GIRI RESEARCH

Get It Right Initiative

THE USE OF TECHNOLOGY TO REDUCE ERRORS IN DESIGN AND CONSTRUCTION

RESEARCH REPORT

October 2023

CONTENTS

THE PURPOSE OF THIS REPORT IS TO CONSIDER WAYS IN WHICH TECHNOLOGY CAN HELP REDUCE ERRORS IN DESIGN AND CONSTRUCTION; TO SUGGEST SOME OF THE SOLUTIONS THAT CAN HAVE THE MOST IMPACT; AND TO ADDRESS SOME OF THE BARRIERS TO THEIR ADOPTION.

EXECUTIVE SUMMARY

GIRI's definition of an 'error' is 'any action or inaction that results in a requirement for re-work, a requirement for extra work, or produces a defect'. (A 'defect' is any failure to meet the project requirements at a handover.) Errors can occur across the whole construction lifecycle: from upstream processes, for example raw materials and manufacturing through to construction, commissioning and handover. An important category of error for consideration in this report is errors in information and data.

GIRI's *2016 Research Report* identified and ranked 17 root causes of error, the top three of which were: inadequate planning, late design changes and poorly communicated design information.

In March 2023, the C-Tech Club published a *Catalogue of Construction Technology Types* that listed 31 categories of construction technology along with a definition of each and example technology providers. The C-Tech Club is a global community of 370 founders of construction-tech start-ups in 30 countries.

We considered the GIRI root causes of error alongside the C-Tech Club construction technology types to determine which categories of construction technology are most likely to help reduce the most important root causes of error. This suggested eight categories of construction technology that may best support error reduction.

We developed this analysis further through discussions with asset owners, contractors, design consultants and start-ups themselves. This produced a more granular and detailed list of the types of technology that can help with error reduction.

These are: checking technology; automated generation systems; workflow engines; visualisation systems; collaboration tools; communication systems; computer vision; IOT sensors; document management systems and digital setting-out tools.

The table on the next two pages summarises each of these types of technology, how each may support error reduction and some example technology providers. These are, of course, just examples: there will be many other categories of technology that support error reduction, along with many other technology providers.

It is also clear from both our own analysis and discussions with contributors to this report that the successful adoption of technology relies on a variety of human, cultural and behavioural factors. The successful adoption of digital tools and technology is made up of a combination of communication and collaboration; capabilities and skills; standards and processes; strategy and governance; and technology and data. As one contributor observed: "the technology itself is only a small part of the challenge. The major part is the people and their motivations. You can never get someone to do something that they don't want to do."

This report is intended to serve as a catalyst for discussion across the GIRI Technology Group, the C-Tech Club and beyond. There is considerable potential for better adoption and implementation of current technologies to reduce error; there is also the opportunity for new technologies to be developed with an error-reduction use-case in mind.

TABLE OF TECHNOLOGIES THAT CAN CONTRIBUTE TO ERROR REDUCTION

TECHNOLOGY TYPE	SUB-TYPE	WAY IN WHICH ERROR MAY BE REDUCED	EXAMPLE TECHNOLOGY PROVIDERS
CHECKING TECHNOLOGY	BIM checkers	Identifies incorrect or omitted design information, allowing early correction of errors	• Solibri • Autodesk Model Checker
	Schedule checkers	Identifies inconsistencies and risks in project schedules	• Nodes & Links • Schedule Reader
	Data checkers	Identifies incorrect or omitted project information, allowing early correction of errors	• Glider Technology • Morta
	Checklists	Pre-empts errors by clarifying roles and avoiding human mistakes	• CONQA • Datamyte
AUTOMATED GENERATION TECHNOLOGY	Design configurators	Designs automatically according to rules, avoiding human error	• Testfit • Hypar • Spacemaker (Forma) • SiteSolve (Vu.City) • Digital Blue Foam • Archistar • Laing O'Rourke Bridge Configurator
	Automated scheduling systems	Produces schedules automatically (before optimising them), based on recipes and production rates, avoiding human error	• ALICE Technologies

TECHNOLOGY TYPE	SUB-TYPE	WAY IN WHICH ERROR MAY BE REDUCED	EXAMPLE TECHNOLOGY PROVIDERS
WORKFLOW ENGINES		Captures and manages processes, avoiding errors between steps	• PROCURE PRO • Archdesk • Applied Experience • ProTenders • Simple Construction
VISUALISATION SYSTEMS	Virtual Reality (VR) and Augmented Reality (AR)	Supports collaboration and greater precision between design models and on-site working	• Fologram • Argyle • XYZReality • RealWear
	Digital rehearsals	Allows teams to practise tasks before undertaking them on site	• Rehearsive • AsBuiltDigital
COLLABORATION AND COMMUNICATION TOOLS		Allows tasks to be co-ordinated better, improving interface management	• Symterra • Letsbuild • CoConstruct • Mobilus Labs
COMPUTER VISION		Allows work undertaken to be captured and checked automatically	• GenieVision • Buildots • Openspace • Contilio
IOT SENSORS		Allows real-time data collection from sites to be monitored to avoid rework later	• Ynomia • Zerokey
DIGITAL SETTING-OUT TOOLS		Links live layout information from the field to digital models	• Dusty Robotics • Rugged Robotics • Tiny Mobile Robots
DOCUMENT MANAGEMENT SYSTEMS		Improves version control document review, and document coordination	• Qualomate • Shapedo

1. INTRODUCTION

1.1 Purpose and context

GIRI was born out of the statistic, gathered from research in 2015/16[1], that 21% of construction project turnover is wasted on avoidable error. Among its objectives is to undertake research to identify, evaluate and prioritise the principal systemic errors in the construction process; and to develop a strategy to address these errors. The better use of technology to reduce or eliminate errors aligns with these aims.

GIRI is already looking at how technology can be used to reduce error. It has a Technology Working Group, which produced a *Technology Research Report*[2] in May 2018. This covered five areas: offsite manufacture, standardisation, improved construction processes, error minimising components and automation. Back in September 2019, GIRI also produced a report[3] on *Barriers to Digital Adoption.*

This report is intended to consider, at a general level, the types of technology that may best contribute to error reduction, along with examples of relevant technology providers and observations on the practical issues and barriers to the successful adoption of the technology.

1.2 What is meant by 'error'?

GIRI's 2016 Research Report defines an 'error' as:

> **ANY ACTION OR INACTION WHICH RESULTS IN A REQUIREMENT FOR RE-WORK, A REQUIREMENT FOR EXTRA WORK, OR PRODUCES A DEFECT.**

A 'defect' is any failure to meet the project requirements at a handover. It is therefore important to note that error reduction is different to and distinct from other improvement initiatives – for example initiatives to improve productivity or reduce over-design.

1.3 What is meant by 'construction technology'?

There are many definitions of construction technology.

The US Construction Industry Institute (CII)[4] defines it as:

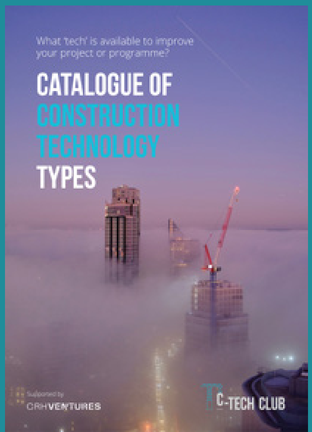
> **"...THE COLLECTION OF INNOVATIVE TOOLS, MACHINERY, MODIFICATIONS, SOFTWARE, ETC. USED DURING THE CONSTRUCTION PHASE OF A PROJECT THAT ENABLES ADVANCEMENT IN FIELD CONSTRUCTION METHODS, INCLUDING SEMI-AUTOMATED AND AUTOMATED CONSTRUCTION EQUIPMENT."**

To that definition we add design and other pre-construction activities that impact on construction productivity and are an inherent part of the process.

[1] Get It Right Initiative – Improving Value by Eliminating Error – Research Report -Revision 3 April 2016 – available at: https://getitright.uk.com/live/files/reports/3-giri-research-report-revision-3-284.pdf
[2] Get It Right Initiative – Technology Working Group on the use of technology to reduce error – available at: https://getitright.uk.com/live/files/reports/6-1805-get-it-right-technology-report-216.pdf
[3] Get It Right Initiative – Barriers to the Adoption of Future Digital Engineering Technology – available at: https://getitright.uk.com/live/files/reports/8-giri-ucl-barriers-adoption-future-digital-engineering-technology-1-452.pdf
[4] https://www.construction-institute.org/resources/knowledgebase/knowledge-areas/construction-tech

