Technology Working Group

Research Report: Harnessing Technology to Minimise Error

The objective of this research was to investigate how technology can be harnessed to eliminate error. The output of the research is to be used to inform how specific areas of technology can be adopted in eliminating error.

The output of the research was required to identify the key areas that are worth pursuing further, together with appropriate contact details and recommendations for the next stage.

The research was carried out by Paul Trewavas CEng MICE, formerly of Sir Robert McAlpine Ltd.

Executive Summary

The principal areas in which technology can be used to eliminate error, in relation to the five topics identified by GIRI, are summarised as follows:

Offsite Manufacture:
- Checking of prototypes and production units by personnel using currently available software on mobile devices;
- Laser scanning of prototypes and production units for comparison with designs using proprietary software; and
- Collaborative use of BIM across project teams.

It is recommended that GIRI engages with specialists in the offsite sector to investigate opportunities for the use of technology in greater depth.

Standardisation:
- This topic is closely related to offsite manufacture in general, and to error-minimising components. The research has so far revealed little in relation to specific developments and opportunities in this area; **any input from GIRI member organisations' knowledge is requested.**

Improved Construction Processes:

- Software applications to record inspections of work;
- Preventing progress on following activities unless required inspections & tests have been completed;
- Provision of practical, easy-to-understand information for site workers about construction details, accessible on their mobile devices;
- Greater collaboration between design consultants and specialist contractors to incorporate construction details in BIM models;
- Augmented reality applications to facilitate understanding of designs *in situ*;
- Visual aids for site workers derived from BIM models and other software applications;
- Infrared sensing cameras on mobile devices to identify poor insulation;
- Use of laser scanning applications to compare as-built conditions with the design and identify out-of-tolerance elements.

It is recommended that GIRI investigates opportunities for technology to be developed to provide site personnel with easy access to technical guidance directly from BIM models or 2D drawings, and also potential developments to enforce Inspection & Test Plans.

Error-Minimising Components:

- The research has discovered little progress to date in the construction industry.

It is recommended that GIRI tries to establish contacts in the aerospace and/or car manufacturing industries for information on their approach to this topic.

Automation:

- Developments to date have originated overseas, with the only application currently known in the UK being the use of robotics in earthmoving and excavation plant.

It is recommended that GIRI monitors developments and opportunities in this area.

The research has revealed a number of technologies that have the potential to reduce errors in construction processes; however they are all closely related to traditional processes and many of them are reactive, in the sense that they help to identify and record errors that have been made already, rather than being revolutionary and with the potential to avoid errors occurring in the first place.

Introduction

GIRI's Strategy for Change identified four topics for investigation in the area of technology:

1. Offsite Manufacture;
2. Standardisation;
3. Improved Construction Processes;
4. Error-minimising Components.

The Technology Working Group subsequently agreed to add a further topic:

5. Automation.

Note: references in the text are shown thus: [x] and are listed in Appendix 1.

1. Offsite Manufacture

The Government announced in November 2018 that it would favour offsite manufacturing for all publicly funded construction projects from 2019.

It is widely acknowledged that offsite manufacture of elements for incorporation in construction projects of all types results in improved "quality" in a general sense; this is attributed to the manufacture typically being carried out in a factory, using a fixed workforce and under stable environmental conditions. In this sense "quality" means aesthetically & technically acceptable, consistent, predictable products. Developments in computer-aided design permit data to be transferred directly to equipment in the factory capable of processing components with little human intervention. There are also safety benefits to be gained through factory working conditions and the use of automation, in comparison with traditional on-site methods.

The elements produced can range from completely finished "volumetric" units (e.g. forming a complete bedroom unit for a hotel), "pods" for incorporation into buildings (e.g. a complete bathroom), panels used to form walls and floors, through to modules of pipework for installation in a structure as part of the building services. Offsite manufacture for construction projects is not a recent development: bridge components for civil engineering projects and lifts for buildings have for many years been prefabricated for later assembly on site.

In relation to quality in general, Appendix 2 contains quotations from recent interviews with Mark Farmer on the subject of offsite construction, in particular the quality aspects, capacity of the sector, and the varying use of digital technology.

Checking of Design and Offsite Production

The offsite manufacturing process does not necessarily guarantee that elements leaving a factory will be without defects, which could be caused by a systemic error affecting all items in a production run. Causes could be, for example, an incorrect dimension in the design; a dimensional error when setting up the production line in the factory; or an unknown defect in a bought-in component. Such errors can be minimised by thorough checking of prototype units before production starts in earnest. Of course, sufficient time must be allowed in the programme for making prototype units and checking them thoroughly; the risk here is that production pressures are allowed to override the assurance process.

