cdbb
Centre for Digital Built Britain

FUTURE CAPABILITIES REPORT

THE CREATION AND THROUGH-LIFE MANAGEMENT OF BUILT ASSETS AND INFRASTRUCTURE

TURNER | HARRIS

FOREWORD

The concept of a truly integrated lifecycle for digital asset care is not new. There are numerous case studies across the automotive and aerospace industries where complex asset data is used confidently to drive predictive maintenance regimes and high levels of automation in operations management and inventory procurement. For our built assets, the challenge is still to be overcome. The timelines associated with long-life infrastructure assets set it apart from the rapid turnover and production-line approaches of the auto and aero sectors, with complexity present in the area of legacy data management and configuration control.

From a technological perspective, we will need significant advancements in areas such as integration between BIM, GIS and Asset Management systems from an IT architecture perspective, and a common class library, or data dictionary to allow these systems to effectively talk together.

We will need greatly improved capabilities in the areas of global information collaboration platforms, IP rights management, configuration control and data assurance, as well as the systems to digitise and categorise our legacy assets cost effectively. Above all of this, we will require a shift in cultures of the constructor and operator entities, to move away from a ‘consumer’ mindset, to one of an ‘exploiter’. To actively use the high-fidelity information at their disposal to reduce costs, increase automation, reduce human hazards and improve predictability of outcome.

James Harris
Chief Executive

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EXECUTIVE SUMMARY

Executive Summary

A digital revolution has the potential to transform how our built environment is managed. How the UK responds to and capitalises (or not) on the benefits achievable from this revolution will define performance and safety in the built environment for decades ahead.

The rapid pace of technological change, supported by an ever-maturing communications infrastructure, has positioned the UK as one of the frontrunners in the global race to successfully use digital technologies to drive economic prosperity and improvements in our quality of life. At the heart of the change, lies new ways in which we will interact with our environment, including with our built assets and infrastructure.

The lifecycle of these assets – the activities that span the first conceptual design of the asset, through to its final decommissioning, demolition and site remediation - is a complex timeline that brings together myriad stakeholders, exposing each to a range of risks and uncertainties. This timeline can be heavily capital intensive and can often span a period in excess of 30-40 years. This presents challenges in how data-rich asset management strategies can be put in place, balanced against the cost of implementation, the impact on organisational capability, and the inherent cyber security concerns that are emerging in the construction sector while prevalent already across other areas of the digital economy.

The UK has some work to do. Whilst 54% of the construction sector as a whole has adopted BIM[1] and related digital technologies, this is heavily biased towards front-end services such as design and planning. The later lifecycle stages are a fraction of this total and are subject to significant risks. Fundamental barriers lie in the way of achieving the potential that digital technology affords us, and further research will be required to develop the tools, skills and behaviours that underpin the transition. Some good progress has been made over the last decade by organisations trying to find solutions to these challenges, with initiatives such as The BIM mandate raising awareness across the industry and prompting many organisations (academic and private) to invest in R&D that drives us closer to workable solutions.

A recurring theme in the work undertaken is the importance of a unified understanding of the goal. Where are we headed and why is that destination a good thing? Rather than asking "what benefits can be drawn from the technology at our disposal?", the question is instead, "What would a high-performance asset lifecycle look like?" Finding a cross-industry consensus on this vision will help to drive concerted investment in the technological, organisational and societal change necessary to realise a shared vision of digital through-life asset management in the built assets class. We need to make a conscious effort to steer technology, not let technology, or those that sell it, steer the industry.

While there is significant supporting information and analysis in the following pages, the conclusions of this report can be summarised as follows:

- The capabilities required to make best use of the next generation of digitally enabled built assets are many and varied and the pathways to realising them are in reach. However, barriers exist to the realisation of a new operating model for through-life management, barriers which are interlinked with other areas of social science and technology, such as man-machine interfaces, intellectual property law, and risk management in the financial sector. Systemic changes must also be explored in the context of technology, Government policy, finance, data science and organisational behaviours and skills.
- The overwhelming focus from the commercial sector is on developing the capabilities to create data-rich designs, we argue currently without enough consideration placed on how that data might be used (or not) by the end client and asset stakeholders. A gulf exists between the maturity of capability for asset information creation, and the ability of owner/operators to effectively use this information to effectively manage the through-life asset.
- There are pockets of research we have identified across UK and international academic and commercial networks that directly or indirectly respond to the emerging capability needs over a pragmatic timeline we have herewith proposed of the next 10 years. However, the overall research landscape lacks cohesion and clarity of purpose.

[1] NBS BIM Report - 2017

The end-state is not clear. The impacts of disconnected initiatives are a fragmentation of research pathways and a dilution of the benefits of invested capital.

- Lessons can be learned through cross-sector dialogue and collaboration with partners from the Aerospace/Automotive, Marine and Retail sectors, but there is a mismatch between the progress achieved by academic organisations and the significant momentum achieved through concerted private-sector R&D investment. Creating a bridge to this wealth of research requires a consensus across the necessary academic, commercial and policy-making stakeholder groups to come together and actively pursue an agenda for transparency and communication.
- The UK must structure and fund a portfolio of integrated research, supported by academic and private-sector organisations that brings together the current proven technology-driven developments and those conceptual but definitely 'in-play' and the commercial/social themes required to underpin sustainable, rapid change in the industry. This structuring requires taking a global view of the developments and potential developments currently being commercialised.

We are aware of the recently established UK Digital Twin project, and the work of the Digital Framework Task Group, and believe that our conclusions may be bolstered in part by the inception and delivery of that programme. However, it is vital that the impact of the non-technological aspects of the Digital Twin are addressed in parallel. We have chosen to exclude the majority of organisational, behavioural and competency-based capabilities, as we understand that separate papers are considering these aspects, however we have afforded some narrative to explaining the risks in context – for example how a shared vision may be impacted by systemic concerns such as cyber-threats, unclear asset definitions, and the shifting demographic of the UK's owner/operator organisations.

A point worthy of note is the challenge faced by the UK in selecting a strategy for the triage and transfer of legacy assets currently in operation, into the digitally managed environment. Whilst we have identified technological capabilities that support development in this area, we believe that this topic requires significant further research. The cost/benefit argument of investment in digital asset ownership should be weighed against the risk of having to manage digitally-enabled and non-digitally-enabled legacy assets under the same organisational umbrella. Our research and experience has highlighted that this argument is central to managing the delays, costs and safety risks seen in many owner/operator organisations making this transition. It is clear that prioritisation is required in the arena of legacy assets, an area deeply complex largely due to the age and different requirements of legacy assets and their management,

Whilst it is difficult to forecast with any degree of certainty the speed and efficiency of progress towards a landscape of success, our research concludes that the UK has at its disposal the strength of academic and commercial experience necessary to act effectively in setting out a clear pathway to a future vision for digital asset through-life management. Careful curation, and robust support from Government is required to keep the construction and built-asset management sectors on track in this respect, and to channel sufficient investment into outcomes that will enable the digitalised through-life asset management elements of our digital economy to become 'business as usual' at the same time providing rich export potential for the country.

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BACKGROUND

Context and Scope

This paper has been commissioned by CDBB to identify what core capabilities will be required within the next decade to signpost the way to an integrated digital asset lifecycle and it will map out the state of the current UK research landscape relevant to achieving those capabilities. In doing so, it hopes to inform CDBB on its further research, particularly in relation to the development of the UK Digital Twin project, and in establishing valuable points of contact with other academic institutions who are pursuing similar topics.

The report is non-exhaustive. It does not identify every capability that presents value; the scope is too broad, and the complexity too great to address within this short piece of work. To guide our work, we have defined a vision for a future state. A ‘postcard from the future’ 10 years from now, and from that, derived a set of capabilities and barriers that we believe are not currently being addressed in any meaningful sense within the UK’s digital R&D landscape.

We have purposefully restricted our research and discussion to those built assets that pose the greatest risk to the UK’s national infrastructure strategy, if the transition to a digital state falters or fails. We have chosen to consider Commercial, Industrial, Infrastructure and High-risk secure (CPNI) assets contexts, and whilst consideration was given to required capabilities in the Residential, Agriculture and Heritage asset categories, these were not included in this report in the interests of brevity and clarity, given the scope of work provided by CDBB.

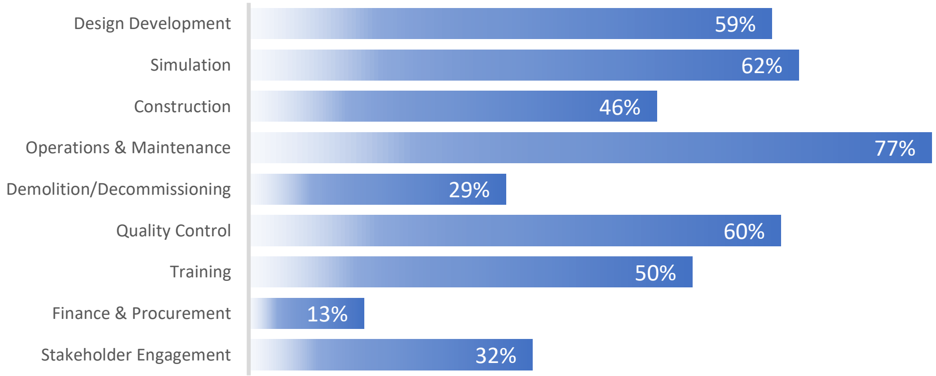
Additionally, due to the growing prevalence of BIM in front-end service organisations, we believe that the maturity of understanding of the ‘Design’ phase of the asset lifecycle was sufficiently high to preclude this topic from being the prime focus of the report.

Emphasis is instead placed on the transition or handover of digital asset information and configuration states to the construction and operation organisations, and in the approach to managing and exploiting this information through life. We believe this presents the greatest risk to realising value from a digital, integrated lifecycle approach to asset care, and by the same token, the greatest opportunity.

Drivers

According to research from the Advanced Manufacturing Research Centre, the digital twin market is set to grow to over £12bn by 2023. Within this headline figure, organisations who are undertaking or considering the move are clear that the greatest benefits lie in improvements to the Operations and Maintenance lifecycle stage. However, this stage also presents the greatest cost risk to the asset owners and investors.

Graph showing perceptions of value across lifecycle stages and functions



SOURCE: High Value Manufacturing Catapult Report: Feasibility of an immersive digital twin: The definition of a digital twin and discussions around the benefit of immersion.

With digital transformations for business operations increasingly seen as essential to the future prosperity of companies across multiple sectors, eight in every ten firms see their digital transformation as a priority, with 61% stating that they are “getting organised”. However, nearly a quarter still feel that their digital maturity is “frustratingly fragmented” and that they are beginning to fall behind their competitors and industry peers. As a component of this statistic, the built infrastructure sector has particularly acute issues, and a hesitancy in senior leadership to commit to capital intensive investments in technology.

As a measurable indicator of how pervasive the efforts for change are across all sectors, the ever-growing digital transformation consulting market, which is now worth more than £40 billion annually[2], and growing at 8% per annum, is a useful yardstick.

Despite strong words of commitment towards digital technologies, recent studies have shown that in around three quarters of the cases, digitalisation efforts fall short of achieving value for the clients who commission the work. The latest of these studies comes from Alpha FMC, with the consultancy finding that ultimately, despite being a top priority for asset managers, digital transformation in the sector is hamstrung by its legacy IT setups and unbound expectations on the limits of technological possibility.

> “Digital Transformation has definitely elevated the importance of asset management
>
> *Steve Treagust, Global Industry Director of finance, human capital management and strategy at IFS*

As part of the research for this paper, a range of asset owner organisations and individual stakeholders within the asset management profession were contacted. The following expectations for future use case for a digitally-enabled through-life asset management approach were captured as part of the exercise:

[2] Consultancy UK and Source Global Research

- Improved tracking of design maturity and requirements management.
- Design for modularisation and service provision
- Improved Documentation, Inspection and Records management throughout the lifecycle.
- Design for economic asset lifecycle cost through ability to model lifecycle activity.
- Effective and efficient Design and Plant Configuration Management.
- Reduced costs with supply chain in a collaborative common data environment.
- Plant simulation supporting training for agile workforce and/or new workfaces/infrequent task rehearsal (Improved quality, time and cost).
- Using Knowledge management for informed decision making.
- Optimised spares inventory and automated demand management.
- Improved emergency management response with improved and up to date asset information.
- Improved Reliability Engineering and predictive based maintenance and asset investment.
- Robust Maintenance Schedule management based on persistent asset information to ensure design intent is maintained
- Single source of truth and improve master data management (reduced ambiguity/variation)
- Improved waste volumetrics - estimating to maximise the income stream from decommissioning.
- Greater 'High Hazard' awareness.
- Reducing unknown unknowns of ageing assets through the increased value of asset information with increased age, without the loss of information across a lifecycle phase.

