different sectors: useful insights from the literature***

Much of the research evidence presented comes from housing sectors. Evidence from this sector is presented from a wide range of sources, including Germany (Schoenwitz et al. 2017), Sweden (Jonsson and Rudberg 2014), the UK (Gibb and Isack 2001), and (Eastman and Sacks 2008). From these studies, it is possible to see that different levels and degrees of modular offsite approaches can be deployed, ranging from offsite production of components, to subassemblies, non-volumetric panels, volumetric elements and then to whole buildings. Hence, modular offsite approaches in housing projects are typically matched with the following:

- Offsite ethos consistent across different project phases, considered as part of the early planning
- Early involvement of manufacturers
- Collaborative approach between different parties to jointly consider trade-offs and offsite approaches at different points.

Modular infrastructure concepts are in their infancy. Within the peer reviewed literature, there are very few systematic studies published to help guide practitioners and researchers. Many examples are anecdotal, taken from examples written up by professionals as case studies in trade outlets, or are very technical in nature, seeking

to report engineering advances or materials testing. Two areas are interesting for the purposes of this report: modular bridge construction which make use of modular bridge decks, and prefabricated concrete slabs to support smart motorways. The focus has been on exploring how more efficient and effective workflows can be adopted to minimise time of disruption to traffic flows during ongoing works.

Modular bridge approaches, typically, involve the use precast concrete elements for most of the components along with ultra-high-performance concrete and glass fiber-reinforced polymer reinforcement. Alongside transportation and crantage, the joints and interfaces between different elements must be carefully planned to support this approach. Evidence show that, firstly, such 'bridge decks' can be developed to meet standards and codes for most highway authorities (Williams et al. 2003), and secondly, that modular approaches are likely to reduce project times significantly (for example, from six months to seven weeks - 71% reduction), when compared with a traditional approach (Hachborn 2017). The focus of modular motorways has primarily been on concrete slab systems so that installation rates can be increased. As experience with these techniques grow, it may be possible to integrate many forms of new technologies that are integrated at the prefabrication stage.

The application of modular design and manufacturing offsite for ease of assembly at offsite or on-site locations in construction sector is adapted from the manufacturing sector, where such practices are deep rooted in its supply chain for at least two decades. The table below highlights some of the manufacturing principles and concepts that has helped original equipment manufacturers (OEMs) to streamline its operations and work collaboratively with its suppliers to develop innovative solutions that are of mutual benefits including move towards modular design.

**Table 2: Manufacturing concepts that facilitate modular off-site manufacturing and on-site assembly**

| Manufacturing concepts                | Definition                                                                                                                                                                                    | Application of Principles/ Tools in manufacturing sector                                                                                                                                                                                                                                                                                                                                                | Rate of application in construction industry                                                                                                                                                                                                                                                                                 |
|---------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Lean Manufacturing</b>             | Focuses on eliminating wastes from the business processes by identifying the non-value added activities and doing only activities that add value from customer perspective.                   | Production processes; supports processes including HR, IT, Finance, sales orders. The key tools from Lean tool box are 5S, <i>Value Stream Mapping</i> , <i>SIPOC</i> , <i>Kaizen</i> , <i>Just-in-time production and delivery</i> , <i>Level Production and Scheduling</i> , <i>Total Productive Maintenance</i> and <i>Collaborative Planning</i>                                                    | The last 5-7 years has seen increasing application of Lean manufacturing concepts within construction projects.                                                                                                                                                                                                              |
| <b>Lean Supply Chain</b>              | Focuses on integrating the supply chain by working collaboratively with suppliers for joint product development, modular design, strategic sourcing, improved quality of items/sub-assemblies | <i>Vertical Keiretsu</i> network as seen in Toyota; <i>Supplier Development team</i> in OEM to help improve the capabilities of supply chain; <i>Supplier Association</i> to give voice to Supply Chain; <i>Long-term relationships with strategic suppliers</i> and involve them early in the new product development process; <i>Learning Cluster</i> including OEM, and suppliers at Tier 2/3 levels | Very slow application especially when it comes to supporting small and medium-sized subcontractors at Tier 2/3 levels                                                                                                                                                                                                        |
| <b>Design for Manufacturing (DFM)</b> | Design method that takes into consideration ease of manufacturing of the collection of parts that will form the product after assembly.                                                       | Focus on cost effective material and process in early stages of product design that will be used in the production; Standardize parts and materials; design for efficient joining; reduce number of manufacturing operations; minimize re-orientations of parts during assembly; seek to reduce material, overhead, labor cost; shorten the product development cycle time.                             | In early phases; DFM & DFA now combined to call DfMA -considered as critical for off-site modular production and on-site assembly; Helping to bring designers, clients, and main contractors (and its supply chain) together. Some difficulties exist under the current contractual mechanisms and project delivery systems. |
| <b>Design for Assembly (DFA)</b>      | Design of products that will transition to productions at a minimum cost, focusing on the number of parts, handling and ease of assembly                                                      | Standardised parts; modular design; functional analysis; design parts with self-fastening and locating features; focus on component symmetry; design parts for retrieval, handling, and insertion; seek to reduce material, overhead, labour cost; shorten the product development cycle time.                                                                                                          | In early phases; DFM & DFA now combined to call DfMA- considered as critical for off-site modular production and on-site assembly; Helping to bring designers, clients, and main contractors (and its supply chain) together. As in DFM, DFA requires commercial review.                                                     |

|                                                |                                                                                                                                                                                                                         |                                                                                                                                                                                                                                                                                                                            |                                                           |
|------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------|
| <b>Failure Mode and Effect Analysis (FMEA)</b> | Used in design phase of the product development to anticipate potential failure modes in the design or manufacturing process. Aimed at identifying failure at its earliest possible point in product or process design. | Risk Management tool; Use of cross functional team to review the design progress and assess its risk of failure; can be applied at design and production stage; Use of the concepts can exponentially minimize the impact the failure is the defects/failures are identified later in production or post production stage. | In early phases; should be used in conjunction with DfMA. |
|------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------|



### ***Modular offsite enablers and barriers identified in the project***

The enablers (Figure 4) and barriers (Figure 5) identified from the interviews and the literature review for off-site/modular construction in the highways sector were summarised on two mind maps, over the same main subjects; decision making, design, Building Information Modeling (BIM), construction, commercial issues and project governance.

#### ***Decision making:***

- Developing a catalogue of available off-site/ modular systems with their usability configuration matrices, showing which off-site/modular component is allowed to be used with which components will be an important enabler.
- The catalogue can be enriched with BIM object families of the components from manufacturers. When ready, the catalogue can be located on a web-server for wider, cloud-based access and easier data management like filtering, commenting, modifying etc.
- Developing a collaborative decision making framework for off-site/modular systems involving designers, constructors, manufacturers, and asset managers will be useful. Inspirations for that kind of a collaborative decision making framework can be taken from the Collaborative Planning system, in which different project stakeholders come together for joint decision making and obstacle removing throughout a project.
- A comprehensive scoping study of available off-site/modular systems in the market, in other countries and in other construction sectors will improve the current decision making capability.
- Also, benchmarking against organisations and sectors that frequently resort to off-site/modular construction systems in their operations like the army or the automotive sector will provide valuable insights for future decision making activities.
- The value definition for off-site/modular systems should be expanded beyond investment costs to cover the whole-life cost and schedule benefits, construction and maintenance health and safety benefits, sustainability benefits, traffic management and end-user impact benefits.

#### ***Design:***

- For off-site/modular systems, earlier involvement of project stakeholders in the design process has been repeatedly recommended both by the interviewees and the literature. Earlier involvement in design has become sort of a truism for the construction industry, due to its benefits in generating value in design, but still not being realised as desired.
- It also seems that the traditional design status-quo should be challenged by developing the product design and Design for Manufacture and Assembly (DfMA) mind-set.
- Design for maintainability should be thought in connection with DfMA.
- In parallel with this mind-set change, the current understanding of design tolerances, interface management between new and in-situ components, off-

site/modular system thinking in design from the substructure to the superstructure, and scalability and interchangeability of components should be increased.

- The low level of standardisation in the design of similar components (i.e. many different designs of the same gantry base) seems like a barrier.
- The interviewees complained a lot about the lack of a robust design constructability review and the high reliance on design software that generally does not lead to “innovative” design solutions.
- Overdesigning components, which does not leave much room for decision making, taking initiatives and proposing alternatives by constructors can be an occasional issue.
- Highways England is required to clearly communicate its off-site/modular specifications and requirements to the supply chain.
- Third party design reviews for constructability and off-site/modular systems can be tried.

### ***Building Information Modeling (BIM):***

- BIM enables a powerful information management process, a large asset information repository, and a comprehensive digital representation of an asset in terms of its geometric and attribute information that hold the potential to integrate the whole project life-cycle.
- For off-site/modular systems, apart from better coordination and collaboration between project stakeholders, prototyping using BIM, 4D (3D BIM+ schedule) simulations for component installation and BIM compatibility with computer numerical control (CNC) machines in manufacturing are important enablers.
- Although still in development, BIM based cost management (5D BIM) practices, taking 3D designs and work schedules into account, are also spreading.
- In line with the suggestion to expand the value definition of off-site/modular systems beyond capital costs, the nD (multi-dimensional) BIM concept, covering those expanded value dimensions for off-site/modular systems to support decision making, should be driven further. Thus, the supply chain will be able to see and compare the effects of specific off-site/modular decisions on whole life-cycle costs, health and safety risks, sustainability, traffic management and end user impacts in real-time to quickly make informed decisions in a BIM environment.
- Developing the current BIM object families of off-site/modular components, sharing exemplar cases of BIM benefits, large service providers and Highways England taking leadership in wider BIM adoption through training will also be useful.
- Ensuring that asset owners also keep ownership of their BIM systems to maintain effective information flow and maintenance.
- The identified barriers to BIM adoption have long been discussed by the industry; interoperability issues between different software vendors, suppliers lagging in BIM capabilities, limited object libraries, BIM narrowly seen as a

“technology-solution” that has not been integrated properly with the people and process factors, and difficulties in quantifying BIM benefits.

### ***Construction:***

- Collaborative working in the form of different manufacturers working together and constructors and manufacturers jointly prototype developing for on-site trials, specifically on critical path components, comes to the fore.
- Some complaints about the faulty view to off-site/modular systems as the panacea to on-site construction problems were recorded. Those systems require detailed temporary works and lifting plans, the absence of which may lead to serious accidents, delays, re-works and quality issues. Therefore, reviewing and standardising the current construction method statements with those comprehensive planning requirements in mind will be vital.
- Control for off-site/modular systems should be extended beyond the on-site installation phase to cover the manufacturing phase as well.
- For larger projects, employing off-site/ modular managers that will monitor the design, manufacturing and installation process should be considered.
- Some large Tier 1 suppliers have chosen to invest in their own off-site/modular manufacturing facilities to be able to control the supply chain better. This practice can be evaluated and if found beneficial/ feasible, can be promoted, at least among the remaining large Tier 1 suppliers.
- Less prescriptive material/ component specifications (the use of more ‘fit-for-purpose’ performance based), leaving room for new trials and streamlined component/ material approval processes are required from Highways England.
- Off-site/ modular learning should be systematically captured both in due course of projects’ execution and at the end of projects.
- Developing a standard template to capture the learnings should be considered.
- Risk aversion for on-site robotics and automation systems, which can bring off-site construction benefits to on-site operations without having to deal with off-site construction’s supply chain management issues, still seems high.
- Highway England can identify some pilot projects to help disseminate the emerging practices in on-site robotics and automation, try to communicate those systems’ benefits better through case studies or research or may consider making some of those systems contractual obligations to enable innovative approaches flourish.
- The supply chain should be careful about “over-modularisation” as it tightens tolerances and leaves no room for constructors to perform site arrangements.