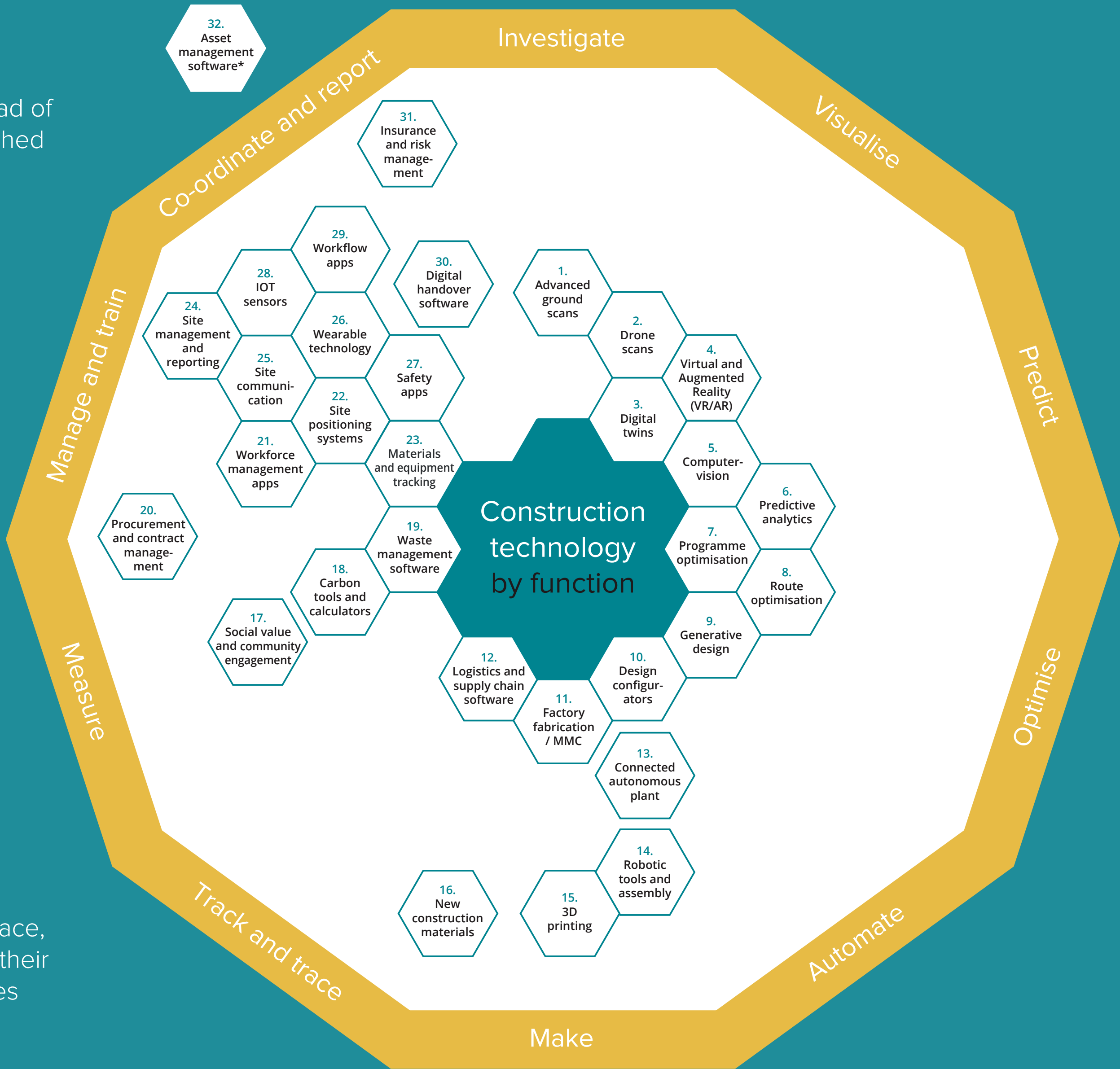
However, beneath this overarching definition lies a myriad of tools, techniques and technologies – some well-established and others new and rapidly evolving.

To help bring some clarity as to what is meant by 'construction technology', in March 2023, the C-Tech Club published a *Catalogue of Construction Technology Types* (or 'contech') that listed 31 categories of construction technology along with a definition of each and example technology providers.



This is best illustrated in the form of a 'map' that identifies the 31 types of construction technology, plus an additional 32nd type that covers asset management software. The technology types are arranged around ten activities that construction technology supports.

That is to say that contech helps people investigate, visualise, predict, optimise, automate, make, track and trace, measure, manage and train, and co-ordinate and report their design and construction projects. Some of these activities will be more relevant to error reduction than others.



*Strictly speaking, Asset Management Software is not a type of construction technology, but it is included for completeness.

1.4 Maturity and value in technology adoption

In parallel to the development of this report, GIRI has commissioned research from consultancy Origin7 into whether technology is helping to reduce errors out on site. The purpose of the Origin7 research is to find out which technologies are being used on projects to ensure that clear, concise and correct information is easily accessible on site.

We have drawn upon the Origin7 work in the development of this report. In particular, insights that have been particularly relevant to our work include the following:

- The five technology types that more than 50% of respondents had adopted on site to help reduce errors in construction were: digital data capture tools for QA forms for example; BIM software; photo capture; digital setting out equipment (total station); and drones/UAV.

- The five error reduction technology solutions that respondents would like to add to or improve on their projects were: digital forms for inspection and test plans, or quality check sheets; communication tools for staff to increase awareness of existing technology; laser scanning, GIS technology, robotics etc; implement a digital collaboration tool; and implement a document management tool.

- The four main reasons (cited by more than 40% of respondents) for resistance to adoption of technology within a construction project were; employee resistance to change; cost to implement new technology solutions: incorrect skillset or insufficient training; and understanding of the value of technology to improve efficiency/ productivity etc.

We were pleased to have had the opportunity to discuss both the findings of the Origin7 report and this report with the Origin7 team.

[5]The C-Tech Club is a global community of 370 founders and CEOs of construction technology start-ups (www.c-techclub.org)
[6]https://www.c-techclub.org/wp-content/uploads/2023/03/v16-C-Tech-Brochure-A4.pdf

1.5 Purpose of this report

The purpose of this report is to consider ways in which technology can help reduce errors in design and construction; to suggest some of the solutions that can have the most impact; and to address some of the barriers to their adoption.

We are not intending to evaluate the benefits (relative or otherwise) or appropriateness of any type of technology. This will depend on the requirements of the project at hand as well as the way in which it is implemented. Nor are we making recommendations about particular technology providers – although, since we wanted to make the report as practical and useful as possible, we have included examples of software and other vendors under each category of technology, where appropriate.

1.6 Contributors to this report

We are grateful to the following organisations that contributed directly to the development of this report through interviews and otherwise:

APPLIED EXPERIENCE (www.appex.ch)
ARUP (www.arup.com)
ATKINS (www.atkinsglobal.com)
CONQA (www.conqahq.com)
FOLOGRAM (www.fologram.com)
GBUILDER (www.gbuilder.com)
GLIDER TECHNOLOGY (www.glidertech.com)
KIER (www.kier.co.uk)
LAING O'ROURKE (www.laingorourke.com)
MCGEE (www.mcgee.co.uk)
MORTA (www.morta.io)
MULTIPLEX (https://www.multiplex.global)
NODES & LINKS (www.nodeslinks.com)
PLANRADAR (www.planradar.com)
PROCUREPRO (https://www.procurepro.co)
PROTENDERS (www.protenders.com)
QFLOW (www.qualisflow.com)
QUALOMATE (www.qualomate.com)
SENSAT (www.sensat.co)
SHAPEDO (www.shapedo.com)
SIMPLECONSTRUCTION (www.simpleconstruction.app)
SYMTERRA (www.symterra.co.uk)
THINKPROJECT (www.thinkproject.com)
XINAPS (www.xinaps.com)
YNOMIA (www.ynomia.io)

2. METHODOLOGY

2.1 Project lifecycle

We can break the construction lifecycle down into eight steps as follows:

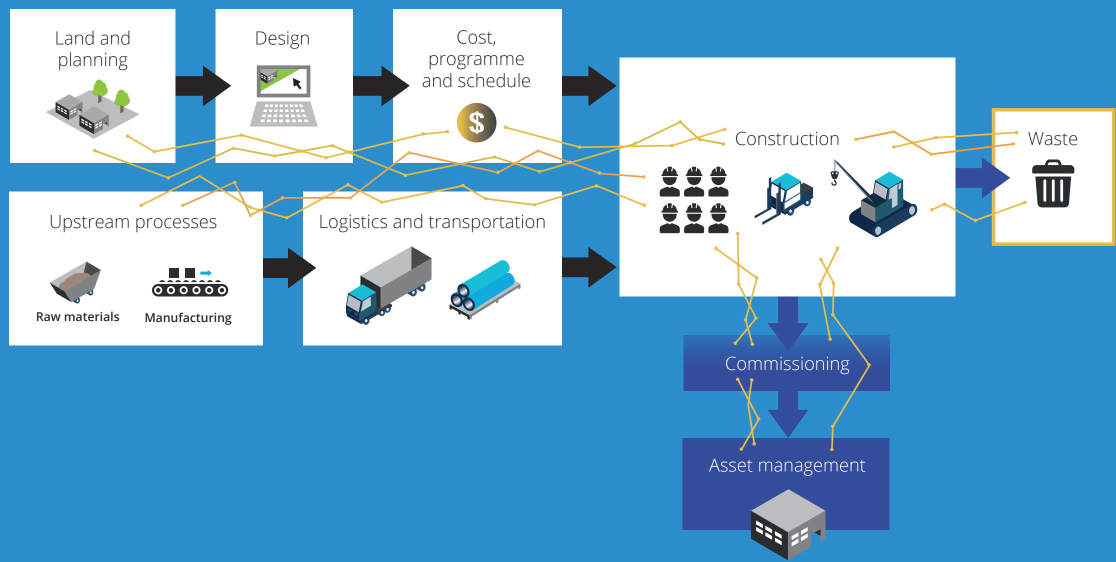
- **Upstream processes** such as the production of raw materials (e.g. quarrying) and the manufacturing of components;
- **Logistics and transportation** to convey the raw materials and components to site or between factories for further fabrication;
- **Land and planning**, which includes land acquisition and the planning processes inherent in securing development permission whether via Development Consent Order, Hybrid Bill or otherwise;
- **Design**, by which we mean the combined architectural and engineering choices at increasing levels of detail so as to envision and specify the project;
- **Cost, programme and schedule**, i.e. the other non-design-related preconstruction development work;
- **Construction**, whether full construction on site or factory-fabrication and assembly on site;
- **Waste management** to secure the efficient removal of surplus and redundant materials from site; and
- **Commissioning and handover** to represent the process by which the main contractor releases the site to the end-user with the proof that everything has been reviewed and approved.

The important task of asset management to manage and maintain the operational asset while it is in use strictly falls outside the set of construction processes, but is clearly a very important, linked and adjacent activity.

To these eight construction steps, we should add a ninth. Specifically:

- **Information and data**, that is the preparation, assurance and transfer of information about the project within each construction stage and between those stages. Increasingly, information and data are becoming the ‘glue’ that connects the project together. They also support effective appraisal of the success of the project and learning and improvement between projects.

There is the potential for errors within and between all nine of these construction steps, although the nature of these errors will differ considerably, just as the construction steps themselves are distinct and varied.