Source: Sellafield Ltd and GlaxoSmithKline plc interviews.

The breadth of expectation for the value that a digitally enabled through-life asset management platform can bring is wide. The industry as a whole is impatient for the promises of BIM and Digital Asset Lifecycle Management to be kept.

Whilst technological, organisational, cultural and social barriers are present, this report seeks to provide the reader with a picture on how the UK's academic research landscape is responding to the needs of the industry, and sheds light on specific examples that may inform and guide further research into the themes herein.

State of the UK Research Landscape for Through-life Asset Management

The state of the UK, (and to a large degree, the international) research landscape on the themes of lifecycle management and how the introduction and incorporation of digital-enabled futures may impact it, is a complex picture.

From our initial research and consultations, and after scanning the horizons both in the academic and commercial spheres, it is clear that whilst many organisations and institutions are engaged in discourse and debate around the benefits of digital asset management, very few were planning, funding or sponsoring proactive research in pursuit of these benefits in a tangible, realisable way.

It was evident that in both the commercial and academic organisations detailed research is being undertaken to look at niche technology problems, without consideration for the overall direction of travel – the system-level argument. Whilst technology is clearly a valued piece of the puzzle, the lack of a unified strategy or programme of research has left the landscape fragmented.

This fragmentation is leading to identical, or highly derivative research work being repeated frequently, often with different outcomes depending on the focus of the group investigating it and the proclivities of the funding body involved. An example of this is research being done into the collection of asset data on existing assets / facilities. Evidence was found of research looking into this topic specifically for railways, highways and power generation companies amongst many others. The research is always focussed on how that specific task can be solved in a way that works for that specific area of the industry with no regard for inter-industry collaboration.

This report, and other peer publications contributing to the discussion, highlights the need for real structural reforms to the innate fabric of organisations, contracts, skills planning, financing and judicial application of currently available, or soon-to-be available technology platforms and processes. Much of the extant narrative around research and trials relative to the benefits of managing a facility digitally through its lifecycle took a focus on the development of granular technology (hardware and software) needed for this, and highlighted areas where because the technology wasn't complete, it wasn't being adopted as a philosophy. The maturity of our technology solutions is not the primary barrier to the digitalisation of asset management.

A diagram of the landscape as identified during our research is shown in Section 2 – Overarching Research Landscape Map.

Learning From Other Sectors:

CDBB and other leading organisations in the sector have rightly identified the potential value inherent in sharing lessons and experience with other industries, sectors and markets. The pace of change across the UK's value chain has not been equitable. There are 'digital headwinds' from the oil and gas, aerospace and automotive sectors that may be powerful catalysts for change for our infrastructure asset owners.

Whist the drivers for change in other industries may differ from those of the built environment, the fundamental learnings and pitfalls are transferable and of significant value to the UK's research into a future Digital Built Britain.

Whilst recognising that looking outside the boundaries of our own industry can provide benefits of perspective, we must also be judicious in controlling the extent to which the outcomes of such tie-ups between sectors is allowed to merge. We must recognise natural differences in the momentum and appetite between them, as the fundamental economic and fiscal arguments are not the same. By following the path of another industry without hesitation, the Infrastructure sector may find itself repeating mistakes or tying itself inextricably to the fate of another, as can be seen in the position of severe technical debt related to PLM platforms that many aerospace and automotive OEMs now find themselves in after close collaboration in the late 1980s.

The reader should note that we have reviewed CDBB's separate report on the learnings from the Oil & Gas sector, which we believe was comprehensive. We have therefore chosen to exclude a review of that sector in this section.

Automotive & Aerospace

The automotive & aerospace sectors have often been held up as an exemplar for other industries looking to make a transition to cost-effective digital lifecycle management. These industries have embraced a range of concerted intra-sector collaboration initiatives, aimed at aligning strategic outcomes from industry participants from across the European Union. Some of the case studies from the sector have been included in our capability summaries, including examples from Rolls Royce's Intelligent Engine Platform, which reports on asset performance and Return on Investment in real time, heuristically suggesting changes to usage to reduce costs and maintenance downtime. (See Capability Summaries: Real-Time Reporting of Utilisation & Return on Investment)

Another example is the EU Clean Sky initiative. It describes itself as the largest European research programme developing innovative, cutting-edge technology aimed at reducing CO2, gas emissions and noise levels produced by aircraft. Funded by the EU's Horizon 2020 programme, it brings together manufacturers, regulators, technology partners and policy makers to assess the needs of the broader industry and work together to unify pathways for strategic technology and organisational capability.

Both industries have heavily adopted digital technologies across all aspects of their business areas, and partner heavily with academic institutions and NGOs to conduct research. Digital can be seen to be used at a cutting-edge level within the design, manufacture, operation and management of these businesses as well as other 'back office' tasks. At a higher perspective, these businesses have made the transition to incorporate digital into their businesses standard operating procedures, using it to deliver value rather than just being a bolt on to address a specific task.

If we look to the automotive industry in the 1980's we can see that the sector pursued concerted investment and development in a rich ecosystem of digitally-enabled systems of work. These included data-rich approaches to lifecycle management, culminating in the first Product Lifecycle Management (PLM) systems.

Over the next 20+ years the automotive industry has pushed these large PLM systems deep into their supply chains; deploying significant capital in the pursuit of process improvement and standardisation. Whilst at the time, these systems presented a new paradigm for the industry by bringing every supplier and customer under a single digital 'roof', recent technology advancements have exposed these systems as overly complex, limiting in flexibility and financially cumbersome. The industry is now facing the music for the technical debt resulting from such focused investment and must find novel ways to migrate their business models, engineering workflows and enterprise systems away.

These monolithic systems are now so woven into the fabric of the organisation that any change to its configuration has myriad knock-on effects on downstream business functions. We think this is a key point for the built environment to consider. Whist full integration can be seen as a tempting exemplar for the industry, it has the potential to negatively impact the cost-effectiveness and agility of the value chain if due consideration is not made to how the industry would move on, as technology advances.

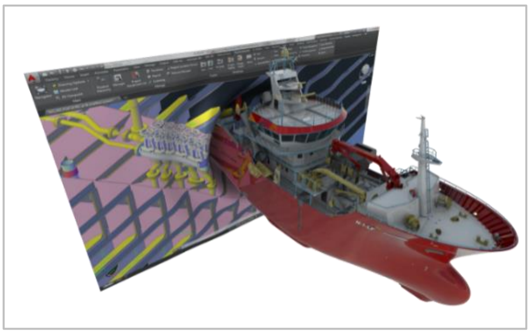
Another key point to consider when looking outwards to the Automotive / Aerospace industries is the nature of the product and the role of the customer in specifying requirements. Cars and aeroplanes are created with long, standardised production runs in mind. The manufacturer creates a product, and the market buys that same product over and over. Modularisation is standard, and digital contributes towards the leaning off the process – analysing and tweaking production to reduce process times by seconds, or fractions thereof. The ability of the customer to change their functional requirements away from the pre-packaged design is limited. The industry is dominated by a handful of 'Primes' – product owners that control vast supply chains and inculcate them into managed service cells.

In contrast, much of the built environment sector is comprised of small and medium enterprises (SME's), huge distributed and multi-tiered supply chains and generally the end clients are comparatively removed from involvement in a number of the lifecycle stages of the asset. By contrast to Aero/Automotive however, the expectation and prevalence of changing requirements, designs, customised aspects and construction processes is much greater. This must be taken into consideration when specifying a future state for the sector.

Marine / Shipbuilding

When we talk about BIM and digital construction, we often refer back to examples where automation and digitalisation of assets has already been largely implemented, these examples are very often focussed on the automotive and aerospace industries. Whilst these industries offer us some good examples, they do also have some significant differences which can't be denied. The main differences often raised are that the automotive / aerospace industries are focussed on building one standard object many times rather than a bespoke object once.

This means that a lot of time can be spent to perfect the design and manufacturing stages because those benefits will then be realised many times over with each object that is created. This is opposite to the construction industry where generally every project is a one off, even if projects should be identical, they are often still different because of other influencing factors on each design. The other difference to consider is that the majority of automotive / aerospace industries rely on production line manufacturing in purpose-built facilities, again this is very different to the one-off builds in the construction industry which are focussed around manual labour on the construction site.



A better example for the built environment in our opinion, would be to look at the ship building industry. Whilst ship building is quite a way behind the automotive / aerospace industries it is still well ahead of the construction industry and so offers a better and closer relation. Effectively most ships are floating buildings which contain many of the same systems, they are usually built as one off's or in small numbers and are highly complex assets which need maintenance over a 20-50+ year period. Ships are built in shipyards and assembled "on-site" which means their construction is closer to the conditions in the built environment than the manufacturing lines of the automotive / aerospace industries. Like most of the construction industry, the ship building industry is also highly regulated having to comply with many different procedures and safety restrictions.

The digital twin concept within shipbuilding is a progression from the historic term “As-Built” but goes a lot further throughout the entire lifecycle of the ship. As with the As-built terminology, all the geometric data and the attributes originating from the engineering CAD tool are included, however, much more data is required for it to be a true digital twin. For the construction this will include linking to items such as:

- Class approvals
- Requirements of the ship linked to the items (parts, assemblies, etc.) that satisfy them
- Change Requests of clients and linked to items which are satisfy change request
- Vendor Furnished Information (VFI) linked to each instance of the item (engine, valve, pump, etc.)
- Production processes such as welding, assembly sequencing, workstation/work centre
- Simulations and calculations
- Paint information

As well, information generated after delivery will be associated with the digital twin such as:

- Service records of replaced items for maintenance, warranty, etc. with information being associated to items
- Actual sensor data of items which record data
- Repair and retrofit changes
- Class surveys
- Removal of fouling documentation

These concepts listed above all apply to the built environment where “As-Built” data is collected from the design documentation but never amended or progressed. Moving to a “Digital-Twin” as per the shipbuilding industry means our design documentation must be updated, expanded and maintained throughout the lifecycle of the asset, whether it be a ship, a road or an airport.

Retail

Another notable reference industry which is advancing the use of digital technologies for asset management is the retail industry, specifically the fast-moving consumer goods (FMCG) sector. Whilst on the surface the retail market doesn’t seem to have much correlation to the built environment, the picture changes when products are considered assets. Using this interpretation, FMCG companies are very clearly focused on the digital lifecycle management of their assets, tracking inventory, location, key information and statistics about it, all of this is then used to predict trends and make informed business decisions. As per the built environment any retail entity is relying on its assets being in good condition and in the right place to enable it to meet its function.

If we look at a specific part of the FMCG sector such as supermarkets we can see that everything is now digitally managed to enable the business to operate. Effectively these businesses would now collapse without their digital management procedures and platforms. Some of the key digitisations in this industry are:

> “
> 70% of grocery shoppers will be shopping online in as few as five to seven years.
>
> *The Food Marketing Institute and Nielsen.*

- Asset tracking, to know if an item is at a distributer, in warehouse, on the shelf or if it has been sold
- Asset condition reporting, to monitor if items are going to go out of date soon
- Asset categorisation, to manage what section each asset falls into (e.g. fresh, frozen, bakery, household, etc.)
- Barcoding, to enable quick access to key asset data such as cost
- Machine learning, to offer suggestions on other assets which might be a suitable replacement
- Live data analytics, to see which assets are performing best / worst and highlight data trends
- Predictive analytics, to suggest what needs to be ordered because it will be needed soon

The retail industry is competitive, with significant risks and comparatively small profit margins, not unlike the built environment. The difference comes in that each retail business must become ever more efficient to maintain its market standing, driven by market forces and consumer demand. As a retail business is built around its assets, it makes sense that the majority of these efficiency savings come from improving the management of these. As we have seen in the case of multiple retail businesses such as Blockbuster vs Netflix, Woolworths vs Amazon, etc. those who don't improve and adapt to digital soon see their businesses fail.

Another interesting comparison to draw from the retail industry is that much of this digital progression they have made is borne from demand from the end user / consumer. When we look at the built environment, we say that the end user is a stakeholder and that they are considered but in reality, they have very little influence over the asset or asset owner. If we again look at the FMCG industry we see that assets are being digitalised, moved online and everything incorporated into apps, this is almost entirely driven by the end user consumers demanding this and the asset owners / retailers not being able to fall behind. For the retail industry this has completely changed the game and made digitalisation of assets a number one priority which is directly linked to the performance and success of the business.