Technology can be used to help the checking process, both for prototypes and production units, although for the latter the process is reactive rather than preventative. For example, checklists on mobile devices can be used (combined with photographic records) [see Improved Construction Processes below, regarding work inspection] and also laser/photographic scanning to check dimensions against the design. [see Improved Construction Processes below, regarding laser scanning.] Remote observation of production by the main contractor is also technically possible.

In the curtain walling and cladding sector “unitised” systems, where elements of the façade are pre-assembled in a factory, are generally accepted to be less prone to defects than “stick” systems that are built up on site from the basic components. Rainscreen cladding systems assembled on site are prone to installation defects in the same way as “stick system” curtain walling. The technologies outlined in the preceding paragraph are equally applicable to this sector of the industry.

Design for Manufacture and Design for Assembly

The risk of design errors occurring should be reduced if project teams use BIM collaboratively and adopt Design for Manufacture (DfM) and Design for Assembly (DfA), approaches that aim to identify, quantify and eliminate waste or inefficiency in product manufacture and assembly. The main principles of DfM/A are:

- Minimise the number of components: thereby reducing assembly and ordering costs, reducing work-in-process, and simplifying automation.
- Design for ease of part-fabrication: the geometry of parts is simplified and unnecessary features are avoided.
- Tolerances of parts: components should be designed to be within process capability.
- Clarity: components should be designed so they can only be assembled one way.
- Minimise the use of flexible components: parts made of rubber, gaskets, cables and so on, should be limited as handling and assembly is generally more difficult.
- Design for ease of assembly: for example, the use of snap-fits and adhesive bonding rather than threaded fasteners such as nuts and bolts; where possible a product

should be designed with a base component for locating other components quickly and accurately.

- Eliminate or reduce required adjustments: designing adjustments into a product means there are more opportunities for out-of-adjustment conditions to arise. [1]

Technology is not essential to achieving the aims of DfM and DfA *per se*, although the approach is one that benefits from the use of technology in terms of communications, design, and manufacturing.

Early involvement of specialist suppliers allows their knowledge to benefit the project, although there is a view that early appointment is made more difficult by current procurement models. [2]

Offsite manufactured units frequently incorporate components that are sourced from specialist suppliers, for example sanitary ware in bathroom pods. Standardisation can reduce risks associated with unproven components, and installation risks can be minimised by careful component design to make assembly in the factory "foolproof". This subject is also touched on in Section 2 Standardisation.

Recent Developments

The US start-up Katerra has recently secured funding for its "vertically integrated, digital manufacturing-led" model for timber panellised construction, principally for residential projects. Whether the vertical integration extends to erection on site is not clear, but the principle of minimising the supply chain fragmentation that exists in most construction sectors in the UK should bring benefits in terms of error reduction, when combined with the use of digital processes. [3]

Berkeley Group has recently announced that it will be building a modular construction factory in Kent.

It is recommended that GIRI engages with specialists in the offsite sector to investigate opportunities for the use of technology in greater depth.

2. Standardisation

Standardised designs have long been used in the building services sector for equipment such as chillers, boilers and air handling units, etc. Equipment suppliers do not manufacture items to the precise duty required by the designer, rather they offer a range of duties and the designer chooses the item of plant that matches the needs of the design. This principle has recently been applied with great success to projects being procured under frameworks in the water sector, where suppliers combine their standard items of equipment as necessary to meet the requirements of new water treatment plants.

- The consultants Bryden Wood have apparently been working for Highways England on the design of gantries for managed motorway schemes and have developed standard designs that can be applied in multiple locations. This has been reported to have drastically reduced design time, although specific information is hard to come by. **Any input from GIRI member organisations' knowledge is requested.**

[See also Section 4 in relation to Component-led Design.]

3. Improved Construction Processes

Site Supervision and Quality Monitoring

Many comments have been made about the demise of the Clerk of Works, who used to be employed by (or on behalf of) the client and who brought long experience to monitoring the quality of work on site and providing advice to contractors on best practice. Technology is unlikely to be able to provide a direct replacement for the Clerk of Works, although remote monitoring of work in progress is possible; this is only likely to be successful if the workforce are supportive and can see the benefits.