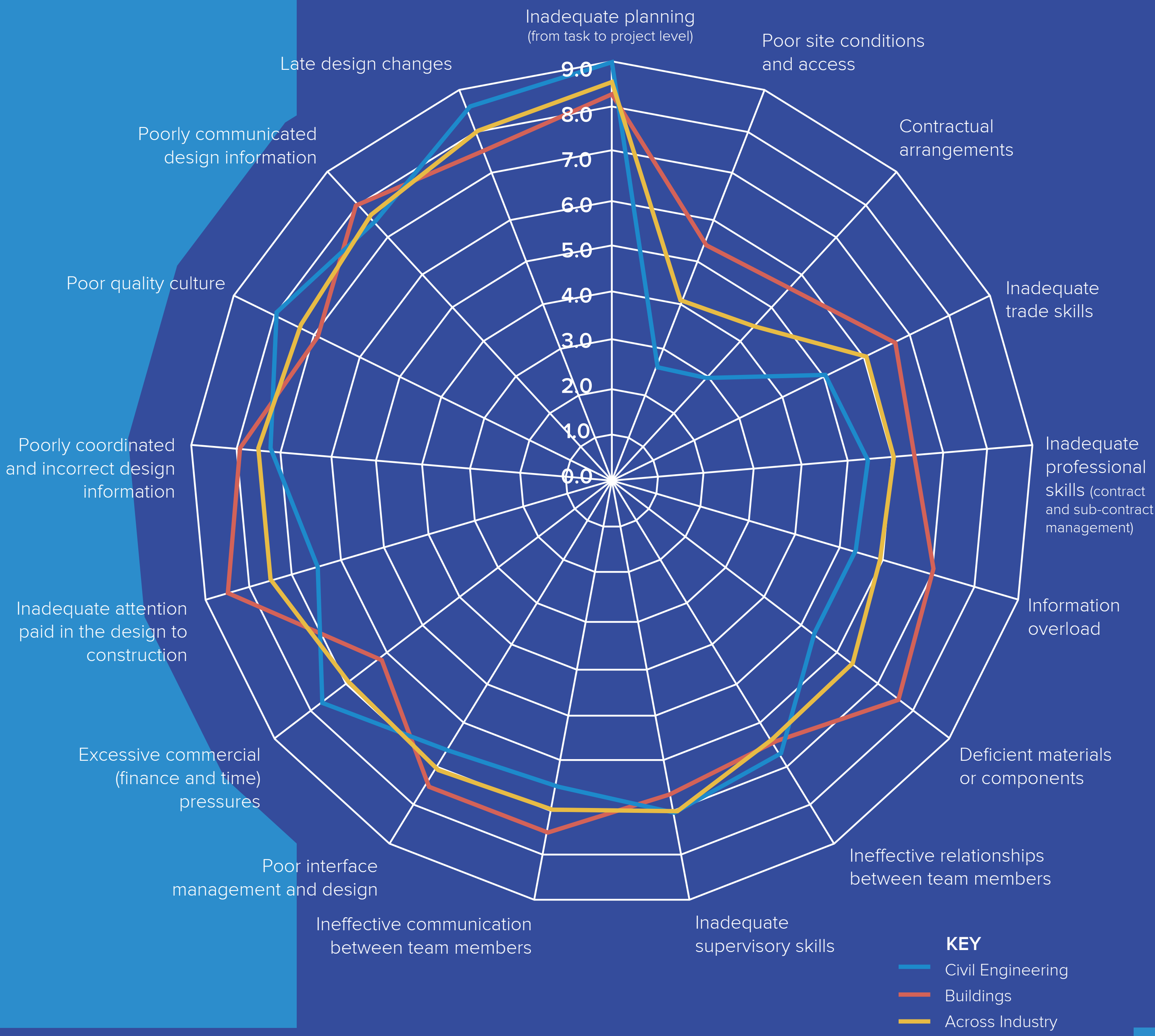
2.2 Errors across the project lifecycle

In 2016, GIRI produced a *research report* on improving value by eliminating error. The research team used a 'Grounded Theory Method' to collect and analyse information on error in the UK construction industry, the causes of error and the methods used for avoiding error. The analysis of the data collected identified the areas of work in which error is financially most significant, the financially most significant causes of error and the most effective methods for avoiding error and minimising the consequences of error.

The graphic on the right, taken from the report, shows the 17 most prominent root causes of error, ranked by importance. The top three were: inadequate planning, late design changes and poorly communicated design information.

These are a very useful input into our analysis of the potential for technology to help reduce errors: if technology can help address the root cause, then it seems likely that it can also help reduce or eliminate the errors themselves.

ROOT CAUSES OF ERROR
AVERAGE VALUES ASSIGNED



2.3 Root causes by construction stage

The root causes are linked to specific construction stages to a greater or lesser extent. As different technologies (and technology providers) are applicable at different stages of the construction lifecycle, it is beneficial to consider which root causes apply at each construction stage (including information and data).

What this demonstrates is that many of the root causes are present, to a strong or partial extent, in multiple construction phases. While the root causes may be strongest in the design phase, their impact is likely to be most strongly felt during construction. We may therefore also expect the technologies that are most relevant to error reduction to operate most commonly in and around the construction phase.

The table below shows the extent to which each of the 17 GIRI root causes impacts each of the construction phases. A solid circle indicates a significant link, with a semi-circle showing a partial link.

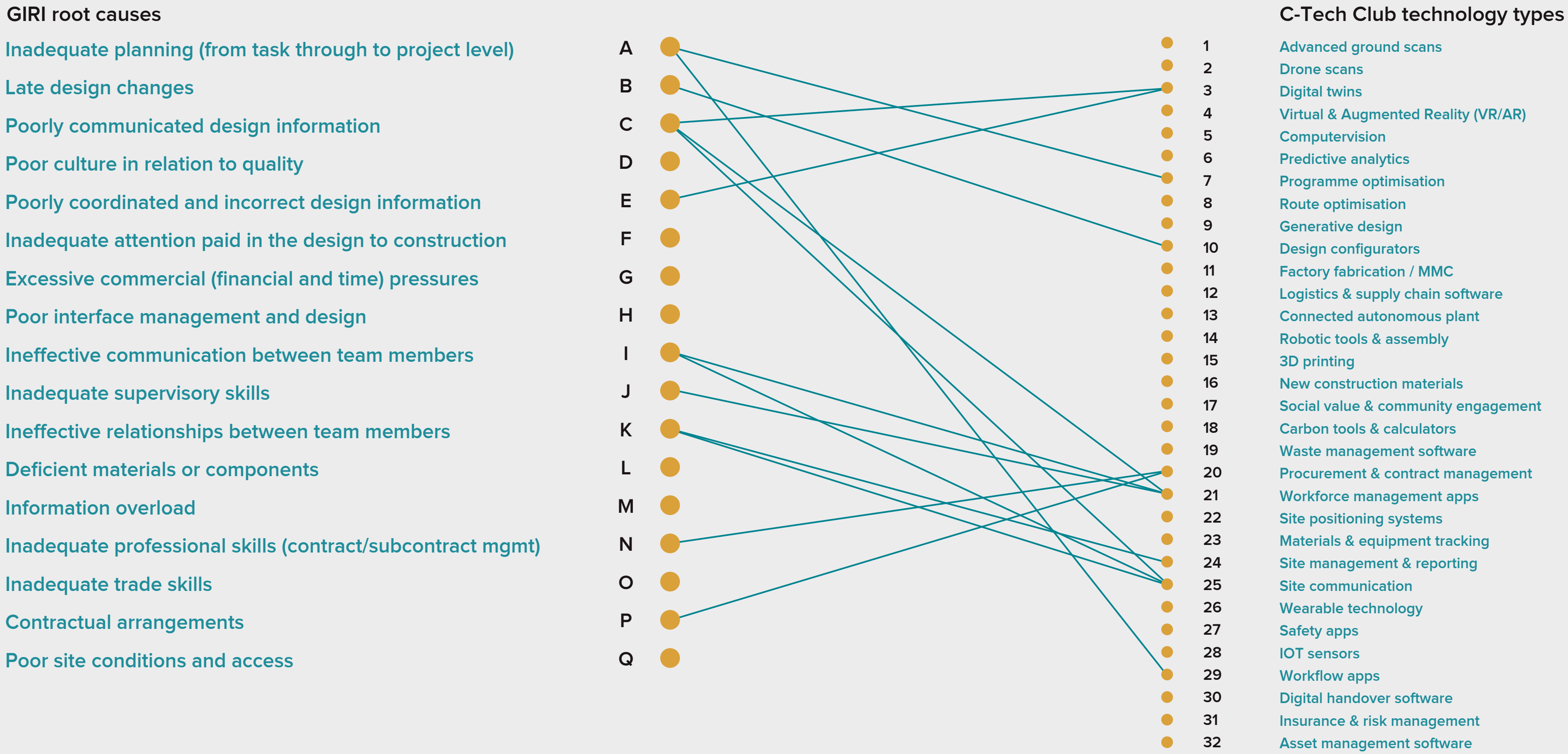
	Inadequate planning (from task to project level)	Late design changes	Poorly communicated design information	Poor culture in relation to quality	Poorly co-ordinated and incorrect design	Inadequate attention paid in design to construction	Excessive commercial (financial and time) pressure	Poor interface management and design	Ineffective communication between team members	Inadequate supervisory skills	Ineffective relationships between team members	Deficient materials or components	Information overload	Inadequate professional skills (contract/sub-contract mgmt)	Inadequate trade skills	Contractual arrangements	Poor site conditions and access
UPSTREAM PROCESSES	◖			◖			◖	◖	◖	◖	◖	●	◖	◖		◖	
LOGISTICS & TRANSPORTATION	◖			●			◖	◖	◖	◖	◖		◖	◖		◖	●
LAND & PLANNING	◖		◖	◖	◖		◖		◖		◖		◖	◖		◖	◖
DESIGN		●	●	●	●	●	◖	●	◖	◖	◖		◖	◖		◖	
COST, PROGRAMME & SCHEDULE	●	◖	◖	◖	◖	◖	◖	●	◖	◖	◖		◖	◖		◖	
CONSTRUCTION	●	●	●	●	●	●	◖	●	◖	●	◖	●	◖	◖	●	●	●
WASTE MANAGEMENT	◖			◖		◖	◖	◖	◖	◖	◖	●	◖	◖	●	◖	◖
COMMISSIONING & HANDOVER		◖	●	◖	●		◖	●	◖	◖	◖	◖	●	●		◖	
INFORMATION & DATA			◖	◖	●		◖		◖	◖	◖		●	●		◖	

● Root cause and construction phase linked ◖ Root cause and construction phase partially linked

2.4 Linking root causes with construction technology types

Next we have mapped the 17 GIRI root causes with the 31 C-Tech Club construction technology types to consider which technologies are most likely to be able to address the root causes. Eight technology types emerge as the most relevant: digital twins, programme optimisation, design configurators, procurement and contract management, workforce management apps, site management and reporting and site communication.

It is clear, however, that while this is a good general guide to where the best technologies for error reduction may be found, we need to drop down to a more specific and detailed description of the technologies (and the way in which they contribute to error reduction) for this to explain the connection between technology and error reduction in the most useful way. This is why we expanded on this analysis through discussions with asset owners, contractors, constructors, technology vendors and start-ups.