### ***Commercial:***

- Project delivery systems enabling early contractor involvement, such as design-build, should be preferred.
- Currently, it was found that off-site/ modular suppliers and manufacturers are not willing to give their inputs early in the delivery process as they do not see any commercial advantage in their early involvement– no job guarantee. To

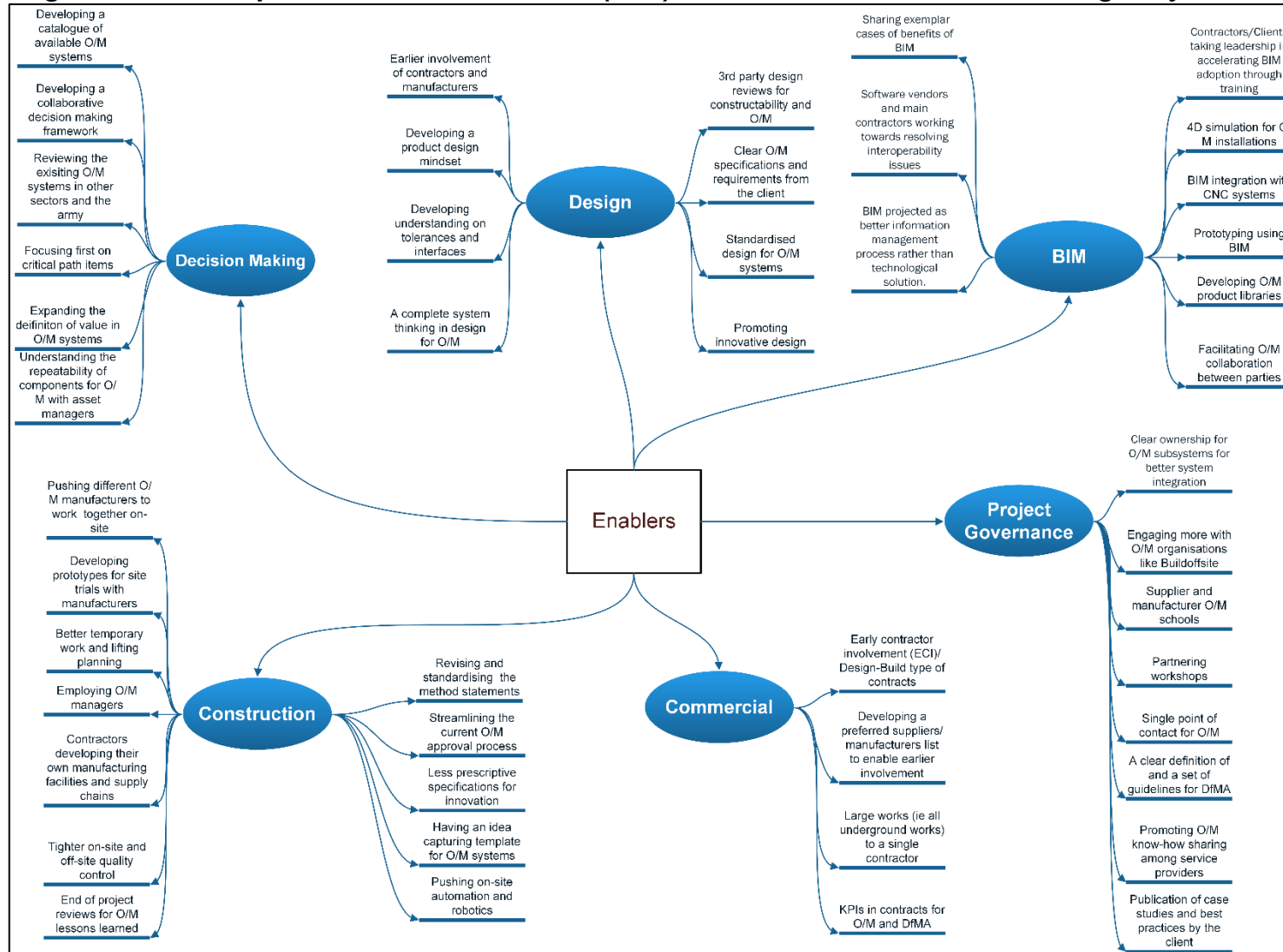
enable early involvement of the suppliers and manufacturers in the off-site/modular delivery process, a preferred suppliers/manufacturers list should be compiled. Constructors and designers can then be asked to engage first with and consider employing companies on the list while the suppliers and manufacturers can be asked to become involved early in the delivery process when their input is needed, as a condition to be included in the list.

- Large work chunks (i.e. all underground works) should be given to a single contractor to improve planning and coordination.
- Work packages should be reviewed for coherence to overcome ownership issues. For instance, instead of giving each off-site/modular components (i.e. steel structure, base, technology components etc.) of a gantry to separate parties, one organisation can be held responsible for the delivery of complete gantry packages with their off-site/ modular components.
- Highways England may consider including off-site/modular, DfMA and maintainability related Key Performance Indicators (KPIs) in contracts.

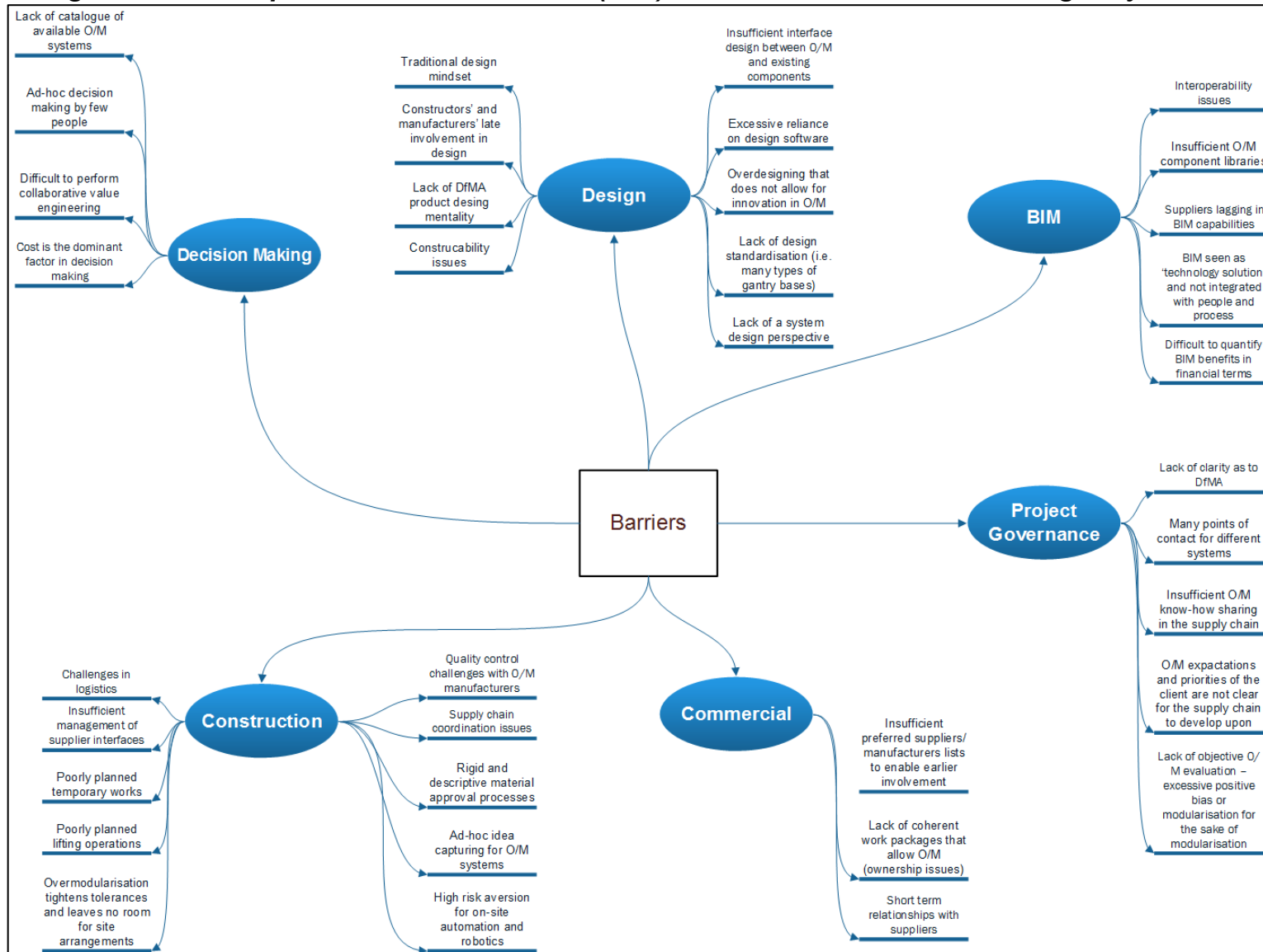
### ***Project governance:***

- A clear definition of and detailed specifications for DfMA are required by supply chain actors. This implies a need for better leadership and guidance in disseminating the DfMA ideal.
- To increase the current know-how on and cooperation for off-site/modular systems in the highways supply chain, it is recommended to increase the engagement with major third party organisations like Buildoffsite (an industry-wide campaigning organisation that promotes greater uptake of off-site techniques by the UK construction industry), planning partnering workshops, publishing best practices and case studies, and setting up off-site/ modular schools will be useful. For instance, at the moment, Buildoffsite has three hubs (work groups) targeting the water, building and refurbishment sectors. Establishment of a highways hub should be pursued to align the current off-site/ modular efforts in the supply chain with the Buildoffsite community. This will also support the delivery of Highways England responsibilities and duties under the Social Value Act.
- Highways England is required to clarify its off-site/ modular expectations, priorities and specifications. When those expectations and priorities are communicated to the supply chain, supply chain actors can be asked to propose their solutions. This will also promote innovation in the supply chain.
- The existence of many point of contacts for different off-site/ modular components in a project was pronounced as a barrier as information may be lost or distorted across many communication layers, alongside complex coordination issues. Having an off-site/ modular manager as a single point of contact in projects may offer a solution to this problem.
- Modularisation for the sake of modularisation should not be the prevalent mind-set; modularisation should add value to projects. However, as suggested for improved decision making, the current value definition for off-site/ modular systems should be reviewed and expanded.