Software applications are available for mobile devices that use checklists for inspections of work on site; photographs can be taken at the same time and filed with the completed checklists. This is a useful tool, but it is only a recording device and relies on the knowledge and experience of the user to identify any errors; it is not a replacement for the traditional Clerk of Works. Software applications available for site inspections include Dalux Field (see also below in relation to Augmented Reality) [4], Autodesk BIM 360 Field, iAuditor and Viewpoint Field View (formerly known as Priority1). Other applications such as Revitzo and Zutec are capable of linking inspection results to BIM model objects, which is a beneficial link to the design. [5]

A potential opportunity for reducing errors on site would be an automated way of preventing further progress if an inspection or test required by the Specification has not been completed. Anecdotal evidence suggests that Inspection & Test Plans are not always prepared, which increases the risk that contractual inspections and tests are not carried out. If I&TPs and short-term site programmes can be linked electronically, there might be a way to flag that an activity should not start until a preceding inspection or test has been successfully completed. **It is recommended that GIRI investigates whether technology can be developed to enforce the proper use of Inspection & Test Plans.**

Some main contractors have employed experienced people in Clerk of Works-type roles and have reported improved quality as a result. Complemented by technological aids such as electronic access to design details when on site and recording applications such as the one described above, this should be an effective route to reducing errors in construction.

Miniature digital cameras are useful for investigation of spaces that are difficult to reach, such as ceiling voids.

NHBC Defect Data and Guidance for Homebuilders

NHBC are proactive in identifying areas of concern with regard to quality of construction. They provide member companies with guidance on best practice in design and construction to reduce the risk of defects arising.

NHBC collect data from warranty claims and from its site inspectors about defects and problems encountered in the construction of homes (98% of home owners report some sort of defect to their builder within the first 8 weeks of moving in). The most recent statistics show the top five items (in order of concern) to be:

1. Superstructure – DPCs and trays;
2. Superstructure – cavities and insulation;
3. Superstructure – Fire stopping and sound proofing;
4. First Fix – plaster and dry lining to walls and ceilings;
5. Substructure & Drainage – waterproofing and ventilation.

NHBC's Building Inspectors (effectively Clerks of Works employed by the organisation providing a warranty to the eventual homeowner) hold pre-start meetings with the builder's site manager, using Risk Guides [6] to aid discussion of "key risks" and identify actions to avoid problems arising. During construction, Inspectors carry out site inspections and undertake formal Construction Quality Reviews [7] with the aim of having any non-conforming work corrected immediately; Inspectors' reports feed into NHBC's analysis of data from all housing projects where they are providing warranties.

There is evidence that workers on site are not getting the information they need to construct buildings without defects. NHBC research with workers indicates that they need:

- Simpler drawings that relate to the construction phase ("*Just the dimensions please mate!*")
- Less jargon like BS numbers and codes; this clutters drawings and unless you have access to them is meaningless
- More clarity on how we understand revisions to drawings; stating "general revisions" doesn't help!
- More 3D images.

Many construction professionals will recognise the five areas listed earlier where defects occur most frequently in homebuilding. How might technology be used to reduce the risk of these occurring?

NHBC technical support is available to homebuilders on "key risk areas": "Key risks are complex areas where increased guidance can help get it right first time". They have developed web-based applications that provide easy-to understand information, including

3D and animated illustrations [8]; these can be accessed using mobile devices, so the next step is to link this information to the BIM model (if applicable) and drawings to provide instant access. Can BIM objects include links to web pages where such information is available? Drawings could include QR codes that will link to the relevant guidance or 3D/animated illustration.

Another homebuilding warranty organization, LABC Warranty, also produces technical guidance that should be capable of being linked to BIM models or codes on drawings. [9]

It is recommended that GIRI investigates opportunities for technology to be developed to provide site personnel with easy access to technical guidance directly from BIM models or 2D drawings.

Building Information Modelling

In relation to BIM objects containing installation information (and this example might not be representative of the situation across the whole construction industry) a webpage of the Finishes and Interior Sector (FIS) about BIM for manufacturers [10] contains information about Product Data Templates. Neither here nor in the links from this item does there seem to be any mention of information required for error-free installation. In particular the BIM Task Group's guide "Product Data Definition" (April 2016) appears to be silent on installation requirements being included in product data sets. [Information from the Construction Products Association and the BIM Hub at Reference 11]

The production of two-dimensional drawings from BIM models is not an automated process; much detail still needs to be added manually in order to provide sufficient information for construction. The process therefore relies on people to know what needs to be shown, critically where there are complex areas or interfaces between different types of construction. Therefore, BIM does not provide direct benefits to the constructor in the sense of providing construction drawings that are necessarily any better than those produced before the advent of the technology: there are likely to be many fewer clashes, and dimensions are more likely to be correct, but the level of detail on 2D drawings for construction will be the same as for traditional design processes. Benefits are available through the production of visualisations derived from BIM models, as described under Visualisation Aids below.