2.5 Discussions with design firms and contractors

To develop further the analysis in sections 2.1 to 2.4, we undertook structured interviews with asset owners, contractors, consultants and technology providers both established vendors and start-ups. We also consulted the C-Tech Club widely and invited suggestions on the types of technology that could contribute to error reduction. The organisations we spoke to are listed on page 11.

The methodology for the interviews is set out below: it is made up of two complementary sets of questions. These questions, however, were only a guide to the discussion and many conversations were more freeform and more useful and interesting as a result.

TYPICAL QUESTIONS FOR ASSET OWNERS, CONTRACTORS AND CONSULTANTS

What can you tell us about the frequency and nature of errors? What are the types of errors and the root causes that you most frequently see?

Do you recognise the root causes in the GIRI study and which are most relevant to you?

Do you recognise the eight categories of construction technology that the work above suggests may be of relevance to reducing errors?

What can you tell us about the frequency and nature of errors? What are the types of errors and the root causes that you most frequently see?

Have you come across/would you be interested in adopting any of the individual technology solutions mentioned in this report? (see Section 3)

How mature are you in terms of your ability to implement technology?

TYPICAL QUESTIONS FOR TECHNOLOGY PROVIDERS (ESTABLISHED SOFTWARE VENDORS AND START-UPS)

What is your view on errors. Is this a use case that you recognise? Is this something that your software/technology firm is aiming to help manage, mitigate and reduce?

Do you recognise the root causes in the GIRI study and which are most relevant to your technology or tool?

What has your experience been of selling/marketing your software to contractors and design firms to try to reduce errors? What have the barrier to adoption been?

Which stage of the construction process (and which part of the supply chain – asset owner, tier 1, tier 2 etc) would be most relevant to the reduction of errors/adoption of your technology to reduce errors – and why?

What other suggestions can you make about who else in the supply chain is developing technology to reduce error?

THE MAIN OBSERVATIONS FROM THESE DISCUSSIONS WERE AS FOLLOWS:

COMPLEXITY

- The design-construction 'system' is very complicated and interconnected. This means that any particular intervention, such as the adoption of a particular piece of technology, is likely to be of limited effectiveness. The technologies most likely to be successful are therefore either those where a particular individual process is digitised or a whole system is transformed.
- Consultants noted that technology is often seen by design teams as an opportunity to increase the complexity of designs and volume of data rather than produce better, clearer, less error-prone information to the contractor.
- Collaboration technology is often used as a way to visualise an increasingly chaotic situation, whereas in the past efforts would have been made to eliminate the chaos. One example given was that Common Data Environments (CDEs) now allow individual drawings to be submitted for approval. In the past, submittals would come as part of a larger, coordinated package that provided design context. It is often very difficult to understand the fragmented information being submitted as part of any coherent whole, especially against tight contractual return timeframes. This increases the possibility of errors being approved on drawings.
- Contractors noted that increasingly complex projects and project requirements can lead to feeling that technology is just a way to keep up with project demands rather than improve quality of delivery. The current increase in projects requiring building refurbishments and reuse of existing elements was highlighted as an area where information quality was inconsistent across projects between new and existing elements.
- It is often difficult to understand the assumptions underpinning contech solutions, and a perception is that too often users deploy them without tailoring them to the realities of the project.
- Main contractors highlighted the interface between different sub-contractors as a key area of potential error. Technologies that can avoid or reveal clashes and gaps and communicate these and the underlying package assumptions are a key area for focus.
- The potential for technology to introduce new sources of error was mentioned, with an example given where foundations constructed out of position when a 'intelligent system' moved them to follow another element. The importance of understanding underlying assumptions and providing the necessary layers of checking was highlighted.

PEOPLE AND CULTURE

- The technology itself is only a small part of the challenge: the major part is the people, culture, behaviours and motivations. As one of the engineering consultants we spoke to said, "You can never get someone to do something that they don't want to do." Part of this is generational: younger workers are more inclined to adapt and change, and to embrace new ways of working.
- Much of BIM and digital engineering is seen as theoretical and disconnected from the way things are done on site. There is a suspicion about the reliability of the data received from further up the design supply chain.
- Several interviewees flagged the limited 'bandwidth' teams had for adopting innovation and new technology. One contractor spoke of 'initiative fatigue'. Site teams are rapidly pulled together when a contract is won and very quickly have to begin work to tight deadlines. As a result, it is often perceived as easier and safer to revert to conventional systems rather than risk adoption of better, new, technology in a live project environment, even if it could help to reduce error. Since consultants' staff are often office-based, it was easier for them to innovate compared to a contractor's project teams which are often dispersed geographically.

CURRENT PRACTICE

- Conversations about quality and health and safety are both site- and project-wide concerns. However, since health and safety is a legal requirement with severe penalties for non-compliance, quality and errors may be seen as a secondary consideration due to the different and arguably lower set of consequences. Minimising cost and time are seen as being of direct benefit to the project teams on site and hence quality can be seen a 'minimum' or pass/fail requirement.
- Some noted that contractors simply do not know what their error rates are, or have reliable processes for measuring them. This creates difficulty for quality champions who are trying to make the case that money needs to be spent on technologies or otherwise to reduce errors. Two contractors gave examples of how they are trying to gain better visibility of these issues through digital reporting and central management dashboards.
- There is often a disincentive to measure and record errors. Although everyone in the industry privately accepts that errors occur continually, no one wants to admit that they occur on their own projects, out of concern for potential consequences for themselves, their team or legally for the company.

PROCUREMENT OF PROJECTS

- Parts of the supply chain are rewarded for errors and their rectification and hence that is a disincentive to change.

- There is a mismatch of incentives between client and contractors, that is, there is no incentive for the contractor to help avoid errors. Because of this, clients are often not presented with the opportunity and/or information to make good decisions at the right time. They are also often not aware that they need to do so for the project to run smoothly.

- While clients are aware of the need for quality, they often ask the wrong questions when appointing a contractor: for example, they ask whether a quality system is in place, to which all contractors can answer 'yes'. They tend not to ask for evidence that the quality system works, and for information on error rates and resultant costs on similar previous projects.

- Main contractors can see the benefits of using a 'model first' approach before construction start and some are asking all their subcontractors to provide construction level models to allow early coordination between packages. Data standards are defined by the main contractor, one noting "we're being very dictatorial". However, sub-contractors working for several main contractors reported that they will work to different data standards depending on who wins the main contract. This presents an added complexity, as they need to work in a different way to conform not only with the main contractor but also with the trades lower down the supply chain.

- A consultant noted that procurement strategies involving future innovation from the client to the contractor's team could lead to incomplete information being issued in the belief it could be completed later. This led to the potential for change, error and contractual problems as it blurred the contractor's scope definition.

PROCUREMENT OF TECHNOLOGICAL SOLUTIONS

- The asset owners look to the contractors and consultants to innovate; and the contractors and consultants will only do what the asset owners want them to do and will pay for.

- Procurement is a significant challenge to the purchase and adoption of construction technologies by asset owners and by contractors on their behalf. Where a technology is novel, there may be only one realistic supplier, but clients are very reluctant to undertake 'single tender actions'. Construction technology start-ups can find the bidding process frustrating and a number have given up trying to sell to public sector clients, preferring private sector clients such as oil and mining companies instead.

- In a fragmented marketplace, there is a limit to how many pieces of technology a large contractor is prepared to invest in, support and impose on its teams. There is a sense of fatigue at the number of different potential solutions being offered and the lack of coherence and integration between them.

SKILLS AND LEARNING

- There is considerable variation in the ability to produce useful data across trades. One main contractor highlighted façade packages as an example of a data-rich subcontractor type, as they were already using this information to coordinate manufacturing across their internal supply chains. At the other end of the digital scale were blockwork subcontractors who have traditionally mainly been a supplier of labour, working from general arrangement drawings authored by the architect and specifications from the engineer.

- There is limited learning across and between projects and production rates at the end of the project are often the same as at the beginning. The same may well be true for error rates. Manufacturing is much better at using 'learning curves' to improve performance over time while construction repeats the same problems over and over again.

- Other than in highly regulated fields such as nuclear, it was felt that there was a reduced emphasis on traditional engineering skills such as checking and specification writing. Instead, the focus was more on using technology to be more creative and to push the design boundaries further.

- Consultants voiced concern that as yet there was no consensus on how checking skills need to evolve in response to new technologies. "How do you check a 3D model?" remains unanswered after nearly 20 years. It was felt that post-Covid hybrid working practices had accelerated the tendency of younger engineers not to have a feel for the drawings and the drawing set. This was particularly evident when they encountered requirements for 'wet' signatures and carbon copies still required by some public bodies.

- Members of the new BIM/digital engineering teams have been drawn to the industry by the technology and need to pick up a lot of skills from designing, drafting and checking, as well as working within a BIM and virtual environments. "They must be totally overwhelmed" was one comment. The loss of checking skills in an older generation of CAD leaders, who have a more established construction or engineering background was mentioned by several interviewees as a reason for there being a less informed and less systematic approach today.

- Artificial intelligence is seen as a powerful new tool, but it was felt that the skills necessary to use it effectively and safely will need to be developed rapidly to avoid new sources of error. The importance of a user constantly acting as reviewer to interrogate and focus solutions was noted.

OPPORTUNITIES

- The Building Safety Act is giving a new impetus and rigour to the use of information and data. The legal requirements on 'dutyholders' and the concept of the 'Golden Thread' will require better traceability of the work done. This is likely to lead to better use and collection of data across the supply chain. The Golden Thread requirements and scope are currently quite narrowly focused on life-safety, and the post-Grenfell aim should be to produce a succinct set of documentation that is coherent and useful in the future.

- Material passports were highlighted by a consultant and a contractor as a new technology area that can be of benefit, allowing carbon, material source, ESG and quality data to become more traceable. However, it was recognised that there is not yet clarity on their form and how this is going to work.

- Scanning and VR were mentioned as very powerful by both consultants and contractors. 'Digital rehearsals', 'digital builds' and 'model-first design' were terms mentioned. A main contractor emphasised that the model was now no longer just part of the original design received, but was regarded as a live document. They were using weekly photographic site scans to produce comparative models that could analyse whether a service duct had been correctly positioned or a service penetration was installed incorrectly. This was flagging and eliminating future costly delays on site.