> “
>
> 89% of shoppers want to shop in a supermarket that understands how to make buying groceries more efficient.
>
> *Cooling solutions provider Phononic*

What if the built environment was driven by the end users? Would we see a fundamental change in asset management strategy if infrastructure had to compete for public acceptance, if people controlled an assets profitability or funding?

Introduction to Our Barriers

Reviewing the primary barriers presented across the asset lifecycle

In order to understand the capabilities needed to improve through-life asset management within the built environment, it is informative to first review and understand the critical barriers to current methods. Wholesale reformation is not the only context in which digital asset management can be viewed. Fundamentally, the concept of digital asset management is a simple one, which has been well-defined in theory, but uptake remains stubbornly low amongst owner/operator organisations.

It is apparent from our research that many of the minor barriers identified could be grouped together to highlight a collective higher-level problem. We have categorised and refined a pool of high-level themes which we believe best summarise our research and discussions. These are shown overleaf.

Whilst, as we expected, technology is raised as a key issue, it was interesting to observe that most barriers came down to people and business operational related issues. This identified that there are some technological challenges involved with the move to digital infrastructure and asset management, especially when considering the volume and complexity of data involved, however these aren't an immediate barrier as companies weren't getting through the other barriers to get to this stage.

One of the key takeaways from this section was that time has a big impact on many of these barriers. Generally, in the built environment assets have operational design lives that lie between 25 and 50 years, with many lasting longer. This is in stark contrast to business strategies and market forces, which are generally much shorter in outlook. This relatively short timescale of business consideration versus the long lifecycle of the asset often means asset management is reduced to a short, isolated period with a fixed start and finish, and is undertaken in the lulls between corporate growth investment cycles.

Some of the key barriers linked with time are contracts, such as asset management contracts to an external party which have a fixed length meaning there is a fundamental breakdown between contracts with almost no continuation of information. Secondly comes funding cycles or budgets, which again are fixed short-term investments.

As a result, any approach to asset management must be broken down into a small-scale, restrictive implementation plans with low risk, but also commensurately low ambition. Similarly, Human Resource and skilling cycles mean that successful transformation can take several years, when accounting for delays in securing key digital skills that are often excluded from standard HR staffing models for asset-centric or blue-collar organisations. At best, this disjointed skilling strategy drives delay. At worst, the transformation itself is undermined, and confidence is lost in the eyes of the senior sponsors funding and guiding the change.

These factors considered, our research and experience has confirmed that the sector as a whole has a markedly short-sighted view of digital asset management, leading to numerous examples of failure by organisations to make meaningful progress in achieving the UK's vision for value-adding, data-rich through-life asset management.

Primary Barriers:

To realisation of future through-life asset management

- **The Owner / Contractor interface – Business models based on ambiguity / hidden information**
  In the current environment, the contractual relationship between Owner/Operator and Contractor promotes confusion and a lack of transparency across the value chain. Rampant use of change orders and T&M contracts are examples of the manifestation of this lack of communication. Digitalisation can and should address some of these systemic problems, as estimating certainty and requirements become clearer.

- **Optimism Bias**
  In context, this barrier represents the tendency of all stakeholders in the lifecycle to view past projects as exemplars, regardless of their flaws or capacity for improvement. Whilst this is a systemic barrier to all forms of digital change, not just BIM, it is of particular prevalence in high-capital, high-profile industries with low turnover of projects, such as infrastructure.

- **The physical and digital asset are managed by different contract mechanisms across the lifecycle**
  Current business practices are focused on the delivery and maintenance of a physical asset. The digital asset is often ignored or kept separate from the engineering and contractual workflows of asset-centric operations.

- **Attitudes to proactive investment in O&M are conservative. “Do more, with less” is the mantra.**
  The asset care and long-term management functions of organisations are often poorly represented or understood at the executive level. Priority is for bare-minimum maintenance to keep an asset operational and profitable.

- **Short-term thinking preventing long-term investment**
  Holistically, digital twins and data-centric strategies as potential revenue drivers are not fully understood, and the cost hurdle is too great for many. Technology-driven investment cases are complex and struggle to get support through short-term budgeting. The ever-increasing integration between IT systems and physical assets blurs the lines of responsibility even further, creating confusion and deferring action further.

- **The scale of change makes a business case slow to receive sponsorship from stakeholders**
  Concerns such as the cost and complexity of transitioning legacy assets and enterprise systems into the new paradigm, and the complex interaction between IT systems, organisational structures, skills and commercial contracts makes many organisations seek for simplified or pared-down plans for undertaking a digital transition.

- **Security / Cyber risk**
  There is a recognised nationwide concern around the implications of big-data economies and the threat of malicious or accidental exploitation of this data if robust cybersecurity technologies and protocols are not in place. As this area of research is still in relative immaturity and has been ranked in the top-5 national concerns, public and private sector asset owners alike are deferring investment in full integration of their digital asset systems.

- **Digital skills and the shifting demographic**
  A lack of relevant digital skills across the lifecycle is a core barrier to the adoption and exploitation of next generation BIM/DALM technology platforms and capabilities. This is particularly acute in the Operations & Maintenance stages, where traditional trade skills, paper-driven workflows and received wisdom have been the bedrock of asset care for generations. Whilst the national demographic shift may positively impact the balance of digital skills in these areas, the transition poses a significant barrier and risk.

- **Limitations imposed by closed data standards**
  The wide landscape of available data schemas, class systems and proprietary, closed-off file formats is a fundamental barrier to the integration of enterprise-wide systems for asset introduction, care and exploitation.

- **Data and Collaboration platforms are predicated on ‘handover’ rather than persistence**
  Current workflows and solutions for BIM-Enabled Common Data Environment and Collaboration platforms are predicated on the principle of packaging and exporting information at the end of each phase into new systems, and with new owners. This creates complexity, risk and cost and undermines Design for Operations.

Introduction to Our Core Capabilities – A 10-year Horizon

Reviewing the primary capabilities required across the asset lifecycle

This section provides detail on the core capabilities that we have identified as on the critical path to achieving the 2030-year vision described in the Executive Summary.

The capabilities have been selected based on a range of criteria covering factors such as their impact on corporate risk, reductions in human hazard, contributions to a more agile and productive infrastructure sector, and their contribution to the socioeconomic fabric of the UK.

We have avoided selecting and describing capabilities that do not add value or direct benefit to one or more of these critical factors. Our approach also excluded those capabilities that are already reaching a point of maturity, and simply require the acceleration of uptake into the sector. These included technology platforms such as Virtual and Augmented reality, which although exciting in terms of their application potential and on an upward curve of adoption, will not in and of themselves change the nature of through-life ownership.

Likewise, we have avoided selecting capabilities that exist in proven and unambiguous terms within parallel sectors, such as manufacturing, automotive or marine industries. We do however recognise the value that these parallel sectors offer with regard to communalising the learning and experience that they have cultivated with the infrastructure sector, and this has been reflected in the 'Learning from Other Sectors' section.

A brief overview of the capabilities identified are shown overleaf.

Additionally, to assist in describing the capabilities in a structured manner, each has been placed into a two-page modular layout (See Section 3 – Capability Summaries). These summaries comprise the following headings:

- Scope of capability;
- The date by which we expect the capability to be acquired and commercially viable;
- Drivers behind the selection;
- Barriers and enablers that impact the capability;
- Expected benefits from acquisition of the capability;
- A radar map of the associated macro-level benefits and their relative strength;
- A narrative, describing the background to the Capability and future state;
- A summary of selected research examples and pathways.

Primary Capabilities:

For future through-life asset management

- **BIM for Investment – Digitally-underpinned through-life value models for funding and underwriting**
  We can raise finance and secure insurance agreements quicker, and under improved terms, based on the contribution that the digital twin makes to increased certainty of lifetime cost forecasting, value chain management, co-ordination and outcome assurance. We know how to define and calculate whole-life value and subscribe to a broadly aligned common model for lifetime value at all stages of the lifecycle - Project delivery to asset demolition.

- **Autonomous operations and maintenance**
  We know how to exploit and configure Building Management Systems (BMS) to integrate with the digital twin and robotic systems to automate Operations and Maintenance regimes, including self-diagnosis, automated spares picking and replacement.

- **Automated legacy asset digitisation through AI workflows**
  We can create a data-rich digital BIM models from our scans of legacy assets, with minimal human intervention, through adaptive feature recognition of the physical geometry supported by techniques such as machine learning algorithms and contextual links to other asset data systems.

- **Context-sensitive hazard and monitoring, driven by the BIM-enabled Digital Twin**
  We can design and construct assets that react to manage hazards. Context-sensitive machine learning algorithms and monitoring led by the digital twin help to keep people and equipment safe.

- **Real-time reporting of asset utilisation and Return on Investment**
  We can track the real-time performance of assets against its lifetime cost and revenue model, to ensure that the facility is generating the benefits expected. The digital twin supports revenue, as well as cost forecasting.

- **Agile organisational structures that adopt digital as a distributed part of their operating model**
  We know how asset-centric business structures can be re-designed to be more agile in investing in, adopting and exploiting digital tools, skills, IT platforms and commercial contracts. We also understand how to recognise and communicate the limitations of technology better. Digitalisation is not centralised, it is part of the fabric for all operational business units.

- **Seamless persistence of data, enterprise system integration and validation.**
  We can make robust links between a range of digital enterprise systems that collectively provide a central platform for decision making, command and control, and the exploitation of the digital asset at all points of the lifecycle. (e.g. Estimating, Requirements Management, GIS, Procurement) Data validation is automated, and central to the sign-off of any work. The E-Artefact becomes a valuable commercial asset in its own right.

- **National Asset Database and Digital Knowledge Library for owners**
  We can leverage a national database of critical and important assets across the UK. The database provides not only a basis for better emergency response, but also a knowledge base for AI algorithms and trend analysis, to support better commercial decision making, reduce design times and facilitate the management of legacy assets under a common national ontology for information.

Capabilities - A Postcard From the Future

What vision do we have for the future of the digital environment supporting asset lifecycle phases?

In reviewing the need for capability development in the context of asset lifecycle management, we have taken a position on what core outcomes must be achieved in a 10-year horizon to support the UK's overarching vision for high-performing, value-adding infrastructure. We have segmented these outcomes, or end-states, into lifecycle stages to aid in the characterisation and linking of these outcomes later in the report. However, many of the outcomes can be seen to stretch across the lifecycle.

THE VISION FOR 2030 – HOW WILL THE INDSUTRY LOOK IN A DECADE?

ASSET INTRODUCTION & FINANCE

- Projects are conceived and delivered with the full lifecycle in mind, using digital (BIM) methods;
- Digitalised collaboration on a single platform from conception / funding / design through to delivery is commonplace;
- Investment cases are predicated on lifetime value, driven by digital simulations of Return on Investment as standard
- Industries share data and knowledge readily and through known, transparent channels;
- There is mainstream use of big data analytics, AI and machine vision in making investment decisions and protecting assets.

ENGINEER, PROCURE AND CONSTRUCT

- The owner procures the physical and digital item at the same time, under the same contract;
- 'subscription'-style supply and maintenance of physical and digital assets is commonplace, and a recognised procurement/supply model;
- The procuring entity has full confidence that their functional and information specification will be met by the contractor, and legal protections to support them;
- The progress of construction is updated in real-time (smart sensors, drones, wearables);
- Rework is dramatically reduced due to clearer communication and availability of design intent.

OPERATIONS & MAINTENANCE

- Maintenance costs and workforces are reduced through workforce efficiency and automation (e.g. predictive maintenance, automated procurement through ERP, critical spares management)
- Asset management is a core business function and funding/resourcing is driven by the Return on Investment model for the asset.
- The Owner/Operator entity has clarity on lifecycle costs (5D/6D forecasting, subscription-based procurement etc.)
- Maintenance is data-led. Maintenance is also done 'on' data assets as well as physical assets.
- Digital tech is reducing hazard and human risk on sites (e.g. wearables, Immersive Augmented Reality, BMS) – human communication is flawed. Improved by this.
- The digital asset supports decision making for decommissioning and/or life extension.

DEMOLITION AND DECOMMISSIONING

- The cost of this stage is known and has been known since the construction of the asset.
- Identification of hazardous and valuable materials and waste streams are known.
- There is a clear technology solution for long-term record management for data/digital models and associated information sources after the demolition of the asset.
- The cost/value of demolition equation is materially different from 10 years ago. Old facilities could be valuable assets, with salvage values known in advance due to the persistence of material information trough-life.
- The owner/operator or demolition contractor meets its regulatory obligations for site remediation at significantly lower cost through use of the digital twin.