**Figure 4: Mind map for off-site and modular (O/M) construction enablers for the highways sector**



**Figure 5: Mind map for off-site and modular (O/M) construction barriers for the highways sector**



## **Opportunities for advanced technologies and off-site/ modular systems: Encouraging production thinking on-site**

In this section, opportunities for advanced technologies and off-site/ modular systems to encourage production thinking on highways sites will be presented. The identified opportunities are from both interviews and the literature. The mind-map of the opportunities can be seen in Figure 24.

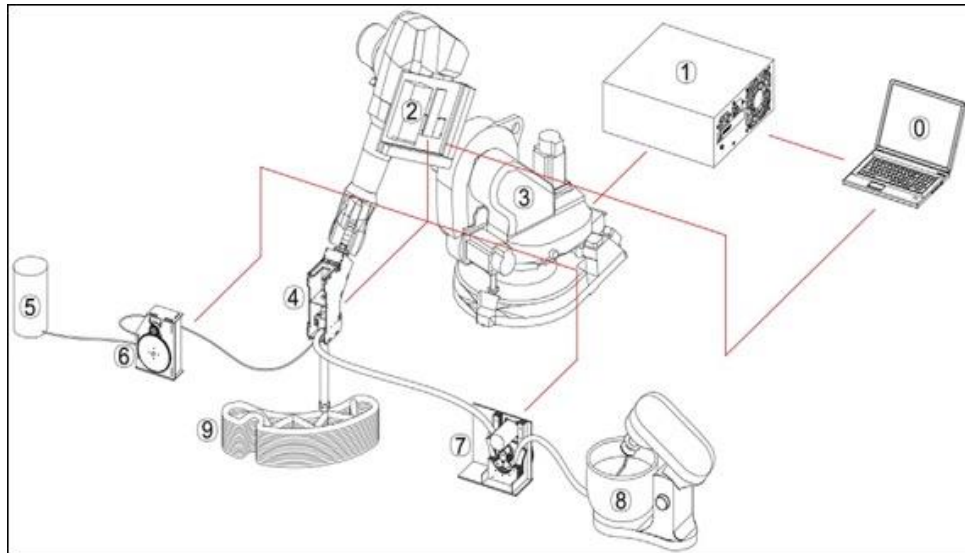
### ***Additive construction***

Additive Construction takes its roots from Additive Manufacturing, a generic name referring to the technologies that build 3D objects by adding layer-upon-layer. Additive Construction can be deployed for both off-site and on-site construction and holds the potential to bring the off-site construction benefits onto on-site operations without having to deal with the logistics and supply chain management issues associated with off-site construction. Additive Construction of smaller-scale construction components has generally been discussed under the 3D material printing concept. Larger-scale components (i.e. a whole building or bridge) on the other hand has generally been constructed following another method called Contour Crafting (CC). Some Additive Construction opportunities for highways projects will be presented in this section.

### ***3D concrete printing and beyond***

3D concrete printing is the process of using computer controlled 3D printers that precisely deposit successive layers of high-performance concrete to form complex structural components – such as curved cladding panels and architectural features – that cannot be manufactured by conventional processes.

During their visit to the Manufacturing Technology Centre in Coventry, the research team were given the opportunity to observe the 3D concrete printing process and to discuss the possible uses of the technology in highways construction projects with the 3D concrete printing research team and the innovation manager (interviewee no. 9 in Table 1). The complete set-up of a 3D concrete printing head can be seen in Figure 6 (Gosselin et al., 2016).



**Figure 6: Schematic of a 3D printing setup: 0. System command; 1. Robot controller; 2. Printing controller; 3. Robotic arm; 4. Print head; 5. Accelerating agent; 6. Peristaltic pump for accelerating agent; 7. Peristaltic pump for premix; 8. Premix mixer; 9. 3D printed object (Gosselin et al., 2016: 104).**

It was identified that the current state of the 3D printing needed some improvements before being deployed on a highways site; (i) structural tests on the special concrete mix to be completed, (ii) necessary permissions and clearances to be obtained, (iii) the current mobility of the setup (print head) to be increased by mounting it onto a HIAB-like truck to turn the process from off-site to on-site and (iv) an automatic concrete batching module to be added to the system to enable concrete printing on the go. All of those improvements can possibly be completed in a short-time frame.

Provided those improvements are carried out, the technology is envisioned to initially find itself a place in three important areas in highways projects:

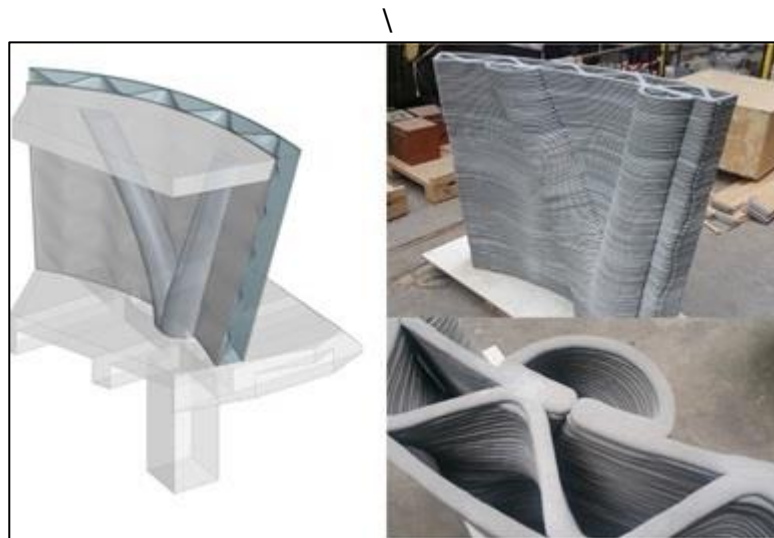
1. Rapidly creating, repairing and maintaining complex shaped (I.e. comb shaped) concrete barriers for better energy absorption during an impact for improved traffic safety, and on-site barrier construction productivity and quality (see Figure 7).





**Figure 7: A complex shaped concrete section (Gosselin et al., 2016: 107)**

2. Quick repair of structural defects and wear on the above-ground highways concrete structures with lesser requirements for traffic management and traffic flow disruptions.
3. Enabling rapid construction, repair and maintenance of complex shaped concrete retaining walls (see Figure 8).



**Figure 8: A 3D printed, complex shaped wall example (Gosselin et al., 2016: 106)**

Until recently, Additive Manufacturing techniques were confined to high value adding industries such as the aeronautical and biomedical industries, mainly due to the high costs of primary materials used for such processes. In the last decade, the development of large-scale Additive Manufacturing in such domains as design, construction and architecture, using various materials such as polymers, metals and cementitious materials has been seen. The near future direction of Additive Manufacturing in construction will be on developing 3D printing prototype setups for bituminous and aggregate/clay based materials.

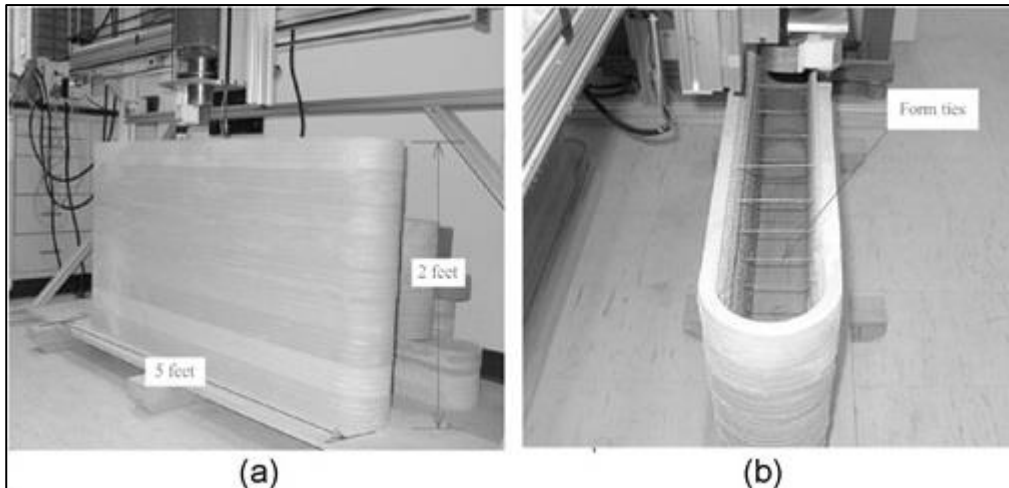
With the advent of driverless construction plant, which have been under development and testing for a while, 3D asphalt printing heads can be mounted on a sensor fitted driverless truck to automatically identify and repair the potholes on the highways network. A 3D asphalt printing project was confirmed to be in the near-future research pipeline by the 3D concrete printing research team and the innovation manager (interviewee no. 9 on Table 1).

### ***Contour crafting***

Contour Crafting (CC) is a fabrication process by which large-scale parts can be fabricated quickly in a layer-by-layer fashion. The chief advantages of the CC process over existing technologies are the superior surface finish that is realised and the greatly enhanced speed of fabrication. The success of the technology stems from the automated use of age-old tools normally wielded by hand, combined with conventional robotics and an innovative approach to building three-dimensional objects that allows rapid fabrication times. Similar to other layered fabrication technologies such as rapid prototyping and solid free-form fabrication, CC uses a computer controlled process to fabricate structures by depositing layers of material, building the structure from the ground up, one layer at a time. However, unlike existing layered fabrication processes, CC is designed for construction of very large scale structures, on the scale of for instance, single family homes up to housing complexes and office buildings.

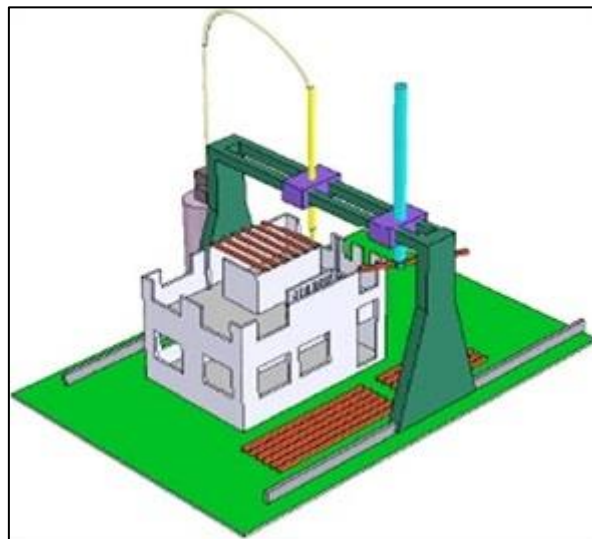
The CC process involves depositing strips/beads of material (typically a thick concrete/paste type material) using an extrusion process. A nozzle extrudes the material in the desired locations. In the original formulation of this system the x–y–z position of the nozzle is controlled by a Cartesian gantry manipulator. As the nozzle moves along the walls of the structure the construction material is extruded and troweled using a set of actuated, computer controlled trowels. The use of computer controlled trowels allows smooth and accurate surfaces to be produced. Because of the highly automated nature of CC, it has the potential to significantly increase the speed and decrease the cost of concrete structure construction. This technique also greatly increases design flexibility with complex geometries that would be difficult to construct using current concrete construction techniques. In addition to automated deposition of concrete-like materials, the system could be modified to allow automated addition of reinforcement materials, plumbing and electrical wiring as the structure is being built.