Visualisation Aids

Augmented and Mixed Reality is another area where technology can aid understanding of construction requirements. Wearable headsets overlay a virtual model onto what the user can see in the real world. This helps to visualise the design, or the construction process, in the context of the actual site conditions. A video produced by Balfour Beatty gives an example of this [12]. The technique can now be used with handheld mobile devices rather than headsets, with the Dalux Field Twin BIM software [13]

Balfour Beatty use 3D printed models as a communication tool to show how components are put together [14]

Contractors are using visual aids derived from BIM models and other software applications to assist in site planning and show workers the site conditions at various stages of construction. The principal benefit of this is to improve safe working, but computer-generated models can also be used to illustrate details of construction. An example [Appendix 3] is an image of a reinforcement cage, generated from rebar detailing software, that can be used to help workers understand the design and plan the installation of the rebar. Such images are a useful complement to traditional reinforcement drawings, which can be difficult to understand in complex situations.

Attachments are now available for smartphones and tablets that will sense infrared radiation and thus indicate poorly insulated areas in buildings. [15]

Dimensional Checks

Advances in laser scanning are bringing opportunities to easily check that work is being done correctly as it proceeds. Problems can arise on construction projects if elements are built out of tolerance and this is not discovered until later, when following components will not fit properly. An example might be structural steelwork erected out of position resulting in cladding elements not fitting. If the problem is not discovered early then the opportunity to correct the out-of-tolerance member(s) or modify the cladding elements to suit will be lost. The Verity software produced by ClearEdge3D takes laser scan data and compares it with the design model in Navisworks, highlighting any elements that are out of tolerance. If this process is done at regular intervals as work proceeds on site, it can provide assurance that dimensions are under control. [16]

4. Error-Minimising Components

This research has found little to indicate widespread initiatives from manufacturers in developing building or civil engineering components that are designed to only be installed the correct way or in the correct alignment.

Areas where such components would bring immediate benefits, in light of current risk areas in construction, appear to be: wall ties for brickwork and blockwork; DPCs and cavity trays; curtain walling and rainscreen cladding; firestopping; and services connections.

Brickwork and Blockwork

In the wake of the brickwork problems on the Edinburgh Schools project, there is little evidence that wall tie makers have turned their attention to developing ties that can only be installed in the correct way (Ancon say that they are producing ties with minimum embedment markers, but this still relies on the worker to take notice; efforts to discuss this further have drawn a blank). The correct type of wall tie has to be used where sound transmission through cavity walls has to be controlled, which is another area where site processes are critical and a “foolproof” product would avoid errors.

Prefabricated cavity trays are widely available but their successful use still depends on correct procurement and installation, the latter being vulnerable to problems with insulation and cavity drainage.

Curtain Walling and Cladding

In the curtain walling and cladding sector, little thought appears to have been given to avoiding errors by designing components that can only be installed the correct way. There are examples on projects of components being installed upside down so that the essential drainage within the support framework is hampered, and of incorrect fixings being used for pressure plates resulting in gaskets not being properly compressed. Another problem affecting gaskets is that if they do not fit correctly at junctions, the gaps are often filled using sealant with the risk of internal drainage channels being obstructed. Although not an application of technology *per* se, the factory pre-assembly of “stick” system components into larger assemblies offers the potential for reducing errors on site.

Firestopping

Correct firestopping is an area of concern on many projects. Given that the materials used are supplied “in bulk” (sheet plasterboard, insulation, sealants and intumescent products) and they are usually installed in voids of varying sizes, there seems little opportunity for developing products that are guaranteed to fit correctly in every situation. The most effective areas for error-minimisation appear to be in design, selection of products, and installation (where online access on site to construction details and guidance, as mentioned in Section 3, is likely to be a benefit).

Pipework

Contractors have suffered serious problems caused by leaks from pipework connections, where the development of quickly-installed fittings has not been matched by security against leakage. Guidance on correct installation has been ignored and workers have concealed the fact that the connections have not been made properly; often leaks only become apparent later on, in the testing and commissioning phase when building finishes are vulnerable to water and chemical damage. This research has found little to indicate progress in the development of “foolproof” fittings.