TAKEN TOGETHER, THESE DISCUSSIONS AND FINDINGS HAVE HELPED US INFORM THE LIST OF TYPES OF TECHNOLOGY THAT CAN HELP WITH ERROR REDUCTION BEYOND THE MORE HIGH-LEVEL LIST IN SECTION 2.4. WE ARE GRATEFUL TO ALL THOSE WHO CONTRIBUTED TO THE DISCUSSIONS.

“

THE TECHNOLOGY ITSELF IS ONLY A SMALL PART OF THE CHALLENGE. THE MAJOR PART IS THE PEOPLE AND THEIR MOTIVATIONS. YOU CAN NEVER GET SOMEONE TO DO SOMETHING THEY DON’T WANT TO DO.

Interviewee

2.6 Discussions with technology providers

Interestingly, a significant proportion of technology providers, in spite of offering technologies that have been shown to reduce errors, and agreeing that most errors are preventable, felt that technology in general was not well placed to reduce errors in the industry. This feeling arose principally from an observation that quality was down to the expertise being brought to bear on the project (e.g. good design, good processes, good communication, experience of other similar projects etc.) and the quality focus of the people employed on the project (including attention to detail, sufficient time to do the job properly, ensuring correct materials and information available etc.). They felt that no amount of technology could persuade a project team that was going to do a mediocre quality job either through lack of expertise or lack of care to do a better one. This is, effectively, noting the importance of attitudes, culture and behaviours on the adoption of digital tools, a theme we return to in Section 4.

This group equally felt that technology might also enable roles to be performed faster, or with a lower skill set, and those savings would likely be applied to improve the financials and/or timeline of the project, rather than the quality. This led them to comment that, whilst their products could assist in reducing errors and in some cases were originally conceived for that purpose, technology purchasing decisions were generally made due to other benefits that the products delivered – specifically around time and cost. That is to say that error reduction is not a significant factor in most purchases today; nor is it likely to be in the future.

The main observations from these discussions were as follows:

CURRENT PRACTICE

- Overall the industry does not value its data. It is often fragmented between departments, stored in silos, lost and then rediscovered, and stuck in spreadsheets. It is hard for technology companies to persuade their clients to extract value from the data they already hold and to appreciate how powerful data science and analytics can be.
- There is a lack of experience among quality managers in how to introduce software systems and get buy-in from the organisation. Because of this, some technology providers sell a package of services alongside their software to help set it up, deploy it and integrate it into existing processes in the organisation.
- Many companies have invested significant sums in internally-built tools that do not work well and fail to deliver the intended benefits. Because of the investment made, they are reluctant to let go of them and replace them with better commercial alternatives which would require them to admit to these internal failings.
- Technology often needs to be sold to multiple stakeholders and contractors on the same project because it is not clear who is responsible for quality. This makes sales cycles long and expensive. Getting agreement from all of the relevant stakeholders to adopt a technology is often fraught with competing agendas, and frustrated by staff turnover.
- Some IT departments are over-protective of data or misunderstand regulations around data security and privacy e.g. citing GDPR, where actually no personally identifiable or sensitive data is being handled in the public cloud. There were suggestion that an industry agreed standard software as a service (SaaS) contract could solve this.

TECHNOLOGY

- Great user experience design is key to success. Products must be instantly understandable and usable with little or no training required.
- Reducing friction with IT departments made adoption easier. For this reason, many products found success by being delivered via a SaaS model on the public cloud, and integrating with existing processes via web and email.
- Overall, technology was adopted best when it was promoted willingly ('virally') by employees, rather than by products being mandated by senior management.
- Unsurprisingly, products that embed seamlessly in current processes were seeing greater adoption than those that seek to change processes more fundamentally. The drawback with this, is that the opportunity for this bigger change is not being taken. We are "paving the path to the cow-shed", as one participant put it, rather than being more radical.
- Some technology providers have highlighted the importance of data ownership. Providing good mechanisms for customers to download their data and integrate with other systems – for example, the development of APIs and the creation of open standards.
- Some technology products seek to pool and mine data, sharing the results between customers as part of their proposition. This could include pooling and sharing information about errors. However, technology providers have found that the transparency this generates is not always welcome. Clients may not like to be told that they are underperforming against their peer group.
- There is a frustration among some technology providers that potential buyers often overestimate the need for excessively high accuracy in their digital processes (e.g. sub-millimetre accuracy), yet at the same time do not possess sufficiently accurate or complete data sets to feed to those processes.

3. TECHNOLOGY TYPES

In this section we consider the types of construction technology that can make a difference to error reduction, along with the way in which they are able to do this. We also give some examples of technology providers within each category.

3.1 'Checking' technology

The first category of error-reducing technology covers systems that can check data and information to look for errors, inconsistencies or omissions. Model checking has proven to be a successful technology to verify requirements and design for a variety of real-time embedded and safety-critical systems. It requires a language for writing requirements and design that has well-defined semantics.

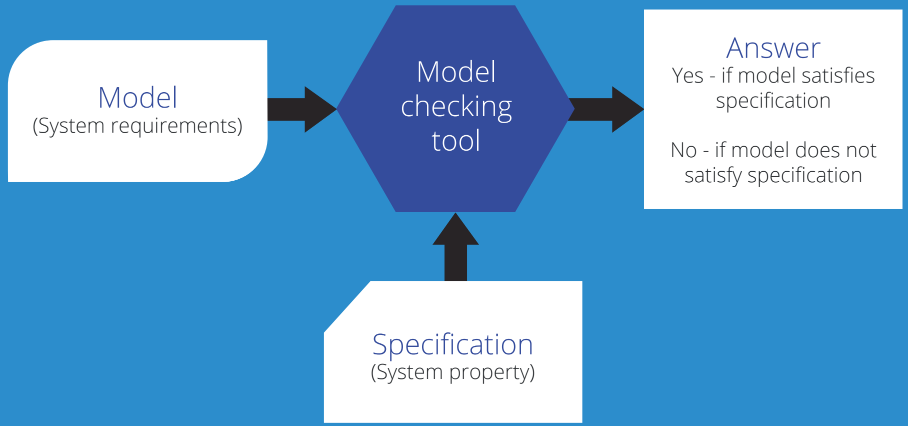


Figure - the model-checking approach

A model-checking tool accepts system requirements or designs (called models) and a property (specification) that the final system is expected to satisfy. The tool then outputs 'yes' if the given model satisfies given specifications and generates 'no' if it does not. The 'no' response details why the model does not satisfy the specification, so by studying this the user can better understand the source of the error in the model, correct the model and try again. With each iteration, the model becomes more 'correct' and the user's confidence in it increases.

There are some parallels between this process and the standard automated testing process adopted by the software industry (known as Test Driven Development). In this, 'tests' are created first and form the equivalent of a specification for the software, and the actual software that satisfies the tests is created after. After every change, the tests are executed to check that the software as a whole continues to satisfy the specification, until all the tests pass. New tests are added as the software specification evolves and more features and complexity are added to the software itself. This methodology also includes a concept known as 'test coverage' which gives an indication as a percentage of how complete the tests (or specifications) are, but this can also be thought of as an indication of how much of the software is not clearly specified by the tests. So it is not simply enough for all the tests to pass; a high test coverage must also be achieved.

From this example we can conclude that checkers are only as effective as the detail and coverage in the specification that they are checking the model against.

EXAMPLE SOLUTION PROVIDERS

3.1.1 BIM checkers

Building Information Modelling (BIM) is a good example of a model that can benefit from automated checking against a specification. BIM models use an object-based approach to information creation with objects defining the 'things' and then metadata attached to these relevant objects to represent the 'information' against the specification. In current BIM checkers the user defines rules or uses the built-in rules to validate the model. The rule set analyses the model and determines its quality against the specification: that is, can the model be considered as a valid BIM model and what issues exist? The following are examples of typical rules and checks that may be applied:

- **Geolocation**. Does the model have correct geolocation and rotation information?
- **Model-merging**. Are the architectural, structural and MEP models correctly aligned in 3D-space?
- **Consistent naming** of levels and floors, object type, spaces and equipment, matching the project requirements.
- **Room finishes**. Do all rooms (spaces) have finishes and colours for all surfaces?
- **Data completeness**. Do all objects have the required metadata fields and have these been assigned a non blank value? This can then be expanded to check the quality of the assigned value
- **Classification**. Are all the building elements, components and spaces classified according to the classification system chosen by the client?

Effectively a BIM checker automates the time-consuming and tedious tasks in BIM quality assurance making the work flow, modelling and quality assurance more efficient by omitting some of the human factor in quality control. Errors in terms of missing or inconsistent information can be spotted and remedied quickly and effectively.

When we consider BIM model checking this level of automation is needed as a model may have several thousand elements within it, each of which may then have 10-50 bits of metadata assigned. For example a model with 3,000 elements, each containing 15 bits of metadata gives us 45,000 bits of data to check. This needs to be automated to be effective.

BIM checking is not the same as clash detection, which is the process of identifying if, where or how what has been designed by two different disciplines (e.g. the structural design and the MEP design) interfere with one another.

Examples of providers of BIM checker technology:

Solibri (www.graphisoft.com) is a Nemetschek-owned BIM checker that analyses BIM models for integrity, quality and physical safety. In addition, it includes functionality for information checking against pre-defined rules. The checks can analyse whether information is complete and whether that information is then a suitable value for that field. It is liked for its ease of use and it also allows visualisation, model walkthroughs, interference detection and model comparison alongside the data checking features.

Autodesk model checker (https://interoperability.autodesk.com/modelchecker.php) is a free Autodesk tool that automatically checks the Revit models based on a set of BIM requirements and generates an automated compliance report. The tool can check data as well as geometry and provide outputs for further analysis.

XINAPS (www.xinaps.com) describes its Verifi3D as 'the spell checker for BIM models'. It simplifies the data validation process and enhances professionals' workflows real-time, through a web-based platform.

EXAMPLE SOLUTION PROVIDERS

3.1.2 Schedule checkers

In a similar way to a BIM checker, checking software can also assess the health of a construction programme or schedule. The Defense Contract Management Agency (DCMA) 14-point Schedule Assessment is a project management guideline established on 14 metrics that help to make a qualitative and quantitative evaluation of a schedule. It is based on a handbook developed by the DCMA for the purposes of the defence industry, but is now used more broadly as a checklist of the metrics that need to be followed and examined in terms of the qualitative and quantitative health of a schedule. These include: the logic, the leads and the lags, the relationship types and hard constraints. There is also a critical path test, which focuses on assessing the integrity of the schedule's network logic. This checking process can be automated through the use of a schedule checker – one of the benefits is to speed up the identification and therefore resolution of potential errors.