The CC process is executed as such; firstly, the system creates a 20mm high permanent shutter using a special material, which it later backfills with a cement based compound. Some reinforcement strategies have been demonstrated by hand placing U-shaped tie rods at every 12 inches horizontally and 5 inches vertically (Khoshnevis et al. 2006). Although the CC process is an interesting concept, i.e. the mould is not disposed of and becomes a part of wall, it still requires three separated steps, i.e. moulding, reinforcing and placing concrete and the build layer depth is ~20mm (see Figure 9).

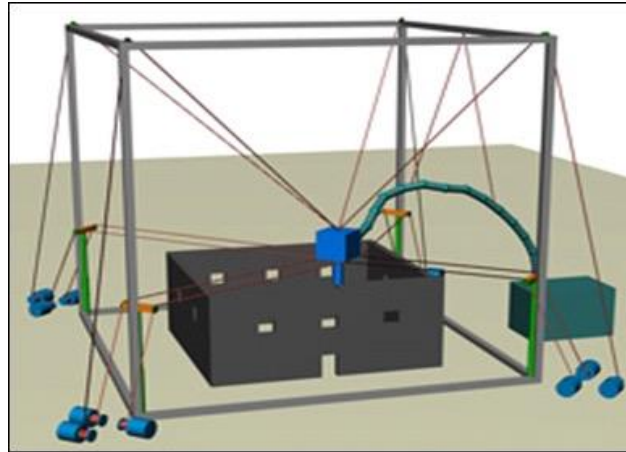


**Figure 9: Mortar based mould created by the CC machine (a) and the ties/reinforcements (b) (Khoshnevis et al. 2006: 308)**

In practice, the CC nozzle and trowels are mounted on a gantry (see Figure 10) for Cartesian motion or on a cable robot supported by adjustable crossbars (see Figure 11). The primary advantage of the cable robot over the gantry is better movement flexibility and abolishing the crane need to build large-scale and large-span objects.



**Figure 10: The CC process on a gantry (Bosscher et al., 2007: 46)**



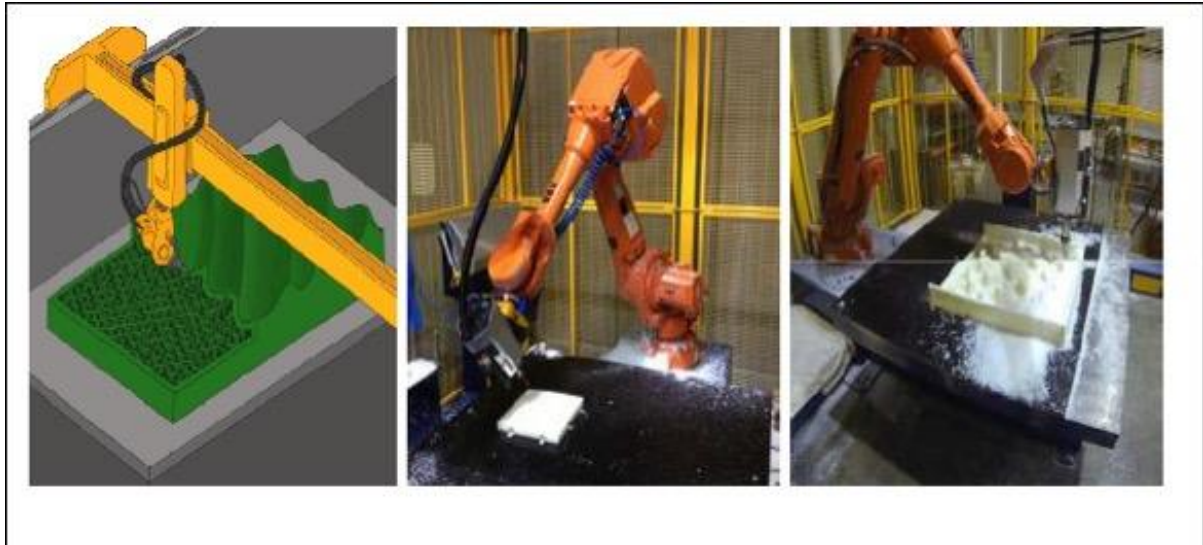
**Figure 11: The CC process on a cable robot with adjustable crossbars  
(Bosscher et al., 2007: 48)**

According to a feasibility study conducted by Bosscher et al. (2007) on a 20 m wide, 0.305 m thick and 4 m tall concrete foundation wall, a cable robot mounted CC process yielded 98 m<sup>3</sup> daily concrete output for the cost of 39 US\$/m<sup>3</sup> with just one foreman; while the production average of traditional concrete structure building methods remained at 77 m<sup>3</sup> daily output for the cost of 40 US\$/m<sup>3</sup>. Considering it has been more than 10 years since the study was conducted, it is expected that the daily CC output figures have improved for lesser costs. Actual scale large-highways civil structures such as buildings, bridges, retaining walls, foundations and refuges may be built by using the CC process and it is worth further investigation for feasibility analysis.

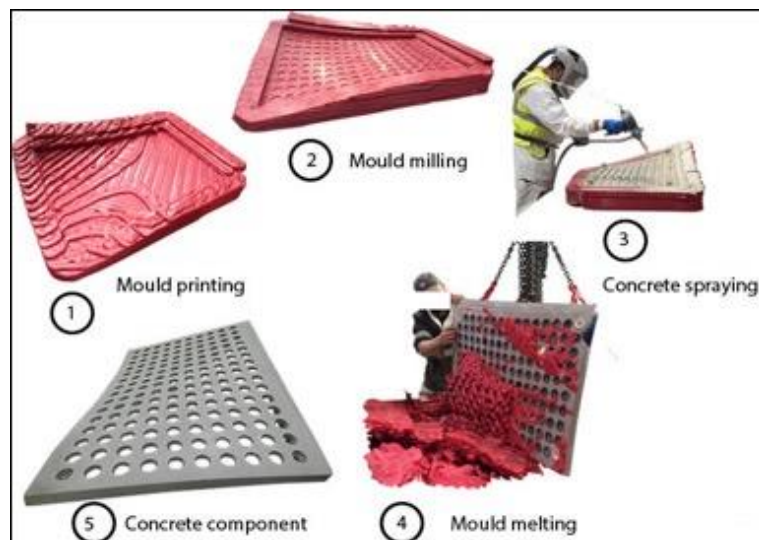
### **3D mould printing**

The mould printing technology combines 3D printing and 5 axis surface milling to deliver a hybrid technology for the fabrication of complex shaped precision moulds for the construction and other industries (see Figure 12). The wax based moulding material can be melted and easily recycled for re-use, which renders the process highly sustainable. 3D mould printing is comprised of the following steps (see Figure 13):

1. Material printing to give the mould its general shape
2. Surface milling for detailing
3. Concrete pouring or spraying on the mould
4. Mould material melting off for recycling and enhanced sustainability
5. Finished concrete based element



**Figure 12: The 3D printing and surface milling elements of mould printing**



**Figure 13: The mould printing process (Freefab, 2017)**

The interviewed off-site construction director (interviewee no. 19 on Table 1) shared a successful use of the 3D concrete moulding technology in manufacturing the glass reinforced concrete linings (cladding) of a station tunnel (see Figure 14).





***Figure 14: Complex-shaped glass reinforced linings (cladding) that were manufactured using the 3D mould printing technology***

The off-site construction director of company Y suggested trying 3D moulding in creating complex concrete mould templates for highways structures like underground gantry bases, chambers and manholes with electro/mechanical service holes already printed on the moulds. The strength of the moulding material should be tested and improved if necessary to ensure the integrity of the moulds during concrete pouring and curing.

### ***On-Site robotics***

One of the common characteristics of today's mass manufacturing sectors (i.e. automotive) is a high reliance on autonomous and semi-autonomous robotics for repetitive tasks. For more than 40 years, the construction industry has been subject to robotics research and application. First construction robots were used in the early 1970s in Japan in order to increase the quality of prefabricated modular buildings. In the 1980s, the first robots appeared on construction sites and since the 1990s, the integrated automated building construction sites concept has been developing (Bock, 2007). Also, wearable robotic-aids for on-site construction and maintenance personnel in the form of exoskeletons have recently been investigated (Bock et al., 2012).

By automation, increased productivity could reduce high labour costs by more than 40% (Bock, 2008). Automated and robotised construction processes lead to a continuous working time throughout the year. It can also present a solution to the industry's acute problems of skill and labour shortages. Introduction of on-site robotics would result in better on-site health and safety performances. The reduction of construction time would improve cost benefit analysis of construction projects due to faster delivery and return on investment. Robots can also be used in multiple projects through their service-life. In short, on-site robotics will bring such advantages; uniform quality and higher accuracy, replacing human operators in repetitive, monotonous and dangerous tasks, increasing productivity and work efficiency.

In this section, a review of the state-of-the art on-site highways construction and maintenance robotics is presented for further consideration of their near-future trial by the highways supply chain.

### ***Robotic highways safety markers for traffic management***

A mobile robotic safety marker system that uses mobile robots to transport safety markers (smart traffic cones) for highway construction and maintenance (Farritor and Rentschler, 2002). The robot units replace the heavy base of a typical safety cone or barrel with a mobile robot; the robots can be piloted by a remote operator, or move autonomously (see Figure 15). The robots work in teams to provide traffic control. Those smart traffic cones hold the potential to save billions of British Pounds every year in losses due to accidents and delays on highways by preventing many maintenance/traffic management related deaths and injuries. Works on increasing the system's reliability, decreasing the per robot cost, and the development of a global control scheme for a group of robots are underway.



***Figure 15: A robotic safety marker unit (Farritor and Rentschler, 2002:1)***

### ***Automated pavement crack detection and sealing systems***

Sealing cracks in roadways ensures a road's structural integrity and extends the time between major repaving projects, but conventional manual crack sealing operations expose workers to dangerous traffic and cover a limited amount of roadway each day. Automated pavement crack detection and sealing systems using cameras, sensors and image processing algorithms have been studied for more than 30 years (Haas et al., 1992; Velinsky, 1993; Cheng et al., 1999). In a more recent field test, an automated pavement crack detection and sealing system developed by the Georgia Tech Research Institute (GRTI) was able to detect cracks smaller than one-eighth-inch wide and efficiently fill cracks from a vehicle moving at a speed of three miles per hour with 83% correct crack identification out of 100,000 images of cracks (Georgia Tech, 2012). The operation requires only one worker to drive the vehicle pulling the trailer where all of the equipment is mounted. With the advent of driverless vehicles, the system can be fully automated (see Figure 16).