CROSS CUTTING THEMES

- Organisations have cyber-shielded data repositories for built assets and use them to reduce the cost, risk and uncertainty of asset ownership.
- There is an informed regulatory landscape that understands the role and benefit of the digital asset and discharges their duties with this in mind. (mandates where appropriate for aspects of digital asset adoption – research theme!)
- Agreed digital asset metrics are defined and data accessibility is fluid. And the organisation understands the value.

Systemic Issues for Consideration and Capability Development:

Despite the rapid pace of change and the ready availability of supportive digital technology, the asset lifecycle is exposed to a range of what we shall describe here as systemic challenges that collectively undermine our ability to make a smooth transition to a new digital paradigm at a similar pace already demonstrated by some other industrial and manufacturing sectors.

This section describes some additional core areas for consideration. While supplemental these issues are very important to consider in the overall narrative and they have informed our approach to the subsequent identification of required new capabilities to meet our vision for the future. Whilst a number of these issues are not confined purely to the topic of digital asset through-life management and may be described in detail in other CDBB research landscape papers, we consider them to be sufficiently important and relevant to be included within scope of this report.

Cyber Security and Infrastructure Assets

A major international Accounting and Consulting firm recently commented that the threat of cyber offences was now a "board-level issue" but warned that few companies understood the risk. For the construction industry, this threat is particularly pertinent, as the ongoing adoption of BIM, with its increased use of digital collaboration during design, construction and operation of a building, creates additional cyber security risks – risks that advisers and insurers are warning the industry isn't taking seriously enough.

All businesses in the construction sector need to start seeing data and information as a physical commodity that needs to be protected. The construction sector is particularly at risk because of its fragmentation. Most construction companies are Small to Medium-sized Enterprise (SMEs).

It is this fragmentation into multiple SMEs that presents one of the industry's biggest vulnerabilities. Although 'Tier 1' constructors e.g. EPC/EPCM organisations such as Bechtel, operating on large-scale projects or infrastructure are more likely to have stepped up protection levels to deal with cyber security threats, their supply chains will include SME subcontractors with far less cyber awareness.

In major infrastructure projects, that network will be complex, from architects to plant and equipment suppliers, law firms, designers. And as the supply chain becomes more extended, the vulnerabilities increase, which means that anyone connected to a site's systems is to some extent a potential point of entry for one of many different types of cyber-attack.

The construction industry represents a lucrative target for cyber criminals (and terrorist organisations seeking 'high impact' publicity/disruption), mainly due to the vast network of associated supply chains. The biggest cyber threats affecting the construction industry include hacking to obtain personal employee data or sensitive commercial information, as well as Distributed Denial of Service (DDoS) attacks which cause widespread business disruption, which can have a knock-on effect through a complex supply chain. Such attacks could occur during commissioning and handover of major critical infrastructure assets (with high technology-dependency across multiple asset classes), causing very significant delay and cost.

Intellectual property-related areas, such as technical drawings, designs or projects for large commercial and infrastructure developments, are all seen as prizes and attractive to cyber criminals, as is commercially sensitive data – contract details, bid data, supplier data and pricing.

"Under attack around the world" - Construction-related hacks from Ukraine to New Jersey

(source UK Chartered Institute of Building)

In the light of the new and developing threats industry leading organisations are adopting a 'triple A' approach to protection. This means protection is deeply reviewed and sourced across 'Any Data, Any Device, Any Cloud' allied to a much more aggressive 'seek and destroy' approach to cyber malware and ransomware threats (i.e. not looking at responding - 'reflex' - but actively preventing key threats from crystallising).

The response among leading edge organisations in reducing Cyber threat draws heavily on Artificial Intelligence (AI) to analyse metadata sets and, as just one example, deploys memory tagging related deep-dive reviews which highlight anomalies and identify potential threats across complex networks.

Cyber-threat case studies

- In December 2015, a first-of-its-kind cyber-attack on a power grid took place in Ukraine. The incident caused a dangerous blackout for hundreds of thousands of people and prompted Kiev to review its cyber defences. The attack involved a team of hackers who targeted six power companies at the same time, according to US officials. Destructive malware wrecked computers and wiped out sensitive control systems for large parts of the power grid, making it harder for technicians to restore power.

- According to a report from the German Federal Office for Information Security (BSI), in 2014, a steel mill in Germany suffered serious physical damage when hackers mounted a successful campaign against the system operators. The hackers used both targeted emails and social engineering techniques to gain access to the mill's control systems. In particular, a "spear phishing" campaign was aimed at individuals in the company, to trick them into opening messages that enabled the hackers to harvest login names and passwords. BSI did not name the company operating the plant nor when the attack took place. In addition, it said it did not know who was behind the attack nor what motivated it.

- In May 2013, an Australian Broadcasting Corporation news programme reported that an unnamed source claimed Chinese hackers had accessed the computers of a "prime contractor" and stolen floor plans, cable layouts, server locations and security system designs for the Australian Security Intelligence Organisation's new Canberra HQ, which was under construction at the time.

- In November 2013 40 million customers of US retailer Target had their payment card details exposed when authentication information was stolen from a Heating Ventilation and Air Conditioning (HVAC) subcontractor. Criminals infiltrated the firm's system, installed malware on its point-of-sale network and stole payment and credit card data.

- The US Industrial Control Systems Cyber Emergency Response Team (ICS-CERT) monitor newsletter reported that the Building Management System of a New Jersey (USA) manufacturing company had been hacked in 2012. Intruders exploited a weak credential storage vulnerability to access its energy management system, controlled by Tridium's Niagara software.

- To demonstrate how easily security could be compromised, in 2013 Jesus Molina, a US cyber security consultant, took control of the lighting, shading and HVAC systems in a luxury hotel in Shenzhen, China, via the iPad in his room.

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Skills Readiness and Modern Organisational Design

The digital owner of tomorrow is yet to be born. – Traditional skills have been about timely, predictable, quality physical maintenance and site management in what has been a predominantly blue-collar workforce.

Whilst recognising that more innovation needs to be introduced, organisations are already dealing with the disruption caused by a shifting demographic. Fundamental digital skills, such as database system management, coding, automation and social systems, have begun to enter the workforce en-masse, and this will accelerate over the next decade.

How to manage and get greatest value from this influx of new skills and keep the balance between digital and hard skills is a challenge with significant implications for management science and organisational design.

In 10 years, we're at the balance point. 50% of staff will be the knowledge holders. The other 50% will be the digital innovators. How do we manage the interaction?

Overarching perhaps all of these considerations is the question we pose here "How do we get new tech / computer skills into Construction? "

We know we need them. People with these skills also likely won't be looking to construction.

A significant issue we are currently observing is that although people with the requisite digital skills are now entering work as part of the 'Generation Z' or 'iGeneration' workforce they are commonly not being hired into the construction industry.

Our research shows that the issue creating this barrier has manifold root causes. Firstly, the construction companies are predominantly assessing new hires based on their current requirements which don't routinely necessitate any kind of digital skill set.

Secondly the potential workforce currently leaving education is regularly being told that the built environment is an unskilled industry which is fundamentally based on manual labour, hence they are being steered into other industries.

For both issues/barriers to be eliminated we need to remove the countrywide stereotype associated with the built environment and construction.

Key facts from our research and related reference points

73% of parents would not want their child to consider a career in construction

54% of teachers and parents believe that there is a lack of career progression and that the industry is associated with lower skilled workers.

62% of teachers and careers advisors held negative views of the construction industry as a route for their students to pursue.
(https://www.kier.co.uk/media/2999/researchreport.pdf)

> "...the whole of the construction space is seen by many teachers and parents as a bad career option. In fact, I've often heard any route into the built environment being seen as one for the 'thick kids'"
>
> *https://medium.com/age-of-awareness/design-engineer-construct-inspire-a266558fc9aaSteve*

The construction industry is notoriously (and understandably) short sighted, regularly focused only on meeting the next deadline or delivering the next project to tight and project-specific timelines. From our experience, few decisions are made digital-strategically in these companies.

This presents a problem when we look at sector recruitment as it is mostly project focused to meet a specific need at that point in time. As stated above, the skills required and evaluated during the hiring process are solely focused on the specific role which needs to be filled and any digital skills a potential employee might bring are more often than not overlooked.

Another problem we currently see is if a digitally enabled person has been hired, they are often not given the scope or authority to make meaningful change. This new generation workforce is seen by the company to be new to the industry and therefore inexperienced. Industry perceives these emerging skills in a young workforce as a risk rather than an asset.

Defining the Size, Scale and Context of an 'Asset'

A big challenge for the digitalisation and transformation of through lifecycle asset management is the vast difference in how an asset might be defined. For example, an asset to one business, such as an office facility man-ager might be as granular as a piece of electrical equipment such as a light fixture.

At the other extreme, an asset to an organisation such as the Environment Agency might be a mound of earth acting as a flood defence barrier. Both are assets which are important to their relative organisations but there is very little commonality in terms of how they are managed, and the data recorded about each.

As well as this complexity around the type of assets there is an added layer of complexity when we consider the granularity of an asset.

For an organisation such as a university, they could have multiple ways of looking at their assets but with a varying level of granularity.

At the highest level each asset could be an individual campus spread across a city, after this the next level down could be that each individual building or facility is an asset, further down still we could look at the components in the building such as the lights, tables, doors, radiators, etc.

Even at this level we could describe parts of these as-sets as individual assets themselves, for example a door has hinges, handles and locks all of which could be classed as individual assets.

The current ways of thinking in the industry don't allow for any flexibility with regards to the management of assets. Because of the way data is collected and used at present it is only suitable for the type of asset and granularity of asset which it has been collected for.

BuildingSMART suggests [BuildingSMART International - Infrastructure Asset Managers BIM Requirements Technical Report] that infrastructure assets as distinct from the broader definition adopted by other sectors due to factors that include:

• The asset is the core of the business rather than just providing a space or platform for a business.

• The majority are effectively one-offs, even if some of their components are mass produced (e.g. precast concrete elements in modular construction)

• Most infrastructure assets are designed for a relatively long life. Indeed, few are decommissioned at the end of a predetermined lifetime.

• Many of the assets are publicly owned and have critical external dependencies, driven by economic function of a city, state or country.

• An infrastructure asset failure can have catastrophic consequences on the surrounding environment and the wider asset base for instance an embankment slip closing a road or a flood overwhelming a bund and causing damage to the adjacent property.

• During its lifecycle, an asset may be reassigned to a purpose that is very different from its original design.

This definition implies, and therefore perpetuates, minimal cross-sector relation and collaboration as each sector believes that it has a unique challenge and there-for needs a unique solution to that challenge. This also means that data about an asset is collected and stored multiple times at each level of granularity with no link or connections between them.

In order to solve this issue, there must be standardisation across the industry regarding through-life management of assets and infrastructure regardless of what sub-sector is curating it.

Whilst standardisation is critical, so is the inbuilt flexibility to cope with the huge variance in the type of assets and their size.

Digitalisation goes a long way to achieving this as once all assets are managed digitally, ideally stored in a single source of truth, then the access and interrogation can be customised to suit the viewers' requirements.