Structural Anchors

Following concern about the security of chemical anchors, centred around the cleanliness of holes and correct installation methods, Hilti have developed hollow-core drill bits that clean the hole when connected to a vacuum cleaner and also special bolts for these applications [17].

Component-Led Design

The principles of Design for Manufacture and Design for Assembly, as described in Section 1 of this report, incorporate the need to design components with appropriate tolerances that are capable of being installed correctly in every situation and without the need for adjustment. Component-led Design is a related area, where reliable, proven components are chosen in advance of detailed design. In addition to helping with the aim of reducing the risk of defects, there are likely to be cost benefits by avoiding bespoke materials, and components can also be combined into assemblies under factory conditions to reduce work on site. A potential drawback from the designer's point of view might be a perception that their design freedom is being compromised, especially in a design & build situation where the contractor wants to decide on the components to be used.

It is recommended that GIRI tries to establish contacts in the aerospace and/or car manufacturing industries for information on their approach to this topic, which has not proved possible during the course of this research.

5. Automation

Although it has been under discussion for many years, the application of robotics to mainstream construction is still in its infancy. Automation in bulk earthmoving is well-established, with dozers and graders able to operate using digital data to achieve required formation profiles. This has recently extended to use on hydraulic excavators for work on foundations, drainage trenches, etc. As well as providing better assurance of accuracy, this reduces the need for workers to be within the hazardous operating zone of the excavator.

The Sam100 bricklaying robot has been developed in the USA, which appears effective for large areas of uniform fair-faced brickwork, although it still requires human labour to feed it with bricks and to finish the joints on the exposed face; it is not clear from the videos available online how the cavity is kept clear of mortar. [18]

In Australia the more sophisticated Hadrian X robot is capable of laying blockwork in complex layouts, although it operates with glued single-skin blockwork and the result is not fair faced: surface render, plaster or other finishes are still required. [19]

Much publicity has been given to 3D printed concrete, but again the applications still appear limited. The process involves the extrusion of cement grout in layers, which can achieve complex shapes, but the end products are not structural concrete as generally understood. A small single-storey building has been created in this way in the USA [20] and individual components have been made in China for incorporation into buildings [21]; the technique can also be used to create permanent formwork for foundations, although whether this is an economic application is doubtful given the set-up costs.

A 3D printed bridge was built in Spain in 2017, assembled from concrete reinforced with thermoplastic polypropylene. [22]

It is recommended that GIRI monitors developments and opportunities in this area.

Appendix 1: References and Contact Details

Reference No	Description	Details
1	Design for Manufacture and Design for Assembly	https://www.designingbuildings.co.uk/wiki/Design_for_Manufacture_and_Assembly_(DfMA)
2	Barriers to Innovation in Offsite methods	At the Offsite Management School's Supplier Day held in Manchester on 20 March 2018, a straw poll of delegates showed that the greatest barrier to innovation in the sector was procurement processes (followed by lack of senior leadership).
3	Katerra	https://katerra.com/en/who-we-are/about-us.html
4	Software for recording site quality checks	http://dalux.com/en/dalux-field/
5	Software for recording site quality checks	https://revizto.com/en/ https://www.zutec.com/site/software-solutions/index.html
6	NHBC Risk Guides	http://www.nhbc.co.uk/Builders/ProductsandServices/TechZone/riskguides/
7	NHBC Construction Quality Reviews	http://www.nhbc.co.uk/Builders/ProductsandServices/technicalstandards/cqr/
8	NHBC 3D and Animated Guidance	http://www.nhbc.co.uk/Builders/ProductsandServices/Standardsplus2018/#1 http://nhbccampaigns.co.uk/3D/0/0/1/ https://youtu.be/GLsl6O3mktY
9	LABC Warranty technical resources	http://www.labcwarranty.co.uk/resources/