**Figure 16: An automatic crack identification and repairing system (Georgia Tech, 2012)**

### ***Emerging on-site robotics for highways***

In this section, emerging and commercially available on-site robotics systems for highways and road construction and maintenance projects are presented.

- Semi-autonomous, remote controlled concrete sawing, demolition, and water based concrete recycling robots (manufacturers/models like Brokk, Husqvarna and ERO),



**Figure 17: A semi-autonomous concrete recycling robot (Haciomeroglu, 2012)**

- Drones for real-time, automatic aerial mapping and surveying of construction sites (manufacturers like Identified Technologies, Skycatch and senseFly),

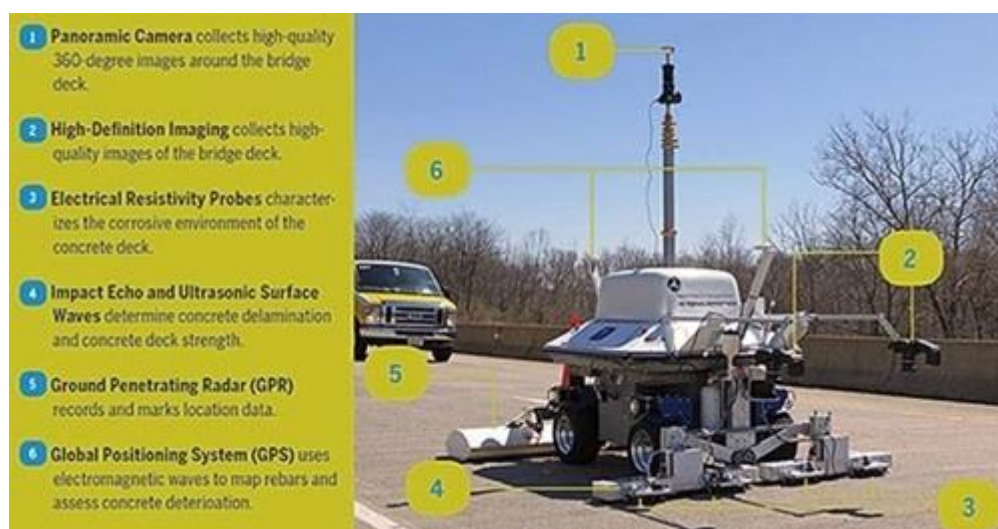


- Concrete or brick paving robots, relieving workers of physically straining work and improving efficiency (manufacturers like Tiger-Stone)



**Figure 18: A concrete paving robot in the Netherlands (Tiger-Stone, 2015)**

- Automatic concrete finishing, troweling and paving robots (manufacturers like Robotus)
- Welding robots (manufacturers like Kranendonk and Kiberys). If their mobility is increased, the robots can be deployed to highways sides for welding connection works.
- Robotic concrete drilling (manufacturers like nLink)
- Non-destructive diagnostic (i.e. testing of watertightness of bridge decks using impulse-response techniques) robots for bridges and other structures (manufacturers/models like InnoTecUK and the Rabbit)



**Figure 19: The “Rabbit” bridge deck assessment tool collects comprehensive data on surface and subsurface deck conditions (FHARaT, 2014)**

### ***Numerically controlled plant***

With their higher-quality – larger output capacities and need for fewer staff, numerically controlled plant may be likened to small-scale manufacturing plants on-site. Numerically controlled earthmoving and grading plant have long been used in highways construction. Similarly, today's road pavers, slip-forming (curbing), concrete placing and spreading, and texture curing plant are equipped with precise control and data collection systems. The main barrier captured from the interviews with respect to numerically controlled plant is the lack of standardisation in practice, meaning despite their benefits, some construction service suppliers still do not use them. The reasons behind this reluctance should be investigated. The client and large suppliers may liaise closer with plant manufacturers to improve and customise the plant's current capabilities. Alongside numerical plant control, plant operators' understanding of their environments has been enriched by integrating digital information onto real-world vision, which is also known as Augmented Reality (AR). In a prototype developed by Talmaki et al. (2010), for instance, excavation operators in a highways construction project can clearly see the location of existing underground utilities in the form of color-coded digital lines overlaid on their front-side camera vision. This Augmented Reality application helped prevent collision of the plant with the underground systems. Also, research and trials in driverless and remote controlled plant have been fast developing. For instance, large-scale driverless plant utilisation can now be seen in the mining industry (Dodgson, 2016) (See Figure 20). In more constrained and controlled environments such as stone/ aggregate quarries or closed road sections, driverless plant for highways operations must be put to test.



***Figure 20: A fleet of driverless trucks operating on a mining site in Western Australia (Dodgson, 2016)***

### **Opportunities for advanced prefabrication and modularisation of highways structures**

#### ***Pavement***

Pavement construction operations are among the most critical in highways projects. Therefore, even incremental improvements in pavement modularisation will induce

many benefits for the supply chain and Highways England. A few important efforts in pavement modularisation and prefabrication will be outlined here for further investigation by Highways England:

### ***Prefabricated bituminous slabs***

The Dutch Ministry of Public Works and Water Management initiated a programme to develop prefabricated bituminous slabs in the early 2000s. Four prefabricated bituminous slab designs proposed by the private sector were constructed and evaluated for functional performance on pilot test sections, while structural evaluation was conducted using the Finite Element Method (FEM) and laboratory research. The mix of research approaches provided sufficient evidence to justify decisions about wider-scale application without the need for 10-15 years of test section evaluation. The evaluations showed that the modular road surface is cost effective and viable (Hugo and Martin, 2004), presenting a pavement modularisation opportunity supported by empirical research and laboratory testing.

### ***Prefabricated plastic slabs***

In 2015, the Dutch company VolkerWessels proposed a recycled plastic based, prefabricated road slab system (see Figure 21). The company announced in 2016 that slab prototypes had been under development to be used by the end of 2017. However, with the exception of a few novelties like the Axion plastic bridge, there is no sufficient research in the area (empirical data), so the company's claims still remain theoretical. Practical issues like structurally strengthening the hollow design of plastic slabs, insulating the seams between modules, health and safety concerns associated with the plastic (i.e. flammability, pulverisation of plastic particles during wear and tear), and unpredictable price for the installation and the maintenance still need to be addressed. However, the idea is promising and worth investigating further to create sustainable, prefabricated road slabs.



***Figure 21: Concept of prefabricated plastic slabs (VolkerWessels, 2015)***

### ***Prefabricated bridge deck sections***

Rapid construction and reduced disruptions for road users are important considerations in the increasing use prefabricated bridge deck sections. Advanced composite bridge decking systems like modular pre-framed steel girders and bent plate box girders integrated with concrete decks are available in the market. Also, highly modular steel-frame panel bridges have been used both as temporary bridges or emergency bridges, and as heavy duty, long-spanning permanent highways or rail bridges. The modular sections are made of interchangeable parts and offer standard lane spans (See Figure 22). Recently, the light-weight fiber-reinforced plastic (FRP), a composite material made of a polymer matrix reinforced with glass, carbon, aramid, or basalt fibers, has been increasingly used in prefabricated deck profiles. Examples of those type of prefabricated bridge decks can be found on the M6 motorway in the UK, B3 highway in Germany or on the New Mile Road Bridge in Cincinnati, USA (Bai, 2013). In precast concrete elements on bridge decks, Ultra-high-performance concrete (UHPC) is a promising new class of concrete material that is likely to make a significant contribution to addressing the challenges associated with the load capacity, durability, sustainability, economy, and environmental impact of concrete bridge infrastructures. The use of UHPC could lead to considerable reduction in the number of girders and girder sizes, and maintenance requirements, and thus decreasing asset life-cycle costs. As of 2013, four highway bridges in France, a highway bridge and pedestrian bridge in Canada, several highway bridges in Australia, Germany, Japan and New Zealand had been designed and built using UHPC (Resplendino and Toulemonde, 2013).



**Figure 22: Modular bridge deck panels with pedestrian way for heavy-duty highways bridges (Mabey, 2016)**

### ***Pre-cast and pre-fabricated structures***

The following suggestions associated with precast/ prefabricated components were recorded from the interviews as opportunities in highways construction. While some of those suggestions have already been widely adopted by the supply chain, some may need further investigation and dissemination.

#### ***Structures that may be prefabricated:***

- Bridge structures like abutments, decks, wing walls, crossheads and piers,
- Vehicle restraint systems with various profiles,



- Concrete drainage chambers,
- CCTV bases,
- Gantry and lighting column bases,
- Cruciform support structures and slabs,
- Underground service protectors,
- Slot drain blocks,
- Concrete stairs,
- Interlocking (Lego-like) wall systems,

#### **Lifting:**

- Using portable lifting cases for vertical and horizontal lifting operations,
- Systematically studying lifting snaps and failures

#### **Structure sliding:**

- In constrained spaces or in bad weather conditions where using large cranes is not possible, a complete structural system (i.e. a bridge) may be assembled near the installation zone and slid in place on a bentonite bed using large hydraulic jacks over a few days' time. In early 2000s, an overbridge on the A500 near Crewe (UK) was built by using the deck sliding method. There are companies specialised in large structural sliding. It is especially effective in minimising road user impact and closures. Supporting operations like backfilling should be planned in detail. 4D BIM can be used as a standard for increased coordination for such complex operations. See Figure 23.