Examples of providers of schedule checkers:

Nodes & Links (www.nodelinks.com) offers a suite of services to improve the efficiency and effectiveness of planners and project managers by using data science techniques to predict risk in scheduling. One such service is a schedule checker that applies the standard 14 DCMA checks and then adds an additional 18 checks. These include identifying isolated networks of tasks, zero duration tasks and circular dependencies between tasks, which can introduce scheduling errors.

Other schedule checkers exist: for example, Schedule Reader (www.schedulereader.com), which applies the 14 DCMA checks and presents the result as a one page dashboard.

3.1.3 Data checkers

Beyond BIM and data schedules, data checking systems can review different but connected datasets to look for errors, omissions and incompatibilities. For example, systems can check that all the expected drawings have been uploaded to a database, that there are no duplications and that what has been uploaded is the latest version.

Examples of providers of data checker technology:

Glider Technology (www.glidertech.com) uses a graph database to analyse and assure the information expected and required for the Asset Information Register (AIR), prior to project handover.

Morta (www.morta.io) allows users to pull data from modelling software, common data environments, document management systems, or even OpenBIM formats such as IFC and COBie. They can then define custom rules to verify automatically information quality in tables. Morta can also be used to create linked documents and databases, so when the user updates one, the other related documents are updated too. This means that if you updates the Employers Information Requirements, the related BIM Execution Plans will also be amended, with a strict hierarchy to determine which document has precedence.

3.1.4 Checklists

In 2009, the World Health Organization published the *Surgical Safety Checklist*, as part of its Safe Surgery Saves Lives campaign[1].

The checklist was adapted from the field of aviation, where checklist use is standard practice. The data has demonstrated significant reductions in both morbidity and mortality with checklist implementation, as well as an improvement environment within which attitudes towards teamwork and communication can be encouraged and improved.

Checklists have been used in construction for decades, the most common being to:

- **Identify potential risks associated with job tasks;**
- **Perform regular tools and equipment checks; and**
- **Implement safety protocols to prevent workplace injuries and deaths.**

The benefit comes from two sources. First, the act of creating the checklist helps codify the set of tasks, so that flaws or inefficiencies in the approach can be identified and improvements made. Secondly, by having all team members working to consistent checklists on every job, a more standardised approach can be introduced. In both regards, errors are reduced by people doing things right more of the time.

Of course, paper-based checklists can be used, but technology can help share the preferred checklists to be adopted and to ensure that all team members are working to the same requirements.

[1]Use of the Surgical Safety Checklist to Improve Communication and Reduce Complications, Pugel et al, (2015) J Infect Public Health 2015 May-Jun; 8(3): 219-225

Examples of providers of checklist applications:

CONQA (www.conqahq.com) aims to transform a complex retrospective process into a simple as-you-go-process. When a worker arrives at an area or finishes a task, he or she opens the CONQA app and finds the relevant task. They tick the completed components and flag the components that need more work. They take a picture for proof. Effectively, this is a real-time quality assurance process with the checklist supporting workers to find issues as they go – as well as log them, fix them and document what they have done.

Datamyte (www.datamyte.com) offer a ‘digital clipboard’ which allows users to create, manage and share construction checklists, whether for construction processes, quality management or safety management. Effectively, it serves as a workflow automation tool of which checklists are just part. The wider functionality allows the creation of projects, tasks and milestones and assign resources and teams against each of these.

3.2 Automated generation technology

Engineering design is, essentially the application of rules combined with good human judgement. The rules are often set out in codes and standards that establish minimum acceptable levels of safety, quality and reliability. Expert rule-based systems can capture and apply these codes and standards, potentially more accurately than humans can.

For very standardised processes such as engineering detailing, this can be not only a way of delivering the design more quickly, it can also lead to a more accurate design with fewer errors.

3.2.1 Design configurators/design generators

In this category, the technology produces an automated layout of the building or asset – either to support decisions at the planning stage with inputs around the market context, site context and planning rules through to the creation of fuller designs and layouts. Whereas a planning stage configurator will work more with topology, a design and layout tool is also likely to understand and apply information about the kit of parts from which the building or asset is going to be constructed.

Errors are reduced because, assuming the rules are correct in the system, the configurator will apply them in a way that does not make mistakes. This does not mean that the resulting designs or layouts will be optimal: that requires additional techniques such as evolutionary algorithms to run, effectively, millions of versions of the possible design or layout and then screen against an 'objective function' so as to come up with the 'best' one e.g. lowest cost, lowest carbon etc.

Examples of providers of design configurators:

There are a range of tools that may best be described as 'planning configurators' that are best used by property developers, planners, real estate agents and architects.

These include: **Archistar** (www.archistar.io), **Digital Blue Foam** (www.digitalbluefoam.com) and Ramboll's **SiteSolve** (www.ramboll.com) tool (which was acquired by Vu.City in January 2022). **Spacemaker**, which was acquired by Autodesk (www.autodesk.com) in late 2020 and rebranded as Forma in May 2023, is also used for early urban design and optioneering.

Testfit (www.testfit.io) stands out as closer to a true design configurator than many of the above tools as it has the capability to prototype building, site and urban configurations based on real-world variables, solving geometry based on competing variables and constraints such as building codes.

Hypar (www.hypar.io) is a web-based cloud platform that executes users' code, in Python and C#, to quickly create tens, hundreds or thousands of designs based on design logic. It is being used particularly successfully to apply a rules-based approach to the design of building services. Hypar is also working with Forsight Digital (www.forsightdigital.com) for healthcare planning.

The Laing O'Rouke Bridge Configurator (www.laingorourke.com) is a modular bridge system consisting of a standard range of precast products that can be readily configured to form high assurance solutions for modular single-span integral bridges with precast prestressed concrete beams, and associated wingwalls. The configuration tool works with a lookup table based on the results of numerous analysis runs allowing the set-up of model geometry.

3.2.2 Automated schedule generators

Better construction schedules can lead to huge savings in terms of time and cost. Improvements in the approach can come from being able to co-ordinate better across design and cost (5D BIM) and through better visualisation such as digital rehearsals.

Generative construction is a new field that uses evolutionary algorithms to optimise construction programmes by running millions of different sets of assumptions and selecting the best in terms of either time or cost.

The relevance to error reduction is that, as with design configurators, the use of a rules-based approach to the generation of schedules produces a more accurate schedule or programme than one that is produced by human planners.

Further, because the algorithm that produces the schedule can be run repeatedly, as and when information about the project changes for example, if there is a delay, the algorithm can be re-run to create a revised schedule. The error that comes from the information in the schedule being obsolete is therefore removed.

Examples of providers of automated scheduling generators

ALICE Technologies (www.alicetechnologies.com) creates schedules from an underlying database of 'recipes' that set out all the necessary steps in the creation of part of a construction project, usually an object or element. These recipes include the resources required; the production rates to indicate how long tasks will take and the predecessor and successor steps.

Alice can therefore produce schedules not only very quickly, but very accurately. It can recalculate schedules as new information is received – for example as a result of delays. A key purpose of ALICE, which uses evolutionary algorithms, is effectively to run millions of different versions of a P6 programme so as to help the user find the 'best' one whether lowest cost, fastest or lowest carbon.

3.3 Workflow engines

Workflow engines are software systems that are designed to streamline processes and help ensure that tasks are completed in a timely, accurate and organised manner.

They can be used to automate mundane tasks, assign responsibilities for undertaking those tasks, track progress and chase overdue tasks when they have not been completed. They also allow a mixed approach to project delivery, where some tasks are assigned to humans to deliver and others can be carried out automatically by an algorithm or a piece of code. The relevance of workflow engines to error reduction is that they can help assign a task to the person, team or system best placed to carry it out. They can also help create an end-to-end system approach to task management which reduces ambiguity as to who is responsible for which task.

In a more ad-hoc 'human' approach to task allocation, it can often be unclear to whom the task has been allocated. A workflow engine can help track the progress of each task through to the delivery of the outcome, checking and reminding the individuals who are responsible for them.

Examples of providers of solutions based on workflow engines

ProcurePro (www.procurepro.co.uk) simplifies and speeds up the procurement of suppliers from running tender exercises to signing subcontracts through the combination of a database and a workflow engine.

The database stores information about the stage of the procurement process that has been reached and the workflow engine sends the request or instruction plus reminders when not acted upon to the relevant party. This combination is able to reduce errors where it is not clear with whom the action lies or where the steps to be followed may be unclear or involve more than one party.

Archdesk (www.archdesk.com) streamlines construction workflows – from the administrative tasks of storing details of projects and clients, through to estimation, accounting, project management, scheduling and programmes of works. It is highly customisable.

Revizto (www.revizto.com) brings together teams and workflows into one integrated platform and facilitates BIM coordination among all project members.

Ontraccr (www.ontraccr.com) not only integrates workflows, but helps automate tasks such as sending emails, dispatching workers, managing approvals and transferring data. Workflow creation and integration is also part of **Autodesk's** (www.autodesk.com) BIM 360 suite and Autodesk Construction Cloud.

Applied Experience (www.appex.ch) is a workflow system that seeks to capture the process knowledge of how to go about complex construction projects. It links process models with a workflow system that prompts all the different stakeholders with items they need to address at a given stage of the process via a series of risk-rated questions. It automates the generation of work orders and tracking for these, along with reporting on progress.

In particular, it covers the process where the client needs to answer certain questions about what they are ordering early in the process, and needs to be provided with enough documentation and information to be able answer those questions. The system also provides the ability for additional lessons-learned to be integrated into the process to improve it in the future and for these lessons to be shared with other users of the platform.

ProTenders (www.protenders.com) applies these workflow concepts to the procurement process to automate the steps of information gathering, documentation and timing of the tendering process. This builds a significant data set on the construction ecosystem, and allows efficiencies and risk levels for projects to be calculated based on the performance of suppliers and contractors gathered across many projects.

Simple Construction (www.simpleconstruction.app) focuses on changes as a primary driver for errors in projects. It tracks project changes and integrates sophisticated workflow and audit trails to support the management of these changes and the automated generation of associated documentation and related claims.

This prevents mistakes associated with failing to comply with contractual obligations related to changes and failing to sufficiently document changes or errors in a timely way. It prevents errors from occurring by ensuring that changes are recorded, agreed and all parties are aware of them and have signed them off according to contractual obligations and timeframes. It provides an end-to-end audit trail between what was designed and what was built.