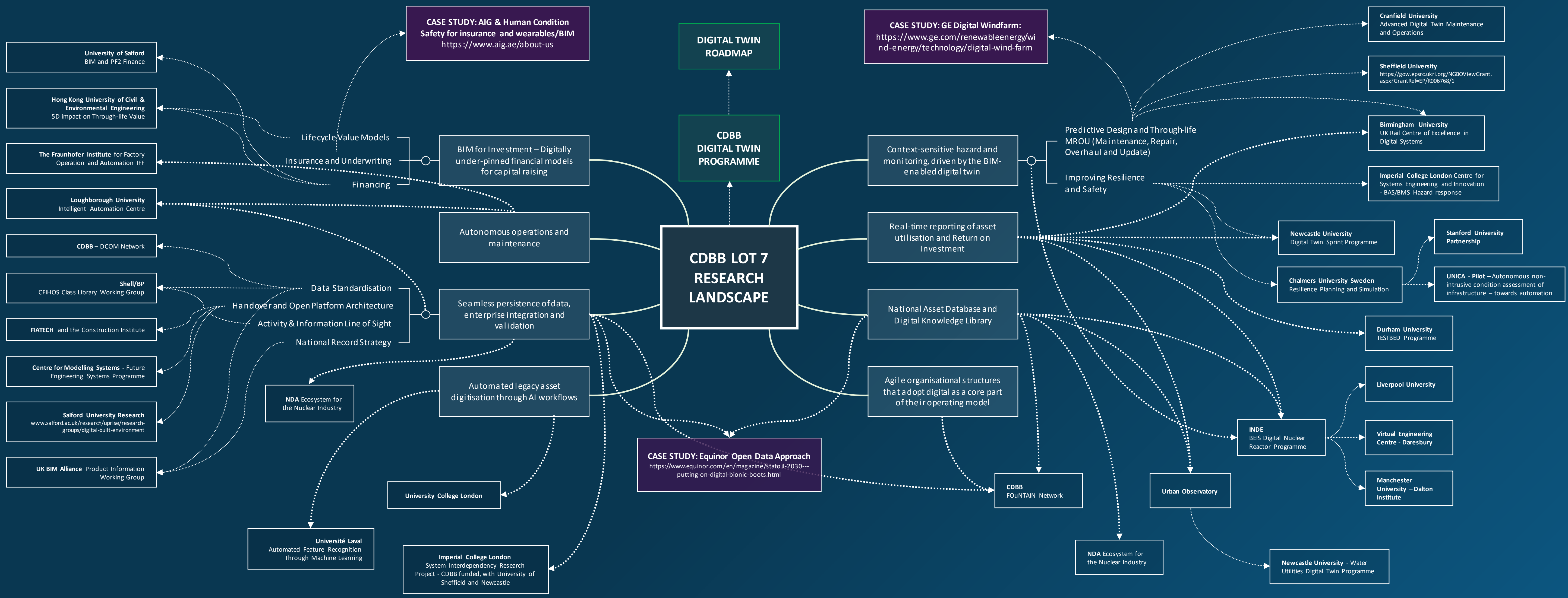
With organised digital data we could look at the asset as a whole (e.g. entire road, railway, building) or break the view down to the assets (e.g. each of the signals on a length of track). This information can all be stored in the same place, but the output is should be dependent on what was is required by the end user. and stakeholders (these can be as varied as a trackside railway signalman running a section of track and an Insurance actuary calculating risk overseas from the asset).

Various technology enablers and capabilities support this important piece of work, such as…

- The clear integration of workflows and data interfaces between GIS (Geographical Information Systems), BIM and a wide array of Asset Care systems.
- Asset Class Libraries with explicit detail about the level of granularity to which asset information is required, and that specifies what is considered as a 'maintainable asset'.
- Open data standards, governed by a single, national ontology framework, incorporating the best thinking of the extant and historical approaches to defining data schemas.

The UK Research Landscape for Through-life Asset Management

An A3 map of selected research pathways and projects funded in the UK and with key overseas institutions that support the acquisition of the Capabilities identified in this report. Details are provided in the Capability summaries and Appendix 1 – Capability Spreadsheet.



Institutions and Commercial Organisations on the landscape

CDBB	**University of Salford**	**University of Sheffield**	**Loughborough University**	**Durham University**	**Newcastle University**	**Cranfield University**	**Heriot Watt**	**Liverpool University**	**University of Laval**
Exeter University	Hong Kong University	Chalmers University	University of Birmingham	UK BIM Alliance	BEIS	Fraunhoffer Institute	Construction Institute	Centre for Modelling Systems	Equinor
AIG	GE	Rolls Royce	Wood	Sellafield	Nuclear Decommissioning Authority	CFIHOS (Shell/BP)	Imperial College London	BEIS	Manchester University (Dalton Institute)

3

CAPABILITY SUMMARIES

Automated Legacy Asset Digitisation

STATUS: PRELIMINARY RESEARCH UNDERWAY

OVERVIEW

The ability to automate the creation of data-rich digital models from scans and surveys of our assets with minimal human intervention, through technologies such as adaptive feature recognition of the physical geometry, machine learning algorithms and contextual links to other asset data systems.

The achievement of this capability will reduce the complexity and risk in migrating the UK's legacy assets towards integration with the digital twin. Academic research and trials are currently underway in this area, but with little broader support currently from government funding routes or academic partnership.

DRIVERS

- The digitisation of legacy assets is the greatest impediment to broader adoption of the digital twin across the UK's owner/operator organisations.
- Current scan technology provides accurate geometrical models but is limited in its ability to provide functionality to subsequently modify the geometry or apply metadata without human intervention.
- The cost, skills demands, and complexity of digitising aging assets is hindering the sponsorship of business cases for investment in new technologies.

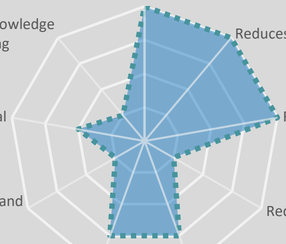
BARRIERS / ENABLERS

- The technology may require the development and open-access provision of a model reference database that would feed machine learning processes to raise accuracy and confidence.
- Appropriate ontologies and semantic rules would need to be developed and adopted by broader industry organisations in order to provide ready access.
- The development of APIs that support a push-pull of data from other sources to connect with the scanned model as linked attributes.

BENEFITS

- Reduction in cost, complexity and risk for legacy assets and expedited integration with digital asset management approaches
- Reduction of cost and complexity in the delivery of new assets which rely on interactions with legacy asset for co-ordination.
- Accelerates the rate of adoption of digitally-enabled processes for complex infrastructure classes where previously the cost/benefit argument was not strong enough.
- Reduces the risk of extended manual survey and walk-down times for engineers, thereby reducing the risk of safety impacts.

BENEFIT RADAR



RESEARCH FOCUS

The Centre for Research in Geomatics, a faculty of the Université Laval in Quebec, Canada has funded research streams into the development of approaches that reduce the barriers to macro-level intelligent data capture and survey for 3D assets. Focus has been on the development of automatic feature recognition for LiDAR and associated scanning techniques. These have been trialled within a limited scope by the researchers. No commercial partnerships have yet been established. Further research is being proposed around the topic of fuzzy-logic applied to scanning to manage uncertainty in the scan results from urban scenes.

(ref: *XING, Xu-Feng; MOSTAFAVI, Mir-Abolfazl and CHAVOSHI, Seyed Hossein (2017) A Knowledge Base for Automatic Feature Recognition from Point Clouds in an Urban Scene, ISPRS International Journal of Geo-Information.*

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Automated Legacy Asset Digitisation

STATUS: PRELIMINARY RESEARCH UNDERWAY

The UK has a dilemma. A rich history of investment in our built environment over the course of the nation's history, and in particular the vast introduction of assets since the industrial revolution and post-war periods have left us with a legacy of complex assets which are culturally rich and economically important.

The question of whether to bring these existing assets into the digital age is a significant one, loaded with financial and logistical challenge. For many organisations looking to make a transition to information-rich digital lifetime ownership and balancing risk and reward, we find that 'fixing forward' - investing in digital processes for new assets only - is often the go-to strategy.

From an asset owner's perspective, the cost, complexity and Return on Investment arguments for digitisation of legacy assets are often difficult to estimate with confidence and leads to difficulties in producing a credible business change for the change. Allied to this is the challenge of ensuring that the organisation's engineering workforce, enterprise systems and design processes are ready for the move.

From a national perspective, the UK's asset base is overwhelmingly non-digitised. If we are to explore the value inherent in a national digital library of our critical assets, (See Capability: National Asset Records and Emergency Response Platform) then the balance of risk and reward must be predicated on something more than purely the cost of the endeavour and must consider the need to establish a baseline for the future.

Technology is advancing. The introduction and maturation of 3D scanning and photogrammetry technologies has made the capture of as-built geometries vastly less time consuming in the last decade. However, the technology remains limited in that the capture process provides only geometrical point clouds, meshes and geospatial data as outputs.

Significant time is spent by designers on converting these outputs into CAD/CAE models and drawings. This process requires a degree of interpretation, technical proficiency and processing time. However, the output remains simply geometry, with no more intelligence or metadata than a traditional CAD model. To attach metadata and product information to the BIM model, yet more effort is required, including as-built walkdowns, audits and checks against procurement and asset management systems.

The potential to bring the geometry scanning and rich data collection together into one automated process is a major capability stepping stone. Machine vision and object recognition technologies have advanced far enough that this has become a capability that is in reach within the next 5 years. Acquisition and translation of basic assets from scans to BIM, such as pipes, floors and walls can already be achieved with a reasonable level of accuracy.

Increasing accuracy and confidence further could be supported through use of a national knowledge database of assets. Object and feature recognition algorithms will need to be 'trained' using this knowledge base to improve accuracy over time. It will also require the establishment of a common ontology for the structuring of data within each class and sub-class of asset.

Streamlining the conversion of scanned data into information-rich digital 3D models could lift some barriers to greater uptake of digital workflows for our legacy assets. Challenges will revolve around the validation of the translated output, perhaps using other enterprise systems to triangulate the result against known records of procurement or installation.

Fundamentally, the decision to digitise legacy assets or not is a product not born purely of cost and technology readiness, but also of long-term strategic positioning.

RESEARCH FOCUS

The Centre for Research in Geomatics, a faculty of the Université Laval in Quebec, Canada has funded research streams into the development of approaches that reduce the barriers to macro-level intelligent data capture and survey for 3D assets. Focus has been on the development of automatic feature recognition for LiDAR and associated scanning techniques. These have been trialled within a limited scope by the researchers. No commercial partnerships have yet been established. Further research is being proposed around the topic of fuzzy-logic applied to scanning to manage uncertainty in the scan results from urban scenes.

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Autonomous Operations, Maintenance and Repair

STATUS: PRELIMINARY RESEARCH UNDERWAY

OVERVIEW

The ability to exploit and configure Building Management Systems (BMS) to integrate with the digital twin to drive autonomous or semi-autonomous robotic systems to automate Operations and Maintenance (O&M) regimes, including inspection, diagnosis, automated repair and replacement.

The achievement of this capability will dramatically reduce the cost and human health and safety risk associated with the long-term maintenance of assets which may present a hazard for the traditional activities of human engineers. It is driven by the stepwise advancements in robotics, machine learning, machine vision and large-bandwidth wireless communications (5G).

DRIVERS

- Worker health risks from hazards such as operations at height, exposure to extremes of temperature, chemicals or contamination is a major factor in managing the liabilities of the UK's asset base.
- The economic and social cost of worker injury or death is estimated at £8bn per annum.
- Our approach to design of assets is predicated on the ability for human workers to access equipment and other maintainable assets with minimal risk. Removing that restriction would potentially allow for significantly more efficient designs and construction practices.

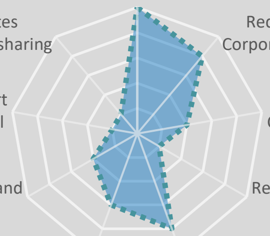
BARRIERS / ENABLERS

- The recent advancements in the maturity and cost of implementation for autonomous robotics enabled with machine learning and intelligent feedback supports the rapid evolution of this capability.
- Liability issues associated with a lack of human involvement in what may be activities critical to asset safety or security is likely to present several insurance and regulatory concerns that will need to be identified and overcome.
- The question of reliability of the maintenance robotics themselves presents a circular argument which requires further review.

BENEFITS

- Reduction in health impacts on the UK workforce across the infrastructure sector. This in turn will have knock on positive impacts on national productivity and GDP.
- Reduction of cost and complexity in the delivery and management of new assets which currently rely on designs which allow for human maintenance.
- The potential to raise the level of digital skills in a traditionally blue-collar workforce will improve agility in modern owner/operator businesses.

BENEFIT RADAR



RESEARCH FOCUS

Loughborough University's Intelligent Automation Research Group has undertaken a number of research topics around the capturing of human operator skills via wearable haptics that is then integrated with machine learning and machine vision systems to allow for the rapid learning of routine maintenance and operations tasks by simple robotic systems.

The University is also focused on research into close human-robotic interaction in hazardous environments, and on the interaction of robotics with Virtual Reality and Augmented Reality environments.

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Autonomous Operations, Maintenance and Repair

STATUS: PRELIMINARY RESEARCH UNDERWAY

A significant factor in determining the overall lifetime cost and efficacy of asset ownership lies in the operational down-time associated with planning and undertaking complex inspection, maintenance, repair or replacement activities.

Whilst this is not the case for all asset types, these activities have the potential to reduce or completely prevent the utilisation of an asset during the maintenance work. This has the potential to impact on the financial performance of the asset, and introduces human risk and hazard, where the replacement of the equipment brings engineers close to a range of hazards, including working at height, electricity, heat, moving equipment, hazardous chemicals, and natural hazards such as bodies of water or landslide risk.

Rapid increases in the level of maturity of remote sensing and handling technologies provide an opportunity for asset owners to leverage greater confidence in these technologies to automate a large array of activities that have traditionally required humans to carry out much of the task.

Our vision of the future for the digital twin, and for the role of data-rich O&M environments includes the realisation of a capability to use autonomous equipment to undertake the routine maintenance, repair and replacement of some key asset classes in high-hazard environments, with minimal human intervention.