***Figure 23: A 4000 tonne bridge was slid in its place on a bentonite bed in 76 hours within the A160/A180 Port of Immingham scheme using hydraulic jacks during the Christmas holiday in 2015 (Department for Transport, 2015)***

#### **Other suggestions:**

- More use of precast Wide (W) beams,
- Scaling large structures into smaller sections,
- Extruding curbs and drainage chambers,
- Creating interchangeable structural parts (i.e. headwalls)

## ***Gantries***

Highways gantries seem to have been given special attention to by the interviewees, possibly due to the fact that they are frequently used in highways projects and contain both structural and technological components. The captured suggestions regarding the gantries are:

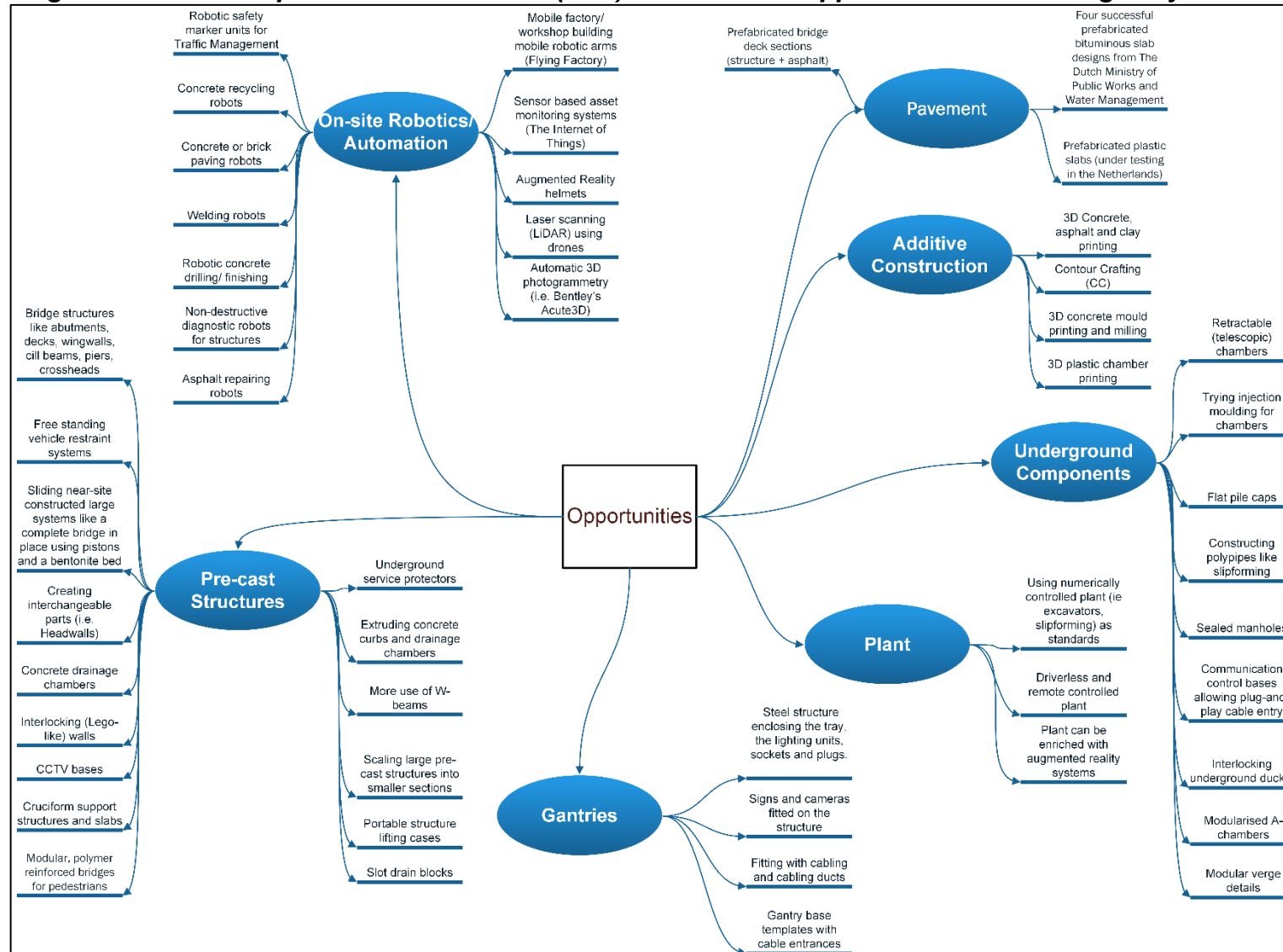
- Steel structures enclosing cabling trays, lighting units, plugs and sockets,
- Signs and cameras fitted (prefabricated) on the structure,
- Fitting gantries with necessary cabling and trays,
- Using gantry base templates allowing cable entrances

## ***Underground systems***

Underground systems were frequently mentioned by the interviewees when talking about the offsite/ modular opportunities for highways construction. The captured suggestions for underground systems are as such:

- Using retractable (telescopic) underground chambers,
- Trying the injection moulding method for the mass production of underground chambers,
- Using flat pile caps,
- Constructing poly-pipes in a similar way to slip forming,
- Sealed manhole designs,
- Using communication control bases allowing plug-and-play cable entry,
- Interlocking underground ducks,
- Modularised A-chambers and verge details

**Figure 24: Mind map for off-site/modular (O/M) construction opportunities for the highways sector**



## Conclusion

Attempting to facilitate the shift from construction to production, this report has focused on two areas perceived to be fundamental to this change. Firstly, the barriers and enablers for modular off-site manufacturing, and secondly, the opportunities to use advanced technologies in different areas of site activity.

In terms of the barriers and enablers for modular offsite construction, this report has identified the areas below as key in the construction to production shift:

- 1) Early design focus on modular offsite, with supporting BIM models, to promote modular offsite.
- 2) Developing the product design and DfMA mindset.
- 3) Appropriate decision support structures to facilitate modular offsite approaches
- 4) Construction processes that promote modular offsite
- 5) Commercial systems that incentivise modular offsite.
- 6) Appropriate project governance to allow modular offsite to flourish

In terms of the opportunities for new advanced technologies in site operations, this report has identified potential for innovation in the following areas:

- 1) Greater use of onsite robotics
- 2) Greater use of additive construction
- 3) Greater use of numerically controlled plant
- 4) Adoption of innovative technologies and off-site/modular construction in specific product areas: pre-cast structures, gantries, underground components, and pavements
- 5) Further upskilling of the engineering/ design workforce

The findings from the study reports some advanced practices both in terms of modular off-site manufacturing (e.g. DfMA) and use of advanced technologies including robotics, BIM, and additive manufacturing, by main contractors and its supply chain to optimize design, assembly/construction, delivery, and maintenance of the built environment. It will also positively impact on functionality, energy performance, aesthetics, construction methods, logistics, and maintenance of the site. The widespread adoption of these advanced practices in the construction supply chain requires significant change in the mindset and behaviors from designers, clients, and main contractors towards Tier 2/3 suppliers to deliver better and greater innovation. Clients requirement for compliance with BS11000 collaborative working standards in future projects may help to integrate the interfaces between parties involved in design, manufacturing, assembly, and construction on-site. BS 11000 provides a framework to develop a collaborative business relationship that may help companies develop and manage their interactions and relationships with other organizations for maximum benefit to all.

Developing collaborative relationships based on trust and mutual benefits is critical to the success of the construction industry. An example of this will be reduced design rework and duplication of efforts between design team and subcontractors with design



responsibilities. The true benefit of digital design using BIM can be realised only when designers and main contractors start using federated BIM model that produce an output in a standard format that can be easily understood by subcontractors at Tier 2/3 levels. The current state of BIM adoption at Tier 2/3 level of construction supply chain is very low. Main contractors need to take leadership to involve, educate and train its supply chain partners to develop their digital design capabilities for promoting DfMA application. Even the true benefits of DfMA and advanced technologies can only be realised when applying collaborative approach along the whole construction value chain to complete projects more quickly and safely, more resource efficiently, and cost-effectively. The combined use of technology with DfMA principles will help in harnessing design rationalisation, effective use of materials, just-in-time delivery, efficient logistics planning that will help to achieve high rates of productivity at site.

This can also address the issues of skills shortage in the UK construction industry as the proposed approaches require less labour for on-site construction or assembly. Nonetheless, there is a challenge of developing the skilled workforce with a broader skill sets in design and technology to meet the demands of advanced technologies in construction sector.

The supply chain is capable of creating innovative off-site/modular systems. However, priorities, specifications and requirements in those systems should be clearly communicated to manufacturers and service suppliers by the client. Construction service suppliers and material manufacturers may jointly design and run in-situ tests on off-site/modular systems. As outlined in the report, there are many off-site/modular opportunities associated with gantries, underground structures, pavement and precast structural elements. Also, the client's leadership seems necessary to create an active community in the supply chain focusing on the adoption of advanced technologies and off-site/modular systems in highways operations. A step to be taken towards that direction may be closer engagement with third party organisations like Buildoffsite. Additionally, off-site/modular related ideas and lessons learned should be collected systematically. Commercial-wise, off-site/ modular systems and constructability may be treated as KPIs, as part of the Project Control Framework. Developing a collaborative decision making system, cataloguing available off-site/modular systems, and a scoping/ benchmarking study to identify off-site/modular opportunities in different sectors and industries will help improve the current decision making. Reviewing the construction method statements and revising/ streamlining the current material approval process were recommended by sector professionals. Challenging the traditional design mind-set for a change toward the product design and DfMA mindset and improving the current understanding on tolerances and interfaces were also found necessary.

The current trend in many industries is extended automation and data exchange in technologies through cyber-physical systems, the Internet of Things (IoT) and cloud computing. In manufacturing, this trend is sometimes called Industry 4.0 and leads to what has been called a "smart factory". Through on-site robotics, additive construction technologies, sensor networks, and numerically controlled plant, opportunities to increase the "smartness" and "automation" are broadening for the highways supply chain as well. The existing high-risk aversion in the supply chain for those systems should be challenged by contractual arrangements, training, case studies - benefit demonstrations and incentivisation efforts by the client and large service suppliers.

Also, further engagement and collaboration with plant and robotics manufacturers, and research institutes to develop state-of-the-art prototypes will be useful to expedite their diffusion. On the other hand, it seems necessary to start thinking about the future roles of redundant workforce and smaller service suppliers, when the human element of on-site construction production and maintenance is replaced by those automated systems, which will happen sooner or later.

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## Appendix

In this section, a detailed transcription of the interviews is presented.

**Table 3: Suggestions to improve the current “manufacturisation” and off-site/modular (O/M) construction practices in the highways supply chain**

| Manager No | Manager Role              | Sector   | Supply Chain Role       | Suggestions to Improve the Off-Site/ Modular Condition in the Highways Sector                                                                                                                                                                                                                                                                                                       |                                                                                                                                                                                                                                       | Notes                                                                                                                                                                                                                                                                   |
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|            |                           |          |                         | Supply Chain Management Suggestions                                                                                                                                                                                                                                                                                                                                                 | Technology/ Technical Suggestions                                                                                                                                                                                                     |                                                                                                                                                                                                                                                                         |
| 1          | Civil Design/ BIM Manager | Highways | Tier 1 Service Provider | 1) A collaborative decision making framework/ process for O/M in the early project stages covering component options, manufacturing, lifting and temporary works. The decision making is down to a few people and largely ad-hoc at the moment,<br>2) Being aware of the latest available O/M systems in other construction sectors,<br>3) Clearly defining O/M ownerships – Who is | 1) Retractable (telescopic), plastic underground chambers to cater for different levelling requirements,<br>2) Injection moulding or 3D printing to produce chambers of plastic, instead of concrete,<br>3) Signs, chambers, lighting | Excessive reliance on design software reduces constructability and leads to missed O/M opportunities.<br><br>The design for manufacturing (product design) mindset is still missing.<br><br>“We (civil designers) do not understand tolerances and interfaces properly” |

|  |  |  |  |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                                                                                                                                                                                                                                                                                                   |                                                                                                                                                                                                                                                                                                                                         |
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|  |  |  |  | <p>to deliver a complete gantry package and manage the different interfaces between the structural and technological components?,</p> <p>4) Simulating the installation process using BIM,</p> <p>5) BIM can also be useful in increasing the O/M collaboration between designers, suppliers and contractors,</p> <p>6) The form of contract is key – the design-build type project delivery system should be preferred,</p> <p>7) Continuous improvement should focus specifically on O/M.</p> | <p>columns, headwalls, panels, beams, modular pieces, gantries are suitable for off-site construction; ducting, cabin technology, drainage chambers can be modularised or produced similar to tarmac or slip forming (on-site factory like production with sophisticated plant- bringing the factory on-site)</p> <p>4) Machine controlled excavation and slip forming should</p> | <p>“We need a detailed, structured, legitimised approach on what should be done or not regarding O/M. You need a process for deciding. A systematic process should be there”</p> <p>“Many different parties are involved in a small TV panel display delivery in Smart Motorways. It is not clear who is owning the whole delivery”</p> |
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|   |                                            |          |                         |                                                                                                                                                                                                                                                                   | <p>be a contractual standard.</p> <p>5) Poly-pipes can be constructed like slip forming,</p> <p>6) Site data collection efforts through laser scanning should be pushed for more data on tolerances and deviations</p> |                                                                                                                                                                                                                                                                              |
| 2 | Structures and Temporary Works Coordinator | Highways | Tier 1 Service Provider | <p>1) Tolerance and interface management requirements for highways components should be better understood (the interface between the in-situ and the off-site),</p> <p>2) For larger components, the temporary to permanent installation transition should be</p> | <p>1) Scaling large-precast parts into smaller sections for easier crange. However, the smaller the parts, the more critical tolerance management becomes (deviations add up quickly),</p>                             | <p>Off-site systems are mistakenly seen as the panacea against all on-site construction challenges. However, large off-site systems (ie. precast beams, girders, parapets) pose their own installation challenges; parapet and longitudinal elements require significant</p> |