3.4 Visualisation software

3.4.1 Virtual reality (VR) and *Augmented Reality* (AR)

The C-Tech Club's *Catalogue of Construction Technology Types* draws a distinction between virtual reality and augmented reality as follows:

- **VR uses headsets** to take over the user's vision to give the impression that you are somewhere else on the construction site or looking at the details of the bridge design. The technology can improve design co-ordination and therefore help reduce errors. It can also be part of digital rehearsals, which enable work sequences to be planned, tested, revised and perfected in virtual reality before being put into practice. It brings together personnel involved in planning and performing a task in a live, simulated site environment, which is created from the building information model (BIM) of the project. Practising beforehand and confirming roles can help eliminate errors.

- **Augmented reality**, on the other hand, adds to the user's vision by offering a data overlay or 3D images in addition to what already see. When combined with hyper-accurate sensors, AR can help with positioning of the work to be undertaken, thereby reducing error.

EXAMPLE SOLUTION PROVIDERS

Examples of providers of solutions based on VR/AR:

In terms of VR, **Yulio Technologies** (www.yulio.com) is a program that allows designers to turn their 3D designs into VR-compatible renderings that they can show collaborators and clients.

In terms of AR, **Fologram** (www.fologram.com) uses AR glasses or goggles with hyper-accurate sensors to combine the BIM model and the actual view of the object in the field of vision with a highly accurate overlay.. This allows the technician to see where holes need to be drilled or how other more complex tasks requiring spatial precision need to be undertaken. This reduces the likelihood of error from the task being carried out in the wrong position. It can be especially useful for visualising clashes or incorrect orientations at the site, but also in driving accuracy in offsite manufacturing. **Argyle** (https://www.argyle.build) also focuses specifically on the use of AR for quality assurance.

XYZ Reality (www.xyzreality.com) has developed the Atom™, an AR headset that allows construction teams to view and position holograms of BIM onsite to 5mm accuracy. The Atom enables real-time validation of works and helps eliminate error and rework. **Real Wear** (www.realwear.com) models has released the second version of its assisted reality 'smart sunglasses' headset, the RealWear Navigator 500.

In terms of digital rehearsals, Mott MacDonald has launched **Rehearsive**, hosted on its Moata platform (www.mottmac.com). This allows infrastructure designers and operators to walk through construction scenarios with their teams and delivery partners in VR and desktop, no matter where they are.. Rehearsive integrates with existing 3D workflows and BIM models, whether from a laptop or a 3D headset.

AsBuiltDigital (www.asbuilddigital.com) has created an 'Immersion Lab' – a portable seven metre diameter, 360° circular studio theatre.

3.5 Collaboration and communication tools

These are a series of technology applications that help ensure that team members do the right thing at the right time – effectively a blend of collaboration and communication. The link with error reduction is less clear cut than with some of the other technology types, but it is clear that getting people to work together better and avoiding misunderstandings, duplications and miscommunications must benefit error reduction. Different systems will clearly contribute to this in a multitude of ways.

Examples of providers of solutions based around collaboration and communication:

In terms of collaboration and communication platforms, **SymTerra's** (www.symterra.co.uk) platform allows easy, instant, and intuitive communication across multiple contractors on the same project. It captures progress and records changes forming a real-time data pipeline back from the site to the designers, with online forms, an audit trail of changes, and dashboard project reports. Rich access controls ensure the platform can be shared amongst multiple stakeholders, and everyone sees only what they should see.

Letsbuild (www.letsbuild.com) helps to centralise all project communications, allowing everyone to focus on the schedule and report progress to the stakeholders who need to know.

CoConstruct (www.coconstruct.com), now owned by Buildertrend, is particularly good for communicating with clients.

In terms of technologies that support enhanced communication, **Mobilus Labs** (www.mobiluslabs.com) has pioneered a two-way bone conduction communication system, built into a construction hard hat, that provides a hands-free, ear-free audio feed.

3.6 Computer vision

Computer vision is a field of artificial intelligence that focuses on the ability of computers to derive meaning from visual inputs, such as photos and videos. Applications in construction include: improving workplace safety, analysing productivity and improving efficiency, monitoring progress, helping with quality management and making better planning decisions. The particular link with error reduction is that computer vision may be able to spot that an error has been made quickly and more easily than a human, and this may make it more straightforward to resolve. This is particularly the case where the computer vision system – which may be in the form of fixed or movable cameras, for example on vehicles or drones, or 360 degree wearable cameras – is linked to a BIM model so that it can determine what should have been built and where it should have been located. However, this does require a relatively accurate site positioning system.

Examples of providers of solutions based on computer vision:

GenieVision (www.genievision.com) is an example of a computer vision system built with error identification and quality management in mind. It allows users to compare the reality of what has been built on site with the 3D model, helping to detect and correct construction flaws before they become major failings. It also supports the reporting of non-conformities. Many other solutions systems connected with computer vision are being developed: **Buildots** (www.buildots.com) and **Openspace** (www.openspace.ai) are two examples. Their use cases include elements of error reduction, but also go much wider in terms of site monitoring and reporting. **Contilio** (www.contilio.com) combines regular site scans with machine learning algorithms to monitor progress and flag risks. This is combined with information from schedules and BIM models to report on project progress and highlight anomalies.

3.7 IOT sensors

In a similar way, sensors connected to the Internet of Things (IOT) can also help reduce error, provided that the combination of the sensor and the analytics system are set up in such a way as to spot that something has gone wrong. The challenge here is to turn the data input into an insight, which is relatively uncommon in terms of an error-related 'use case' for construction; this is much easier to achieve in manufacturing.

Examples of providers of solutions based on IOT sensors:

Ynomia (www.ynomia.io) describes itself as a 'Connected Jobsites IoT Digital Twin'. Now part of PCE, it is an asset tracking system capturing the real time status of every component within the model, via Bluetooth technology, which is then visualised within a digital twin. Error reduction comes from avoiding equipment or materials being in the wrong location.

Zerokey (www.zerokey.com) has produced hyper-accurate positioning sensors (to 1.5mm precision), which are more common in a manufacturing than construction environment. By equipping an operator with gloves with sensors on them, the system can determine whether all of the steps in an assembly process have been followed. When an error occurs, corrective feedback is provided to the user instantly, resulting in a highly automated and streamlined quality control process.

3.8 Digital setting out

A construction layout is the capacity to specifically earmark below- and above-ground structure locations. The aspect of surveying where a team transfers a layout from construction drawings into the ground is called 'setting out'.

Robots can autonomously print a full-scale model onto the construction surface in a fraction of the time it takes a manual layout crew, eliminating the errors of incorrect layouts or misplacements.

Examples of providers of solutions based on digital setting out:

Dusty Robotics (www.dustyrobotics.com) has developed its FieldPrinter solution, which can handle site layout ten times faster than humans with a string line and chalk and can achieve accuracy within 1.5mm. The robot must be paired with a Leica Geosystems total station that communicates geopositioning data through an on-board prism, and also needs a clean, dry surface.

Rival systems include **Rugged Robotics** (www.rugged-robotics.com) and **Tiny Mobile Robots** (www.tinymobilerobots.com), although the latter can only print lines and not other data from a plan set or BIM model.

3.9 Document management systems

Although electronic document management systems have been around for some time, it is clear from the Origin7 work (see section 1.4) and our discussions with contractors and consultants, that the better use of document management systems and the common naming conventions and version control that they encourage are considered an important source of business improvement. Construction and engineering design consultancies are full of individual files stored on individuals' computers or on shared drives. Finding a particular file is difficult, with the risk that the wrong version of a document may be issued or used, or that key documents are missing. People can spend a considerable amount of time trying to find a legacy document and then substantiate its status and level of assurance.

Cloud-based collaboration tools allow team members to work on the same documents at the same time turning what is otherwise a linear process into one that can take place concurrently. Google docs and Sharepoint through Microsoft 365 are examples of basic electronic document management systems. Again, this is made much easier through a clear approach to document management.

There are particular needs for document management in construction that go far beyond what is required in other sectors. Firstly, the documents for a building or other asset can be very large in number and complexity. Secondly, the system may need to include other file formats, including BIM models. Thirdly, access to the documents may be needed in a variety of formats and circumstances, such as out on site.

Fourthly, different groups may need access to different files at different times – for example, subcontractors and clients may need to be able to review and edit some documents but not others. Finally, there may be significant legal and liability-related issues around the provenance and quality of documents.

It may be necessary to prove the 'chain of custody' of a particular material or object and/or substantiate that installation was carried out in a particular way. Digital handovers are a contractual requirement on many projects. While there are many general document management systems, our list focuses on those that offer particular features and benefits for engineering design and construction.

Examples of providers of document management systems:

Common Data Environment document management systems can be grouped together containing many similar features. Essentially all of these systems store files giving access control, version control, file metadata and file sharing workflows. These CDE systems include; **Asite, Autodesk Docs, Projectwise, Aconex, Viewpoint, Trimble Connect, Newforma, Plangrid, Cabinet, etc.**

Qualomate (www.qualomate.com) automates the extraction and review of data from materials tests and inspection reports. The data in the reports can be compared against ranges or thresholds to give a pass/fail result and then shown on a site map. This ensures that the information is shared and acted upon as soon as the report is available and avoids human error in processing the reports. Also it provides analytics and automates the filing and versioning of the many thousands of documents that need to be handled.

Shapedo (www.shapedo.com) automates the identification of changes in plans. It ensures changes are not missed when new versions are issued and that changes go through a review process, which is faster and more timely because the changes are clearly identified. It then supports the change orders and contractual requirements processes that arise from the changes.