The application of robotics and automation in reducing human hazard is not in itself a new concept. The use of robotic handling equipment in the manufacturing and construction sectors has met with success. However, the application of this technology in the inspection and maintenance context is in its infancy, and presents some unique challenges in terms of integration, cost and agility – given the natural turnover and upgrading of equipment over an asset's life.

We believe that autonomous maintenance is a natural evolution, building upon the developing maturity of the predictive maintenance platforms currently being demonstrated (and actively exploited) across a range of UK asset classes. [See CASE STUDY: Predictive Maintenance Analytics at GE's Windfarms].

In terms of current research into this field, we have identified a number of national and international research groups that are focused specifically on the topic of asset care. These can be seen described in the section at the bottom of the pages in this section.

Whilst the overarching benefits of automated or semi-automated O&M activities are easily attributable to the potential for reducing the risk of human injury and error, there are also broader benefits to be derived from the increased reliability, and therefore utilisation of the assets in which these automated systems are used.

Reductions to downtime, increased certainty of maintenance periods, and the potential to design equipment layouts without the constraints of human access requirements all provide material benefit to the UK's approach to asset ownership.

RESEARCH FOCUS

The Fraunhofer Institute for Factory Operation and Automation IFF in Germany has partnered with a number of private-sector organisations to develop automated or semi-automated robotics with the appropriate cost and flexibility characteristics to justify application over a range of inspection and routine maintenance activities. However, we do not believe that the robotics developed to date are managed by integrated asset information hubs, or predictive maintenance platforms. This may present an opportunity for cross-border collaboration.

Whilst no well-defined UK partnership with other NGOs or Academic institutions currently exists, Fraunhofer is currently developing a new internationalisation strategy - "with the twin goals of setting out strategies for cooperation with the highest-calibre international partners and qualitatively bolstering its own institutionalized commitments abroad." (Source: Fraunhofer Annual Report 2017)

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BIM for Investment – Capital Raising and Underwriting

STATUS: PRELIMINARY RESEARCH UNDERWAY

OVERVIEW

The ability to raise finance and secure insurance for major project delivery and through-life investment quicker, and under improved terms, based on the contribution that the digital twin makes to increased certainty of lifetime cost forecasting, value chain management, co-ordination and outcome assurance.

By achieving this capability, we will know how to define and calculate whole-life value and subscribe to a broadly aligned common model for lifetime value at all stages of the lifecycle - Project delivery to asset demolition and environmental remediation.

DRIVERS

- The infrastructure sector has a measurable impediment to securing competitive asset finance and project insurance, when compared to other high-value industries, such as technology, aerospace and mining.
- Projects and asset owners are unable or unwilling to adopt modern best-practice digital approaches to through-life ownership due in part to the lack of funding to transition. Likewise, investors are unwilling to finance such change.
- Stranded asset risk is high for legacy assets in the operational phase that struggle to communicate residual value of the lifecycle.

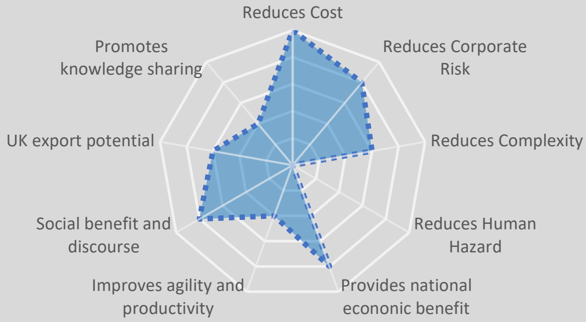
BARRIERS / ENABLERS

- The terms for financing of major projects reflect the perceived risk and uncertainty of asset delivery projects and are driven by norms from the past 50 years. Proving that these norms do not reflect the projects of today will be an important aspect of the challenge.
- Optimism Bias is prevalent in the sector – the tendency for organisations and individual stakeholders to view successful past projects as the exemplar for all future projects – rejecting any proposed change to future delivery, even where the exemplar had inherent inefficiencies and/or failures. A symptom of risk aversion.

BENEFITS

- An overall reduction in the cost of through-life asset ownership, particularly design and construction costs.
- Greater ability to estimate net contribution of value to the UK economy from infrastructure, and valuation of the NPV of these assets to support national asset finance initiatives and PFI in the future.
- Added momentum to adoption of digital asset lifecycle management approaches, as the cost of capital begins to align to the through-life cost model, driving asset owner behaviours.
- An acceleration in the number and quality of high-value CAPEX and OPEX infrastructure projects across the UK. Social benefit through the increase in critical national projects, including power and transport.

BENEFIT RADAR



RESEARCH FOCUS

Researchers at the University of Salford, Manchester were commissioned in 2017 in partnership with the International Islamic University of Malaysia to produce a paper titled "Critical Success Factors and Contractual Risks for Private Finance projects implementing Building Information Modelling".

The authors identified a series of critical success factors and recommendations on novel contractual structures which they believe could materially improve the transparency and attractiveness of BIM-enabled project delivery to prospective investors. The study includes extensive dialogue with investment stakeholders, which highlight the perceived lack of understanding of the risks/benefits BIM across all parties involved.

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BIM for Investment – Capital Raising and Underwriting

STATUS: PRELIMINARY RESEARCH UNDERWAY

A central benefit of BIM and associated digital engineering processes lies in its potential to provide organisations with a heightened ability to forecast and control costs, to co-ordinate complex design tasks, and to reduce the loss of fidelity (and therefore confidence) that is often associated with the handover of information between lifecycle stages.

However, traditional financing and underwriting models for the design, construction and ownership of new assets (often predicated by the standard Capital Asset Pricing Model – CAPM) does not recognise these benefits or consider them against the overall risk profile for the investment. This has resulted in no material change to the Weighted Average Cost of Capital (WACC) or hurdle rates for major infrastructure projects, despite the increase in adoption in BIM and associated Digital Twin concepts.

This perceived lack of responsiveness from the financial community has had a dampening effect on the willingness of projects and asset owners to invest in digital technologies. As finance costs are typically between 4-6% of the total lifetime cost of ownership for non-contentious large UK infrastructure projects, there is significant pressure on the asset/project owner to tailor a project plan to the investment criteria of the lender, rather than appear contentious, or introduce what investors perceive as unnecessary additional technology risk.

We believe that significant and sustained engagement with the investment and insurance communities is required to provide the right levels of confidence and domain knowledge to support BIM and associated technologies becoming a central component to their method for evaluating overall project cost and risk.

Central to this will be the establishment of a unified baseline cost model for lifetime value, which is predicated on the use of modern digital lifecycle management platforms and processes. This unified model will need to be supported by norms captured by developers, operators and public-sector organisations, and will require industry-wide collaboration to code these norms into terms that investors recognise, and that can support the refinement of their traditional risk assessment models.

This issue has been recognised by several financial institutions, including national infrastructure banks and multilateral agencies, but we do not believe that structured research into the alignment of digitally-enabled lifetime cost models to investor risk models has yet been commissioned.

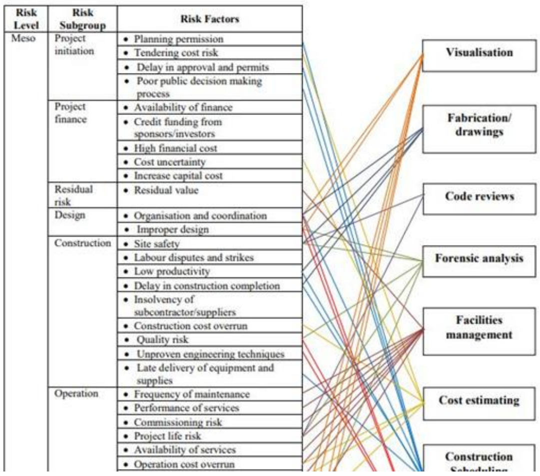

Figure 1. Typical interactions between lifecycle risk factors and BIM/Digital Twin functional elements - Abdullah Habib, Critical success factors and contractual risks for Private Finance 2 (PF2) projects implementing BIM (2017)

We understand that the recently established UK National Digital Twin (NDT) programme of which CDBB is a lead partner, has provision within its definition of the Digital Twin of the requirements for closer integration across the investment decision making process, including with investor stakeholders. We believe that this could act as a strong vehicle for structured research into the topic and bring together public-sector and private investment stakeholders to define a new model for through-life value.

RESEARCH FOCUS

Researchers from the Department of Civil and Environmental Engineering at The Hong Kong University of Science and Technology have authored papers on the impact of 5D cost simulation using BIM data on the ability of a project to secure financing. Whilst typical application scenarios for 5D BIM focus on estimating cash outflow, the researchers have turned this approach around and considered the benefit of simulating cash inflow analysis and project financing.

Their paper proposes a BIM-based methodology framework for cash flow analysis and project financing for revenue-generating asset types. The framework considers contract models and retainage to estimate cash inflow, and cash outflow patterns for equipment, manpower, and materials in order to more accurately measure spend rate and funding needs. The research was completed in 2015 and published in the International Journal of Project Management [Volume 34, Issue 1, January 2016, Pages 3-21].

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Seamless Persistence of Validated Asset Information

STATUS: ADVANCED RESEARCH UNDERWAY

OVERVIEW

The ability to make robust links between a range of digital enterprise systems that collectively provide a central platform for decision making, command and control, and the exploitation of the digital asset at all points of the lifecycle. The E-Artefact becomes a valuable commercial asset in its own right.

We can create a validated, decentralised single source of truth across a wide range of enterprise systems - cross-referencing various sources of information and digital model data across an organisation to ensure that these sources properly align. (e.g. Estimating, Requirements Management, GIS, Procurement) Data validation is automated, and central to the sign-off of any work.

DRIVERS

- Asset owners often struggle with the integrity of handover of information between lifecycle stages and handling organisations. This is in turn driven by the disparity of tools, processes, file formats and transfer mediums across organisations and suppliers
- Information silos across the range of enterprise software systems often results in a lack of consistency, which undermines trust in the idea of a common data environment at the organisational level.

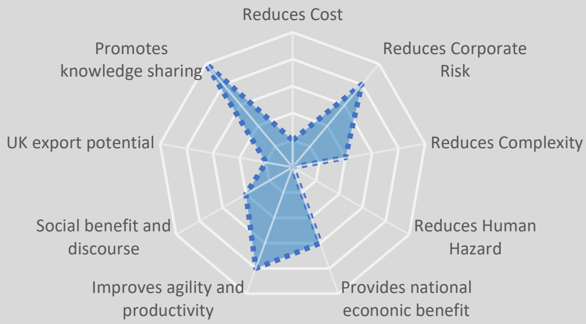
BARRIERS / ENABLERS

- Different ways of classifying and naming assets is commonplace across asset-centric organisations, often driven by the persistence of historical conventions brought across with legacy assets.
- Software developers are not keen on open data formats, which some see as undermining their IP, and ability to capture customers into a single ecosystem of applications from the same vendor.
- Asset introduction projects are often undertaken based on ‘handover’ rather than ‘persistence’. The asset owner is often not involved in the delivery of the project until commissioning.

BENEFITS

- Replacing ‘handover’ with ‘persistence’ reduces the loss of information further and brings organisations and suppliers closer together – promoting knowledge sharing.
- The risk of loss of design intent, IP and auditable trails through lifecycle stages is markedly reduced.
- Organisations can extend their core design and operational systems out to their supply chain – improving productivity and automating information transfer. Changes to core systems will be available immediately to the supply chain. avoiding technical debt.

BENEFIT RADAR



RESEARCH FOCUS

FIATECH is an international working group, managed by the Construction Institute, and facilitated by the University of Texas. The Fiatech Sector champions the development of technology within the capital projects industry. It is funding a range of “fully formed” research and technology projects designed to produce creative, innovative solutions that tangibly improve performance and capital efficiency.

FIATECH’s Information Management working group is running specific research streams on information handover, assurance and operational readiness, as well as the integration of operational systems to BIM data. These research streams will persist to 2020.

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Seamless Persistence of Asset Information

STATUS: ADVANCED RESEARCH UNDERWAY

Information is at the heart of our future for asset introduction and ownership. It is the backbone from which the broader spectrum of capability is hung and is fundamental to the successful functioning of the software and data platforms that will enable a digital through-life environment.

The ability of organisations across the lifecycle to transition information openly and coherently between lifecycle stages and stakeholders is still immature globally. The lack of a functioning exemplar for the industry represents a significant hurdle in the digital transition planning for those organisations who wish to commit to a data-centric asset ownership strategy. It also serves to create confusion and hesitation across the IT functions within these organisations who are tasked with integrating data across the gamut of corporate services and functions to support better enterprise decision making.