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|  |  |  |  | <p>thoroughly thought,</p> <p>3) Build a database of available O/ M systems with their usability configuration matrices and BIM families,</p> <p>4) Construction method statements should be reviewed and standardised for O/ M</p> | <p>2) Studying the opportunities in turning large components into smaller interchangeable parts (i.e. head walls),</p> <p>3) More use of Pre-cast head walls,</p> <p>4) More use of Pre-cast concrete drainage pipes,</p> <p>5) More use of Wide-beams,</p> <p>6) The common lifting point failures should be studied. Portable lifting systems and lifting cases that can be used both horizontally and vertically can be tried</p> | <p>temporary installation systems (supports), logistic challenges, different lifting requirements, space and storing issues, high intolerance to dimensional deviations and tight design tolerances. They are particularly challenging in the interfaces between the in-situ and newly built components</p> |
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| 3 | Civil Design Manager | Highways | Tier 1 Service Provider | <ol style="list-style-type: none"> <li>1) The client should promote innovation in O/M systems by service providers,</li> <li>2) Different people have different ideas about what Design for Manufacture is. Consistency and a systematic approach are needed.</li> <li>3) Publicising some case studies to outline the expectations of the client,</li> <li>4) Integrated team/ contractors/ design team should come together. It is still disruptor. In the development stage and detailed stage. From stage 3 onwards,</li> <li>5) Focusing first on critical path items,</li> <li>6) Large service providers should consider setting up their own O/M production facilities</li> </ol> | <p>“Ad-hoc approach to O/M systems is common”</p> <p>“Nasty incidents with temporary works happen on-site with for example, concrete panels. Constructability should be considered from the very beginning”</p> |
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|   |                 |          |                         | <p>and internal supply chains,</p> <p>7) Just because it is O/M, both on-site and off-site quality control should not be overlooked</p>                                                                                                                                                                                                                                                                                                                             |                                                                                                                                                                                                                                                                                                                                                          |                                                                                                                                                                                |
| 4 | Project Manager | Highways | Tier 1 Service Provider | <p>1) Having a catalogue of available O/M products,</p> <p>2) Developing the BIM library for O/M components,</p> <p>3) Collaborative decision making for O/M systems,</p> <p>4) Logistics and space planning can be overlooked,</p> <p>5) O/M value definition should be reviewed and better understood,</p> <p>6) Design for manufacturability needs to be adopted on a larger scale,</p> <p>7) Earlier involvement of service providers in the design process</p> | <p>1) Building large, complete structures near the site (i.e. bridges) and sliding in place over 2 days using pistons on a bentonite sliding bed – a robust technique that eliminates the need for craneage or risks like windy weather etc ,</p> <p>2) Extruding concrete drainage chambers and curbs,</p> <p>3) Using 4D BIM (3D+schedule) for the</p> | <p>“Many individual components are already manufactured off-site. They can be combined to build modules”</p> <p>“The decision for O/M still mainly comes down to the cost”</p> |

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|   |                 |          |                         |                                                                                                                                                                                                                                                                                                                                                                                       | <p>communication of O/M systems,</p> <p>4) Using drones and the LiDAR for surveying (point cloud) and tagging items for asset management and operations</p> |                                                                                                                                                                                             |
| 5 | Project Manager | Highways | Tier 1 Service Provider | <p>1) O/M suppliers would welcome more contact with designers and main contractors,</p> <p>2) Early involvement of contractors, suppliers, manufacturers in the design process,</p> <p>3) A catalogue of available and approved O/M systems,</p> <p>4) The client may have a preferred suppliers or partners list that will be willing for early involvement to help with the O/M</p> | <p>1) Reinforcement bar cages,</p>                                                                                                                          | <p>No systematic O/M decision making mechanism.</p> <p>Constraints (i.e. having to keep the road open or working in short windows) lead people to thinking innovatively in terms of O/M</p> |

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|   |                             |          |                         | decision making                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                                                                                                                                                          |                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
| 6 | Structural Designer         | Highways | Tier 1 Service Provider | <ul style="list-style-type: none"> <li>1) Tolerances and interfaces between O/M components and in-situ systems should be considered,</li> <li>2) A tight coordination and control of O/M manufacturers both on-site and off-site,</li> <li>3) Innovative thinking should be encouraged,</li> <li>4) Complete system thinking of a structure (i.e. bridges) for O/M is missing – from the substructure to the top,</li> <li>5) A catalogue of available and approved O/M systems</li> </ul> | <ul style="list-style-type: none"> <li>1) Flat pile caps</li> <li>2) Lego mentality in bridges (interlocking) from the foundation to the deck</li> </ul> | <p>Decision making is largely ad-hoc and based on few people's past experiences at the moment.</p> <p>Tight contractual conditions (i.e. design-construction executing in parallel) often times push people to thinking innovatively for O/M</p> <p>Overmodularisation can be problematic on-site due to bringing down tolerances with the existing/ in-situ structures and conditions. On-site teams should also be left with some flexibility</p> |
| 7 | Production Engineering Lead | Highways | Tier 1 Service Provider | <ul style="list-style-type: none"> <li>1) Reviewing and increasing flexibility in the current</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                   | <ul style="list-style-type: none"> <li>1) Lego blocks (interlocking concrete)</li> </ul>                                                                 | <p>People are constrained by Highways</p>                                                                                                                                                                                                                                                                                                                                                                                                           |

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|  |  |  |  | <p>material/ component approval process,</p> <p>2) MCHW (standards for highways) and design for roads and bridges are dated and need either be relaxed or updated,</p> <p>3) The specifications need to be less prescriptive to give room for innovation,</p> <p>4) Health and safety benefits of O/M systems should be better highlighted to promote those systems across the supply chain. The health and safety card is very powerful,</p> <p>5) Being careful about overdesigning components,</p> <p>6) Collaborative decision making for O/M systems will be useful around a decision making template,</p> <p>7) A catalogue of</p> | <p>blocks),</p> <p>2) Precast CCTV bases,</p> <p>3) Plastic, modular technology chambers clipping together,</p> <p>4) Precast slot drain blocks,</p> <p>5) Fitting or a plug-and-play system for gantries</p> <p>6) Use of precast stairs as opposed to construct in-situ,</p> <p>7) Using precast concrete channels as a soil retaining solution,</p> <p>8) Precast service protections like cable protection blocks, markers etc</p> | <p>England's specifications and standards.</p> <p>Excessively bureaucracy like the "CE" mark requirement slows down the adoption</p> <p>O/M systems are more of a logistical operation than construction</p> <p>Procurement and installation costs of large concrete precast systems are very close to in-situ construction; however, they bring additional benefits like reduced time, risks and better health and safety, and quality.</p> <p>Large precast systems allow for night time operations as there</p> |
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|   |                                       |          |            | <p>standard designs for O/M,</p> <p>8) Improved design standardisation,</p> <p>9) Learning from the army as to O/M systems</p>                                                                                                                                                                                                                                                     |                                                                                                                                                                                                                                                  | <p>is no concreting; which helps with programme execution and traffic disruptions</p> <p>We are far from design standardisation. For example, there are many different designs for sing or gantry bases.</p> |
| 8 | Senior Process Improvement Consultant | Highways | Consultant | <p>1) Being clear about O/M specifications, priorities and requirements,</p> <p>2) Having an idea capturing template for O/M systems for project personnel,</p> <p>3) Involving manufacturers in on-site prototypes and experiments,</p> <p>4) Having a database of available O/M options,</p> <p>5) Simplification and streamlining the material/ component approval process,</p> | <p>1) Communication control bases allowing direct cable entry with a plug-and-play type of cabling system</p> <p>2) New Jersey profile, precast, free standing vehicle restraint systems with tension bars</p> <p>3) Sealed precast manholes</p> | Ad-hoc innovative idea capturing for O/M systems                                                                                                                                                             |

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|   |                    |                            |                         | 6) Using standard forms for innovation/operations efficiency                                                                                                                                                                                   |                                                                                                                                                                                                                                                                                                                         |                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| 9 | Innovation Manager | Infrastructure / Buildings | Tier 1 Service Provider | 1) Pushing automation and robotics through the supply chain through engagement and contractual obligations,<br>2) Removing skilled workers from the repetitive tasks,<br>3) Establishing supply chain schools for O/M, robotics and automation | 1) 3D concrete printing for complex barrier walls, retaining walls and concrete repairs,<br>2) Asphalt printing for automatic pothole repairs,<br>3) Mobile robotic arms for on-site welding/drilling operations,<br>4) Mobile robotic arms to quickly build workshops and temporary facilities near construction sites | Additive construction and robotics hold the potential to bring the off-site construction benefits to on-site operations without having to deal with the logistics and supply chain management challenges of off-site construction (bringing the factory on-site).<br><br>Risk aversion for the automation and robotics is high in the supply chain, due to the initial costs. The client can lead by demonstrating the benefits in pilot areas or projects. |