10	Installation information in BIM models	https://www.thefis.org/about-us/special-interest-forums/bim4fitout/bim4manufacturers/
11	Installation information in BIM models	https://www.constructionproducts.org.uk/news-media-events/news/2017/march/lexicon-a-single-process-for-bim-data/ https://thebimhub.com/2017/11/28/pdt-pds-bimhawk-lexicon/#.WtoCLeSG-70]
12	Augmented Reality	https://www.balfourbeatty.com/expertise/meet-our-experts/?type=trending&videoid=fagZfbohBW0
13	Augmented Reality	http://dalux.com/en/dalux-field/twinbim/
14	3D Printed Models	https://www.balfourbeatty.com/expertise/meet-our-experts/?type=latest&videoid=EogNa8LAWQg
15	Infrared Photography using Smartphones and Tablets	https://www.thermal.com/compact-series.html
16	Verity Software (marketed in the UK by Excitech)	https://www.excitech.co.uk/Products/Verity-construction-verification-software
17	Chemical Anchors	https://www.hilti.co.uk/medias/sys_master/h75/hd3/9130726817822.pdf
18	Robotic Bricklaying (SAM 100)	https://www.youtube.com/watch?v=G_Pj2GI6-xc
19	Robotic Blocklaying (Hadrian X)	https://www.fbr.com.au/
20	3D Printed Concrete Building	http://www.bbc.co.uk/news/technology-43411581
21	3D Concrete Printing in China	https://www.youtube.com/watch?v=SObzNdyRTBs
22	3D Printed Bridge in Spain	https://iaac.net/research-projects/large-scale-3d-printing/3d-printed-bridge/

Contact	Topic	Contact Details
Adam Box, ClearEdge 3D	Verity software for dimensional checks	adam.box@clearedge3D.com
Ian Heptonstall, Offsite Management School	Offsite manufacture	ian@supplychainschool.co.uk
Richard Trevaskis, Georg Fischer *	Prefabricated pipework modules	richard.trevaskis@georgfischer.com
Luke Woodall, Metsec *	Error-minimising components	luke.woodall@voestalpine.com
Robert Pannell, NHBC	Construction quality processes at NHBC	rpannell@nhbc.co.uk
Simon Kitchingman, Ancon *	Error-minimising components	skitchingman@ancon.co.uk
Sean Wilkins, Brick Development Association	Workmanship & design standards	seanwilkins@brick.org.uk
Martin McGuire and Campbell Brown, Careys Civil Engineering	Visual Aids derived from software applications	0208 900 0221
Dr Luke Whale, Staircraft Ltd	QR codes on components, linked to installation information	luke.whale@staircraft-ltd.co.uk [see https://staircraft-ltd.co.uk/innovations/enhanced-labelling]

* Limited direct benefit to the research

Appendix 2: Quotations from interviews with Mark Farmer about Offsite Construction and Quality.

Mark Farmer interview with Design Building Wiki (9 February 2018) [ref]
Offsite manufacturing obviously gives speed, which is partly what housing associations want, but if that could be combined with certainty of quality then the housing association and also the Build to Rent sector could prove to the wider market that, with the advance of technology and BIM enablement, offsite means something different from perhaps even 5 years ago.

Mark Farmer interview with UK Construction Online (5 February 2018) [ref]
Also, some of the issues relate to the perception of pre-manufactured or what has historically been termed 'pre-fab'. In the housing market there is still a perception of what 'pre-fab' represents linked to poor quality, temporary type housing rather than what it can be now – truly permanent, 21 century precision engineered manufactured components. The recent quality problems experienced in traditional delivery also call into question the long held beliefs that artisan trades can deliver a better solution.

and

There is a great opportunity to address what is a growing concern about traditional construction quality, particularly in the housebuilding sector. We have a seen an increase in media interest in poor delivery quality in the housebuilding sector over the past six months. I believe there are a lot more stories to come that you will find pretty shocking about how traditional construction, poor workmanship, design and supervision have contributed to a sub-standard product that wouldn't be acceptable in any other industry. The clear challenge and opportunity for offsite and pre-manufacturing is that if you are going to use fully precision engineered, digitally enabled techniques of assembling products, ensuring ultra tight tolerances, interface working, that can absolutely overcome all the issues and risks you have with onsite materials and workmanship assembly. The biggest risk is that the emerging offsite sector replicates some of the problems that the traditional industry is experiencing. If we had a situation where too much demand was placed on too small a supply of capacity in the offsite sector, it is likely mistakes would be made. That is the big risk constraining what is a potential opportunity. There's also big difference in some of the solutions out there in the offsite sector. Some of them are fully digitally enabled, high tech and underpin quality; others aren't that dissimilar from traditional working but just done in a factory environment. Absolutely, the offsite sector has an opportunity to embrace high quality and be seen as a byword for better quality than traditional but it also needs to learn from the problems traditional industry has had and grow sustainably with the Government's help.

Appendix 3: Image of Reinforcement Generated from Rebar-Detailing Software (Courtesy of Careys Civil Engineering)