3.10 Other systems that can support error reduction

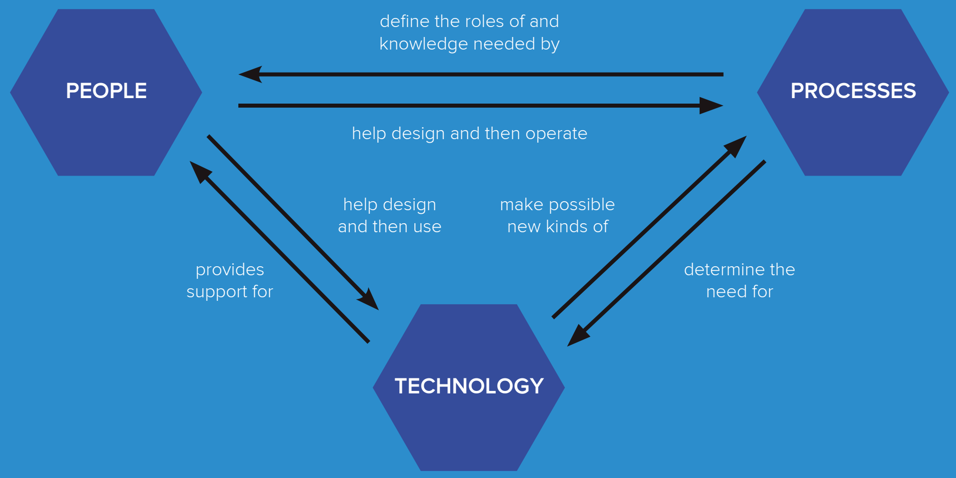
The above types of technology are the ones that we identify as having a direct impact on error reduction. There are many other types of system that can have a beneficial effect on a design or construction team, part of the impact of which can include the reduction of errors. Particular examples that we would point to include the following:

- **Visilean** (www.visilean.com) applies last planner/lean planner thinking to programmes using a digital platform and links to a BIM model.
- **Synchro,** now owned by Bentley Systems (www.bentley.com), is a popular way of linking programmes to BIM models, supporting better visualisation of schedules.
- **Propergate** (www.propergate.co) assists with the planning, registering, ordering, scheduling, unloading and reporting of material deliveries to site allowing more of a 'just-in-time' approach.
- **innDex** (www.inndex.co.uk) began as a fast-track onboarding solution for new workers on site. The range of services now extends to digital inductions, access control and on-site briefings.
- **Planradar** (www.planradar.com) is a global SaaS platform that digitises daily processes and communication, enabling time savings, cost savings and allowing projects to be completed to a higher quality.
- **GBuilder** (www.gbuilder.com) is an end-to-end tool white-labelled specifically for residential homebuilders. It covers the building process from sales lead capture and the off-plan sales process through specification, building, documentation, inspection, handover and snagging. It integrates with Customer Relationship Management and Enterprise Resource Planning solutions, with a focus on the design phase and compliance with the New Homes Quality Code.
- **QFlow** (www.qualisflow.com) audits all materials entering or leaving a site and highlights where errors or risks might occur. It also tracks carbon emissions through movement and embodied carbon. In particular it can highlight issues with materials specifications (e.g. uncertified timber) and non-compliant handling of waste and scheduling of deliveries for high-risk items that can have significant impact on projects leading to rework, downtime or fines.
- **Sensat** (www.sensat.co) provides 3D visualisations from drone surveys that are linked with BIM models for site visualisation, measurements and planning. This provides accuracy and accessibility to non-specialists in early site surveys and facilitates planning for access and set-down areas, and plant operating zones avoiding clashes between contractors, and leading to more accurate pricing. The same model can later be used for planning maintenance during asset operations.

4. THE CHALLENGE OF SUCCESSFUL IMPLEMENTATION

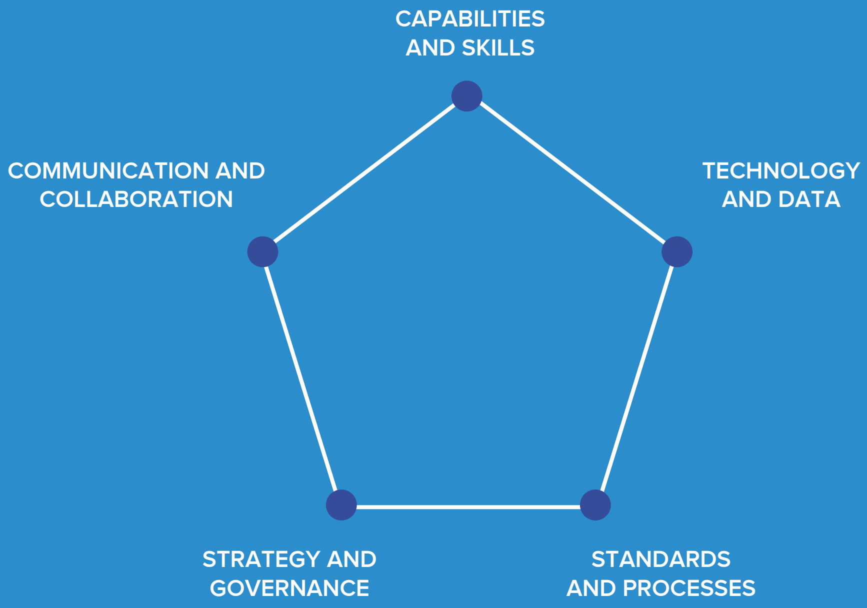
This section looks at how to successfully implement technology to reduce errors in design and construction.

As mentioned earlier in this report, many of the participants in our interviews suggested that the successful adoption of technology relies on a variety of factors around people, processes and technology, which, together, we term 'digital maturity'.



Beneath this three-way approach lies a whole host of factors around culture, attitudes and behaviours. It is useful to break these down into a combination of five factors: strategy and governance; capabilities and skills; communication and collaboration; standards and processes; and technology and data.

It is only by developing a level of maturity in all five of these aspects that technology adoption can be successful.



Each of the five factors can be broken down into a number of sub-critera which, together, can form a useful framework to track, measure and monitor digital and technology maturity.

STRATEGY AND GOVERNANCE	Vision and goals	Availability of vision and goals related to digital, so that digital is not as a stand-alone development, but is integrated in overall strategy. Extent of 'SMARTness' of goals.
	Management support	Availability of budgets and resources to enable digital initiatives, sustainability of resources for the long-term. Also includes other evidenced management support such as a policy.
	Leadership	Availability of champions, so that digital is embedded at the various management levels of the organisation. Effective decision-making and steering. A figurehead for digital.
	Supportive culture	The organisation has an inbuilt culture for digital and embeds this in its business approach.
CAPABILITIES AND SKILLS	Motivation	Willingness of people in the organisation to change, to make the transition to digital. This motivation is closely aligned to a supportive culture (leadership).
	Capacity	The extent to which people with digital capabilities are available to run projects and guide new initiatives. This also relates to having standards and principles for recruitment to attract digitally-skilled people or people that are willing and able to learn.
	Capability / skills	The extent to which the organisation has standards for a digitally capable workforce. Also the extent to which structured training programmes with role-specific skills are in place.
	Roles & responsibilities	The organisation has an inbuilt culture for digital and embeds this in its business approach.
COMMUNICATION AND COLLABORATION	Information sharing	The organisation's use of data platforms in the cloud to support intra-and inter-organisational collaboration. Information sharing is considered and based on a single source of truth.
	Industry engagement	The organisation's engagement with wider industry to progress its use of digital, take lessons learnt from others and share its developments.
	Internal communication	How well the organisation is able to communicate change internally. Is there a digital community inside the organisation promoting change and supporting its implementation?
	Collaborative attitude	Effective collaboration is rooted in the organisation's culture and behaviour. In a digital supply chain this requires a sense of openness and transparency that places an organisation's interest below that of the project as a whole.
STANDARDS AND PROCESS	Synergy of process and technology	The rethinking of processes as a result of changing workflows and technology in a way that the process supports the technology and vice versa.
	Standard, methods and procedures	The adoption of international, national, and project-level standards. This also includes the creation of relevant organisational methods and procedures for digital delivery.
	Change management	Digital change and innovation can be disruptive to existing organisational processes, so change should be managed dynamically to ensure process quality.
	Quality assurance and quality control	Quality assurance refers to the availability of workflows and procedures that steer the quality of processes, whereas quality control checks the output of processes, e.g. by means of inspection or quality checks.
TECHNOLOGY AND DATA	Digital / IT infrastructure	Appropriate hardware and facilities have to be in place that support the use of digital tools internally, and collaboratively in an inter-organisational context. The infrastructure needs to be proactively developed to support digital innovation.
	Application landscape	Availability and interoperability of tools that support the task at hand. The extent to which this architecture is managed holistically so that tools work together and data interoperability is ensured.
	Information management	This is the manner in which the organisation deals with information management in terms of creating, storing, managing, and using data. This also includes checking and validating information.
	Data exchange	The extent to which data exchange is defined and what (open) standards are used to make sure other parties can use that data effectively. This also includes legal and security considerations around data-sharing across parties.

When it comes to the successful implementation of technology to reduce or eliminate errors, some of the above will be more important than others. For example, quality assurance and control is clearly front and centre when it comes to accuracy in delivery.

However, because attitudes and motivations are so important, it is crucial that organisations consider and address the above factors holistically. If they are weak on any aspect, the likelihood of successful implementation can diminish significantly.

The above list of five factors and 20 sub-criteria should be tailored to the situation and circumstances of the change programme or project in question.

They can be applied qualitatively, or some sort of quantitative scoring mechanism can be used. More important, though, is the wish and commitment to change and improve: wherever any organisation is on the digital/technology journey, the most important step is the commitment to get better. From that point on, everything is possible.

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5. NEXT STEPS

This document is intended to be used as a reference source for quality managers, technology directors and others who are seeking a technology-related solution to support or enhance their error management programmes.

The technologies set out in this report address the most prominent root causes of error, as identified by GIRI research, with the intention of highlighting those most likely to make a genuine impact in this area.

Our report represents a snapshot in time: technology is constantly evolving and new systems and platforms emerge on a weekly basis. The companies and vendors mentioned are featured as examples.

GIRI welcomes comments on the ideas and technologies that have been included, and any suggestions for new technologies to consider. In addition, GIRI plans to revisit the topic in a year's time to assess how technology deployment has progressed. This annual review will also look at the extent and maturity of technology take up across the industry.

GIRI research has shown that errors in design and construction contribute to between 10 and 25 % of project cost, depending on size and complexity, amounting to roughly £10-25 billion annually in the UK construction sector. Technology and data can play a significant part in reducing this. But which types of technology are most relevant, and how can they best be deployed? This report, produced by GIRI, is intended to answer these questions. Based on interviews with users and technology providers, with input from start-up founders from the C-Tech Club, it is a valuable reference source for quality managers and technology directors alike.

Get it Right Initiative Ltd is a company limited by guarantee in England and Wales.
Company Number: 10532177.
Registered address: Get it Right Initiative Ltd, Office 7, 35-37 Ludgate Hill, London, EC4M 7JN, UK.

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