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| 10 | Lighting/<br>Technology<br>Manager | Highways | Tier 1<br>Service<br>Provider | <ol style="list-style-type: none"> <li>1) Constructability and modularability checks of the designs by third party organisations,</li> <li>2) More whole-life costing and value analysis of the components for O/M decision making (initial costs vs. whole life costs),</li> <li>3) Giving larger work chunks (i.e. all underground works) to a single contractor for better coordination and to overcome the compartmentalisation,</li> <li>4) Build a database of available O/ M systems with their usability configuration matrices,</li> <li>5) A simpler O/M approval process; suppliers will get their approvals from the client once.</li> </ol> | <ol style="list-style-type: none"> <li>1) Modular underground ducting systems – Lego like,</li> <li>2) Gantry base templates with all the cabling entrances,</li> <li>3) Gantries fitted with the cabling and cabling ducts – the steel structure can enclose the tray, the lighting units, sockets and plugs.</li> </ol> | <p>The current design practice is the major issue. The designers have rarely been to the sites, mostly relying on the historic data, traditional design and computer outputs. They do a lot of desktop design, often leading to missed O/M opportunities.</p> <p>There are various modularisation opportunities for the technology components. However, ownership (commercial) of the modularisation is an issue – who is going to deliver the modularised packages as a whole?</p> |
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|    |                     |          |                         | 6) A single point of contact is necessary – an O/ M manager or engineer to be appointed,<br>7) An O/M learning and feedback mechanism should be in place after each project                                                                                                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                         |                                                                                                                                                                                                                                                                                                                                                 |
| 11 | Engineering Manager | Highways | Tier 1 Service Provider | 1) A collaborative decision making framework/ process for O/M,<br>2) Build prototypes and run on-site trials together with the supply chain,<br>3) Focus on the critical path items first for O/M options,<br>4) Obtaining support from off-site/modular specialists (i.e. from the building sector) for new ideas for the highways sector,<br>5) Build a database of available O/ M systems with their usability configuration | 1) Modularised underground A-chambers,<br>2) Modular verge details,<br>3) Combine the underground chamber modules to minimise the excavation footprint,<br>4) Use flexible/ rubber connections to better cater for on-site tolerance mismatches,<br>5) Use portable lifting frames,<br>6) Using robotic | Highways construction often requires installing new components into existing facilities (i.e. underground services, existing/ old highways infrastructure etc). Therefore, the interfaces and tolerance issues between the existing and new components should be paid special attention to.<br><br>Modular items are installed on highways work |

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|    |                   |       |        | matrices                                                                                                                                                                                                                          | <p>arms to print and mill concrete moulds made of wax/plastic. The process is quite sustainable as the wax/plastic can be melted for re-use,</p> <p>7) Abutments, wingwalls, decks, parapets and retaining walls can all be pre-fabricated</p> | <p>sites that are highly “unmodular”. Flexible connections, and field tests and trials are essential in that sense.</p>                                                |
| 12 | Managing Director | Water | Client | <p>1) Developing a O/M catalogue with their usability configuration matrices,</p> <p>2) Instead of designing several times, design once and put it into your design catalogue; then drag and drop from the catalogue into the</p> |                                                                                                                                                                                                                                                | <p>“Product design management – anything that is done more than once can become standard”</p> <p>“Designers can resist the Design for Manufacturability mentality.</p> |

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|  |  |  |  | <p>project,</p> <p>3) Executing part – component-assembly-asset level O/M analyses.</p> <p>4) Encouraging service providers to share their O/M catalogues and databases with each other,</p> <p>5) Creating a forward visibility of the workload for service providers,</p> <p>6) Studying design for manufacturing practices in the aerospace and automotive industries,</p> <p>7) Being able to challenge the existing standards – Risk vs value,</p> <p>8) Reviewing and revising the definition of value to reflect O/M systems broader benefits in projects' whole-life cost, construction/ maintenance time,</p> |  | Operators generally like the end-result" |
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|    |                     |       |        | health and safety benefits etc                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |  |                                                                                                                                                                    |
| 13 | Engineering Manager | Water | Client | <ol style="list-style-type: none"> <li>1) An O/M catalogue with their usability configuration matrices,</li> <li>2) Establishing long-term relations with suppliers,</li> <li>3) Sharing the savings through O/M can be a key incentive,</li> <li>4) Being clear about your O/M specifications and requirements and creating the environment in which the supply chain can innovate. Invite the supply chain in for their ideas,</li> <li>5) Sitting down with asset managers to look at the forward programme for repeatability and talking with manufacturers with the identified opportunities</li> </ol> |  | <p>“There is value in repetition and component standardisation. This approach will be more sensible if those companies come together and share their products“</p> |

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| 14 | Performance Manager | Water/ Highways | Tier 1 Service Provider | <ol style="list-style-type: none"> <li>1) Taking a wider, programme-level approach for O/M decision making ,</li> <li>2) O/M systems and BIM connection should be better established. The first step should be building the O/M BIM libraries,</li> <li>3) A co-located and collaborative decision making mechanism involving project managers, design managers, construction managers and subcontractors,</li> <li>4) Collaborative planning techniques and stepwise improvement should be employed to drive the O/M knowledge.</li> <li>5) Design for manufacturing and design for construction mistake</li> </ol> | <ol style="list-style-type: none"> <li>1) Cruciform support structures and slabs- back to back stacked (Lego like),</li> <li>2) Skid design in the water/plant sector should be studied for underground chambers and technology components in highways,</li> <li>3) High modularisation potential in metallic frame structures (i.e. Gantries),</li> <li>4) Modularised bridge sections with parapets and decks</li> </ol> |  |
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|    |                                                     |                      |                         | proofing should be improved,<br>6) Two critical activities; scanning and cataloguing available O/M options in the market, and systematically deciding on what on-site components can be turned into O/M,<br>7) Getting involved earlier in the design phase,<br>8) Having an after-project lessons capturing and dissemination systems for O/M |  |                                                                                                                                   |
| 15 | Project Director (Mechanical/ Electrical/ Plumbing) | Industrial/ Building | Tier 1 Service Provider | 1) Employing an O/M consultant for large projects for decision making support,<br>2) Having an in-house off-site manager reviewing the project drawings and controlling the O/M supply chain,<br>3) Using O/M related KPIs for the service                                                                                                     |  | “One should not modularise for the sake modularisation. The modularisation effort should be justified through value engineering.” |

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|    |                                                             |                         |                               | <p>providers in their contracts,</p> <p>4) Establishing an O/M school for the suppliers</p>                                                                                                                                                                                                                                                                                                                   |  |                                                                                                                                                                                                                                                    |
| 16 | Project Manager<br>(Mechanical/<br>Electrical/<br>Plumbing) | Industrial/<br>Building | Tier 1<br>Service<br>Provider | <p>1) Having O/M project review/feedback meetings at the end of projects (feeds into project learnings),</p> <p>2) Collaborative value engineering (not just for the cost element but safety, quality and delivery time as well) for O/M systems at the early stages of a project,</p> <p>3) A systematic constructability and modularisability analysis of designs perhaps by 3rd party service provides</p> |  | <p>Being able to affect the design as early as possible. This generally refers to a desire for the design-build type project delivery system.</p> <p>“Constructability” or “Off-site/modularisability” can be turned into a project design KPI</p> |

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| 17 | Managing Director | Infrastructure / Industrial           | Material Supplier (Corrosion protection and monitoring management systems) | <ol style="list-style-type: none"> <li>1) Being clear about your O/M requirements – What are the priority areas?,</li> <li>2) Engaging with leading O/M business organisations more to understand their current capabilities (ie. Buildoffsite),</li> <li>3) Learning from the best practices in similar sectors like the rail sector,</li> <li>4) Build a database of available O/ M systems with their usability configuration matrices</li> </ol> | <ol style="list-style-type: none"> <li>1) Interoperable, open network based structural monitoring, environmental monitoring, corrosion monitoring, traffic assessment, webcams and lighting controls that are compatible with the Internet of Things (IoT) intentions. Parallels can be drawn between those applications in construction and the Industry 4.0 trend in manufacturing .</li> </ol> | Although there are many discussions about and push for O/M in the highways sector, the actual take up is slower than the other construction sectors. The conventional construction mindset is still prevalent. |
| 18 | Managing Director | Infrastructure / Industrial/ Building | Management Consultant                                                      | <ol style="list-style-type: none"> <li>1) The clients should define their O/M performance</li> </ol>                                                                                                                                                                                                                                                                                                                                                 | <ol style="list-style-type: none"> <li>1) Subsurface chamber modules,</li> </ol>                                                                                                                                                                                                                                                                                                                  | "If as a client, you write a performance                                                                                                                                                                       |



|  |  |  |  |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                                                                                                                                                                                                                                                                                              |
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|  |  |  |  | <p>specifications, architecture and interfaces clearly,</p> <p>2) If the clients issue a performance specification, people can come up with different solutions,</p> <p>3) Large supply chain clients should share their O/M specifications with each other,</p> <p>4) It is important that both organisational and physical interfaces are managed,</p> <p>5) The awareness of the real value of and new solutions in O/M should be increased in the supply chain</p> <p>6) Close collaboration is required between permanent works designers, temporary works designers and precast module detailers,</p> | <p>2) Signalling equipment are prime candidates for modularisation. Make the system plug-and-play like,</p> <p>3) Precast concrete beams, abutments, cill beams, piers, crossheads parapets and wing walls can all be manufactured off-site</p> <p>4) Big data analysis will highlight O/M priority areas in the future</p> <p>5) Remote structure monitoring is developing</p> <p>6) Reducing carbon is one of the big agenda items – alkali activated cements</p> | <p>specification, If you define the module architecture and the interfaces, then anybody can develop a package that can do the job”</p> <p>“The off-site world needs to move into a product thinking to drive the efficiencies in my opinion. But the clients can do a lot to help that”</p> |
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|  |  |  |  | <p>7) The Early Contractor Involvement (ECI) form of contract facilitates the establishment an entire project team at an early stage when all parties can bring their expertise to influence the development of a proposal before design concepts are finalised,</p> <p>8) Partnering Workshops can be held throughout the design development process enabling trust to be built in the team leading to the commitment to develop new and radical solutions,</p> <p>9) A document control and transfer protocol should be in place,</p> <p>10) BIM is useful in maintaining the coordination, clash detection, precise design and</p> |  |  |
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|    |                           |                                       |                         | simulation for O/M installation                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                                                                         |
| 19 | Head of Industrialisation | Infrastructure / Industrial/ Building | Tier 1 Service Provider | <ol style="list-style-type: none"> <li>1) Product design mentality should be established,</li> <li>2) A database or catalogue of items available for O/M should be created,</li> <li>3) BIM libraries should be extended,</li> <li>4) Long term alliances with some selected supplier and manufacturer partners,</li> <li>5) Field tests and collaborative prototypes,</li> <li>6) Large construction service suppliers should consider establishing their own O/M facilities and supply chains,</li> <li>7) O/M suppliers should be talking with each other for better site coordination</li> </ol> | <ol style="list-style-type: none"> <li>1) Modularisation of technology components (chambers etc),</li> <li>2) Lego like concrete walls and support structures,</li> <li>3) Plug and play type gantry bases</li> <li>4) Standardisation of the use of advanced plant like numerically controlled plant, vacuum excavators, slip forming plant etc.,</li> <li>5) On-site robotic arms for drilling and welding,</li> <li>6) Driverless construction plant</li> </ol> | Design culture change for product design thinking and manufacturability |



**ART  
DESIGN  
ARCHITECTURE  
HUDDERSFIELD**

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