Due to the comparative complexity and velocity of change in this area, this report will not go into granular detail on the current industry arrangements and limitations with regard to asset data management. For a more comprehensive overview of the state of digital infrastructure data, we refer the reader to the "New Technologies Case Study: Data Sharing in Infrastructure" report produced by Deloitte for the National Infrastructure Commission in November 2017. We are in broad alignment with the findings and recommendations of the report and have expanded on the required future capabilities herein.

To meet our vision for a future, the core capability of achieving a seamless, transparent, lossless data transition across the complete lifecycle stages is imperative. To add focus, we believe that the crux of securing this capability lies in the development of four themes of data and organisational capability:

- A nationally championed ontology for asset data
- Organisational capabilities to show line of sight between lifecycle activities and information requirements
- The integrated digital enterprise
- Robust national lifetime record strategies

The rapidly strengthening confidence in, and technological maturity of cloud-based systems provides an interesting lens with which to view the realisation of the four themes. In a transparent digital economy, cloud systems could be part of the answer to opening up networks of collaboration between sectors, industries and even international market players. It could act as a platform for a common, unified foundation for data structures, and could provide a through-life platform for an organisation's entire software application architecture to reside – extended out to all parts of the supply chain as a common backbone.

In other sectors, such as aerospace, PLM systems have traditionally taken on this role. All suppliers and delivery partners co-ordinated activities through a single system, integrated by virtue of its strict prescriptions on file formats, integrations and workflows. Many of the organisations who invested in this 'locked-down' model for lifecycle management are now struggling to unpick what has become an unwieldy, over-engineered and maintenance-intensive monolith.*https://www.engineering.com/PLMERP/ArticleID/14370/Boeing-Airbus-and-the-Hardship-of-Dealing-with-PLM-Obsolescence-TV-Report.aspx)*

Organisations are now looking to models that follow a doctrine of more loosely coupled, but open source application architectures. Cloud systems play well in this approach, and the future could look very integrated if the momentum of functional expansion continues. However, the burden is still on the providers of such cloud platforms to demonstrate a robust ability to secure data against cyber threats and manage the risks of intellectual property theft. Two areas where many high-value asset organisations feel exposed and reluctant to invest in a meaningful way.

We have broken out each of the four capability themes for further description in the pages following. For each, we have attempted to identify high-profile areas of national research that support the achievement of the overall end-state for the capability.

RESEARCH FOCUS

The Centre for Modelling & Simulation (CFMS), an independent, not-for-profit research collaboration group which includes Cranfield University and Bristol University as well as several aerospace blue-chip companies is funding the **Future Engineering Systems programme.** This programme will develop and demonstrate a prototype future engineering system infrastructure to fully integrate engineering data sources within the process lifecycle management (PLM) tool chain. Within the FES, the project will demonstrate the integration of raw data from CFD and FEA analyses via open source data standards and formats with Uncertainty Quantification and Management (UQ&M) functions and automated agent-based quality control. With a project value of £4.22m, FES will complete in 2019. The project is delivered as a partnership between the Department for Business, Innovation & Skills (BIS), the Aerospace Technology Institute (ATI) and Innovate UK.

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Seamless Persistence of Asset Information

STATUS: ADVANCED RESEARCH UNDERWAY

The UK-wide championing of an Open, Fully-described Data Ontology for all asset classes.

We will require a well-developed data ontology for all aspects of asset-centric information and how it relates to other organisational data points. Work is already underway in the UK, undertaken by organisations such as BuildingSMART, The British Computer Society (BCS) and NBS – who are developing the Uniclass system – to create class systems that describe the majority of the UK's typical built asset and equipment types.

The success of these class systems hinges greatly upon the speed of uptake and is threatened by the appetite of asset owners to select alternative systems that, whilst less widely supported, may be more mature in describing certain types of asset. A good example is in the Oil & Gas and Marine sectors, where Uniclass is eschewed in favour of more descriptive classification systems that focus on the needs of equipment-heavy use cases for asset care. Over time, a patchwork of class systems has spread across the UK infrastructure sector.

Finding parity and facilitating the open sharing of information and models across different organisations is made significantly more complex due to the mapping that is often required to bridge the mismatch in enterprise information ontologies.

In our vision for the future through-life management of assets, the UK has championed a single, fully-described data model for assets of all classes. Working groups from across the public, private and academic spheres are active to help maintain the configuration of the system baseline, and the mandating of the system into major value chains is being undertaken through direct government policy making. By having a common foundation for asset classification, the management and interrogation of national assets can be more easily undertaken, major project delivery will become more predictable and the nation's ability to move towards a transparent commercial environment that promotes efficiencies and modular design and construction can be improved.

Unbroken line of sight between lifecycle activities and information creation and management

A lack of clear information requirements from the end-user has been a perennial problem for designers, constructors and commissioning agents. In a traditional infrastructure project model, the functional requirements of the asset took centre stage. The end-user/operator wanted certainty that the asset did what it was required to do, but the information required to own and operate the asset into the future was often only considered towards the end of the construction phase – too late for meaningful efficiencies from the design phase.

Whilst BIM and associated digital engineering methodologies have helped to raise the profile of this issue, O&M functions within many asset owner organisations are not mature enough in their understanding of digital systems to be clear on their needs for operational data from front-end project teams. Organisations are often using Dickensian or obsolete platforms for enterprise asset management, and the configuration management of the asset is often poorly controlled as a result.

In our vision for the future, these information requirements are mapped to the activities that will demand the information. Each major operations and maintenance activity type should have a profile for data required, and these should be described within a wider system of requirements. Asset class types themselves should also have clear information requirements. Additionally, the asset configuration and Information Management arrangements for change on existing plants must be clearly defined, to ensure the benefits are not confined solely to new asset creation.

We are not aware of any co-ordinated research specifically tailored to the outcome of 'line of sight between activities and data requirements.' However, a case study from the heavy industry sector does show a co-ordinated commercial research pathway for information requirements related to asset classes: Case Study: Capital Facilities Information Handover Specification.

RESEARCH FOCUS

The UK's Digital Reactor Design Programme is a Department for Business, Energy and Industrial Strategy (BEIS) funded as part of a UK government research programme with the aim of developing the first stages towards an Integrated Nuclear Digital Environment (INDE) which will:

- Develop a digital integrated framework to support future nuclear reactor build – design through to decommissioning – including information persistence and records
- Provide a safe environment for scenario planning
- Provide value to existing nuclear infrastucture programmes

The project has completed Phase 1 of the work, with academic partners including Liverpool and Manchester University, CDBB and a number of commercial organisations in the sector. Phase 2 is due to commence in March 2019, for a duration of 2 years, with a value of c. £4m

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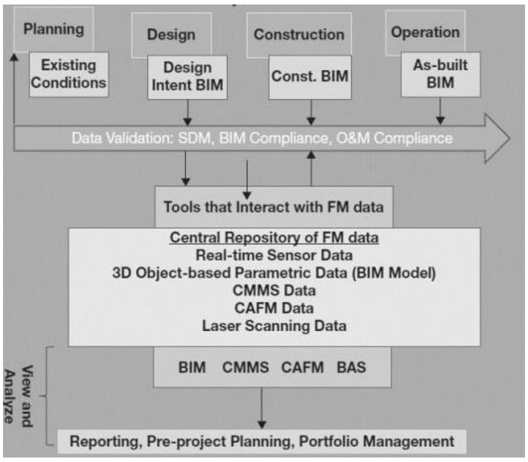
Seamless Persistence of Asset Information

STATUS: ADVANCED RESEARCH UNDERWAY

Integrated and Validated Enterprise Systems Data

Having achieved the capacities of a clear national data ontology, and a fully described set of information requirements, the next challenge for asset owners is in the transition and integration of this data across the lifecycle stages without loss of intent, fidelity or ownership. The information must also be readily available to, and augmented by, a range of other enterprise systems. These could include works planning, inventory management, financial management and procurement and visual reporting tools. The seamless interaction and validation between enterprise systems is a crux point for the achievement of a functioning digital twin.



Example system architecture for an integrated asset-centric organisation.

Some lessons can be learned from the manufacturing sector, where Product Lifecycle Management (PLM) and Enterprise Resource Planning (ERP) platforms have been used for decades to unify a range of management systems and tools, but this monolithic approach is now causing wide-ranging problems within these organisations, as these systems require substantial ongoing licensing and overhead administration costs to maintain. It moves against the principles of agility, transparency and cost-effectiveness that the UK Infrastructure sector aspires to.

In our vision for the future, the platform for the integrated and validated enterprise lifecycle is the backbone of the asset-centric organisation. It brings together tools, data, strategic planning and communications into one managed area, but does not rely on one single application to knit the pieces together. De-centralised cloud systems that provide IAAS functionality can unify entire value chains under a single shared environment without the large overheads of PLM-esque systems. IP is managed through these systems, as is advanced DRM, contract management and quality assurance. A validated, integrated system will also raise the importance and prominence of the E-Artefact as a legally viable instrument to support litigation and improve corporate accountability.

National Record Strategies

Our assets are diverse. Infrastructure exists in the UK currently that will still be standing in 100 years or more. There is a need to identify and deploy a strategy (technological and cultural) for the long-term retention of information that will be critical to the management of the latter phases of the asset lifecycle, through to decommissioning and return to greenfield.

In our future vision, the UK has a national digital asset library – a central repository of information and geospatial reference data for those assets that constitute the most critical components of our national infrastructure. Assets related to transport, power, public utilities, defence, communications and physical hazards should be represented there. Knowing what data to store, in what format, and how to protect that information from obsolescence, malicious or accidental attack, contamination or degradation is important. Parallels can be drawn with the UK's initiatives on digitising services for public bodies such as the NHS and the DVLA.

A national record strategy will rely on very clear requirements for information, and a national approach to asset data ontologies to ensure consistency and structural parity of information. Organisations involved in the creation and management of through-life information will need to be clearly instructed on their obligations to contribute to this national database, perhaps through policies and a new digital asset regulator.

RESEARCH FOCUS

The UK Nuclear Decommissioning Authority has recently developed and released a private cloud system that represents a First of a Kind for secure Infrastructure as a Service that is able to host information at high levels of security classification and national criticality, over and above the current provision within the Government G-Cloud. It will be used by project developers, regulators, safety specialists and site owners to co-ordinate major projects, asset information and data, unifying delivery systems into one central hub.

The platform is intended to be developed further, in collaboration with UK Government, major supply chain partners and academic institutions to explore its use as a central data spine for the nuclear industry, able to serve applications, workflows, knowledge databases and information exchange.

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Real-Time Reporting of Utilisation & Return on Investment

STATUS: PRELIMINARY RESEARCH UNDERWAY

OVERVIEW

The ability to track the real-time performance of assets against their lifetime cost and revenue models, to ensure that the facility is generating the benefits expected. Building Automation Systems and the Digital Twin create feedback loops to business management and asset care systems. Reports allow businesses and asset owners to manage the utilisation and cost-effectiveness of their investment, use trends to predict future needs, and to make decisions that improve their return on capital employed.

DRIVERS

- Asset owners and operators often rely on ex-post reporting to measure the performance of an asset and its zones and equipment.
- This reporting is often highly subjective and based on a range of assumptions and rules-of-thumb. This delay and uncertainty creates delays in decision making and a lack of clarity when valuing an asset or estimating future costs of ownership.
- Poor organisational ability to measure or estimate return on investment can lead to an increase in the cost of capital, or the ability to raise finance at all, if investors are unable to trust the data.

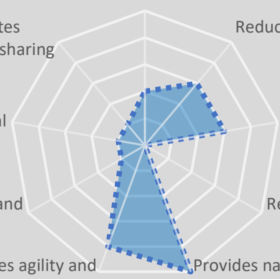
BARRIERS / ENABLERS

- Building Automation Systems, machine vision and IoT sensor technology must be developed further to support the end-state.
- Unambiguous relationships between reported asset metrics and the derived financial performance must be developed. Lessons to be learned from the FMCG and Aerospace sectors.
- Communications infrastructure and wireless provisioning must be vastly improved to support the level of sensor integration required for a clear picture of all aspects of a complex asset's performance.

BENEFITS

- Allows far greater granularity and concurrency in the reporting of asset utilisation and RoI. This in turn supports an increase in the liquidity and availability of asset finance, as the investor can be provided with a line-of-sight to the financial performance.
- Increases the productivity of asset owners and operators due to the availability of up-to-date information on asset utilisation and trends
- Overarching benefit to the UK economy as asset performance can be more accurately reported and predicted, which supports fit-for-purpose budgeting and fiscal surety for publicly owned assets.

BENEFIT RADAR



RESEARCH FOCUS

Birmingham University has been selected as the lead partner for the UK Rail Research and Innovation Network's Centre of Excellence in Digital Systems. The research projects funded under this arrangement are diverse, but all relate to the application of BIM and related BAS and sensor technology to the management of the UK's rail network. Specific to this Capability, the University is running research into how benefits (financial and operational) can be realised through digital technology on rail assets. The group has worked with major organisations within train operating companies and infrastructure. It has received prestigious awards for engineering innovation at a national level for work using in-service instrumentation to target maintenance on a third rail network. Algorithms developed at Birmingham are also used within Network Rail's Intelligent Infrastructure programme, which continuously monitor the health of over 5,000 sets of points.

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Real-Time Reporting of Utilisation & Return on Investment

STATUS: PRELIMINARY RESEARCH UNDERWAY

An important lesson to take from the digital success stories of other industries, such as Aerospace and FMCG, lies in their ability to exploit data in pursuit of better visibility of costs and utilisation.

Rolls-Royce's Intelligent Engine concept is working in collaboration with Bristol University researchers to explore the potential for data provided through the telemetry within its Trent series engines to drive not only predictive maintenance, but also to provide real-time feedback on the efficient performance of the engine and the financial impact of its operation to its customers. The platform will also provide heuristic analysis of alternative configurations and flight characteristics that will provide better RoI. *https://www.rolls-royce.com/media/press-releases/2018/06-02-2018-rr-intelligentengine-driven-by-data.aspx*

An example from the utility sector can be seen in the smart meter roll-out programme, which is fundamentally engineered to assist power producers and distribution grids to balance supply against demand, give consumers greater control over their costs, and calculate revenues for generators and transmission operators more accurately. This, and other demand response technologies have the potential to save the UK £2.9 - £8bn per year by 2030.

Away from these pockets of modernity, much of the UK's asset base, utilisation, revenue generation and costs are reported ex-post. Asset owners rely on rudimentary and often paper-based tracking systems to provide basic metrics. Examples being footfall through a certain area of the facility measured by number of turnstile rotations in a time window, or energy costs based on monthly meter readings.

In our vision for the future, asset owners will make use of the digital twin, enabled by a robust matrix of sensors and Building Automation Systems (BAS) to gain real-time feedback on the performance of their assets.

This will be of interest not only to asset owners and operators, but also on the investment and insurance community who fund the lifecycle activities of these organisations. Greater clarity and timeliness of performance data will provide new levels of transparency to stakeholders across the value chain, commensurately reducing the perception of risk and uncertainty.

Asset owners will have more reliable and granular information at their fingertips to make decisions on operational efficiency, redirecting and balancing resources according to demand. This could be partly or fully automated in the future, when BAS systems respond to changes in utilisation by opening new areas of facilities or turning off non-critical systems during periods of low demand.

Examples of the latter are already in demonstrable use across the UK's road network, where smart motorways are using real-time sensors and automated response software to manage the flow of traffic to ensure best utilisation of the asset even in the face of unpredictable and extreme situations.

Significant improvements in the way asset-centric organisations specify and integrate new BAS systems into their facilities and business models will be required to achieve the capability. Substantial up-front cost will need to be met, including the upgrade of asset-wide data communications infrastructure. The inception of 5G networks in the UK may provide a springboard for this investment.

RESEARCH FOCUS

TESTBED is a major interdisciplinary project coordinated by Dr Hongjian Sun at Durham University, with contribution from Heriot Watt, that combines insights from three academic disciplines - Electronics Engineering, Power Engineering and Computing Sciences, to address the difficulties of data transmission and feedback technology integration in smart grids. The EU funded project will coordinate action of 5 Universities and 3 enterprises from EU and China, to build and test sophisticated ICT to facilitate the successful implementation of smart grid applications.

he project will develop and evaluate function-driven communication frameworks, as well as develop and verify new data integration and analytic techniques for enhancing power grid operations. These will be extensively tested and evaluated in 4 well-equipped Laboratories at HWU, EPRI, ICCS, and CAS.

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Context-sensitive Hazard Management & Monitoring

STATUS: PRELIMINARY RESEARCH UNDERWAY

OVERVIEW

The ability to design and construct assets that can identify and react to manage hazards and maintenance requirements. An evolution of predictive maintenance, the capability will require context-sensitive machine learning algorithms and monitoring led by the digital twin and integrated sensor systems to help to keep people and equipment safe and assets operating at peak effectiveness.

DRIVERS

- Whilst comparatively low, safety statistics for standardised incident rates across asset lifecycle activities have flatlined for the past decade. (Online HSE Statistics Query – 2018)
- Investigations into major infrastructure incidents such as the Grenfell fire and the Ponte Morandi motorway bridge collapse point to poor monitoring and maintenance regimes as root causes of failure.

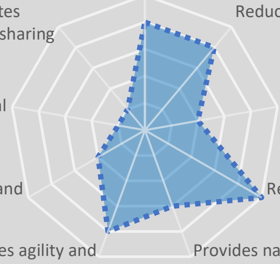
BARRIERS / ENABLERS

- Building Automation Systems, machine vision and IoT sensor technology must be developed further to support the end-state.
- Communications infrastructure and wireless provisioning must be vastly improved to support the level of sensor integration required for a clear picture of all aspects of a complex asset's performance.
- Must be done in tandem with an organisational review on safety systems and built into the safety management and response plans, as clarity must be found on legal aspects of automating safety response.

BENEFITS

- Keeping people and assets safer reduces the risk of injury, death or compromised asset operations.
- Reduces operational downtime as a result of incidents, providing increased productivity and contribution to organisational profit as well as UK GDP.
- Improved asset resilience and security due to increases in the monitoring of sensitive and hazardous aspects of the asset
- Reductions in corporate risk supports lower financing and insurance premiums and improves regulatory confidence.

BENEFIT RADAR



RESEARCH FOCUS

Chalmers University is undertaking a three-year project in collaboration with Stanford University and the City of Stockholm to create a digital twin platform that analyses changes in a range of environmental and physical criteria to drive better asset management and response planning. Part of the UNICA programme.

Pillar I – Data Collection: integration of terrestrial, satellite and airborne inspection with climate data and historical infrastructure data for comprehensive Structural Health Monitoring (SHM) strategy.

Pillar II – Modelling: optimized integration of the most current data (Pillar I) with advanced physics-based and data-driven models into a Digital Twin of a transport network as a decision-making support tool to assess the risks to infrastructure. The project is funded by the EU Horizon 2020 and the Barbro Osher endowment fund.

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Context-sensitive Hazard Management & Monitoring

STATUS: PRELIMINARY RESEARCH UNDERWAY

In this capability, we have a vision for assets that can actively respond to changes in a range of factors that could have implications for human safety by predicting complex events. This could mean closing off part of a facility to human access where a hazard has been detected, or shutting down equipment that may be approaching catastrophic failure. There are two angles to this capability.

The first lies in the **interaction between humans and machines.**

Predicting how humans respond to hazard is a complex task for automated systems. Examples can be seen from the automotive industry, where the next generation of driverless cars is fitted with intelligent machine vision prediction algorithms and full-spectrum camera systems is providing its customers with growing confidence in the technology.

Many examples also exist in construction plant equipment, where protective functions on assets such as cranes, cutting equipment and site vehicles are now fitted with the ability to recognise when a person is putting themselves in harm's way, and will act to avoid any unpleasant outcome.

The same is true of assets where security is of critical importance. Facilities such as nuclear power stations, chemical production labs and Defence sites can use intelligent sensors to automate access control for verified personnel through features such as face recognition and context-sensitive pattern recognition – i.e. The activity being performed by the individual is unusual, given their historical trends, and may need to be flagged up. This functionality exists already within the on-line space to identify attempts by staff to steal corporate or sensitive data from secure networks.

In the second angle, lies the **evolution of predictive maintenance**, which sees an asset respond to changes in its condition in real-time to avoid failure or to improve efficiency, revenues, availability and resilience.

Achieving this capability will require a leap in the prevalence of seneors and linked Building Automation Systems in our assets. The challenges around cost/benefit, and in the approach to retrofitting our older facilities with these systems will need to be reviewed with care.

Modern facilities are the most obvious target for investment in these integrated technologies, but arguably our aging assets are perhaps where our greatest human hazards and reliability issues can be found.

Examples can be found in industry and academia of research into cost-effective implementation. Rolls-Royce's Intelligent Engine platform provides customers of their Trent series engines with realitime analytics on engine performance and return on investment, predicts the most cost-effective maintenance regime given the data trends, and also suggests alternative use characteristics to reduce costs and increase longevity and reduce delays for passengers.

https://www.rolls-royce.com/media/our-stories/insights/2018/using-data-to-reduce-flight-delays.aspx

GE plc has been providing its PREDIX system to operators of wind turbines and other generating assets since 2016 and has been heralded as a game-changer in the field of industrial IoT and automated asset response.

https://www.ge.com/uk/b2b/digital/predix

The topic requires further research to evaluate the logistical implications of bringing man and machine closer together in hazardous environments, but also in navigating the issues around legal liability. If an automated system acts without prompt in response to a hazard, and through that activity causes additional harm or damage, who is held liable? Again, the automotive sector and to a degree the manufacturing industry also, are exploring these themes extensively. Portability to the infrastructure and asset management sector is a natural progression.

RESEARCH FOCUS

Imperial College London's **Centre for Systems Engineering and Innovation** is running a two-part research project into systems to predict hazards and emergency response requirements, and to integrate these models into a working Building Automation System. Part 1 of the research will cover the systems engineering-driven simulation of how management of emergency evacuations in large, complex public occupancy buildings could be improved. Part2 of the research project will be researching coupling physics, humans and machines in holistic, resilient and automated systems for building management. The outcomes will be a software tool that allows students, researchers and practitioners to couple constituent models of an entire building system in a simple, flexible and informative manner. Our tool will provide an application programming interface to combine models of a building's climate, occupancy and management system.

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Agile Organisational Structures

STATUS: PRELIMINARY RESEARCH UNDERWAY

OVERVIEW

The ability to know how asset-centric business structures can be re-designed to be more agile in investing in, adopting and exploiting digital tools, skills, IT platforms and commercial contracts. We also understand how to recognise and communicate the limitations of technology better. Digitalisation is not centralised, it is part of the fabric for all operational business units.

DRIVERS

- Changes to demographics, and the availability and demand for skills in digital technologies and their implementation.
- Threat of knowledge loss as organisations do not react to changing market conditions.
- Changes in the competitive landscape for owner/operators of commercial assets.
- Risk aversion in the latter stages of the asset lifecycle, driven by short-term investment horizons and an unclear model for through-life value.

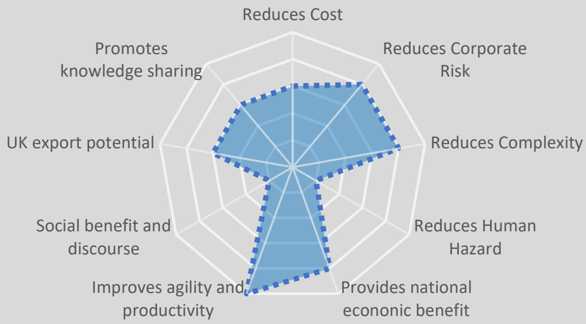
BARRIERS / ENABLERS

- Regulatory oversight for organisations with critical asset classes, such as power generation, utilities and defence facilities may struggle to reform if the regulator considers the change to threaten the stability of the asset or its owner.
- Management Science approaches the topic in general terms. Specific research is required on behaviours for asset owners. Very few examples in the UK for successful digital transitions for asset owners.
- Commercial contract model changes may have wide-ranging impacts on supply chain stability if not managed during the change.

BENEFITS

- More digitally mature business structures and workforce skill profiles will bring high-value jobs into the economy.
- The tension between regulators and asset owner/operators which require structural reforms to meet the increasing demands for transparency, agility and information provision will be reduced.
- Corporate risk will be significantly reduced, as the internal conflict between digital evangelists and traditionalists driven by ambiguity in corporate strategy and structure will be reduced.
- The complexity and cost of digital transformations will reduce.

BENEFIT RADAR



RESEARCH FOCUS

The CDBB Fountain network and National Digital Twin programme have both highlighted business structures within their Terms of Reference and review.

Whilst there are extensive examples of consultancy insights and case studies in the UK from agents who have helped asset owners transition to digital working practices, very few of them venture into the structural reforms needed to set the foundations for a sustainable digital owner/operator.

Many of these engagements focus on the provision of a specific capability or technology, or reforms to the IT function to allow it to respond more effectively to the demands of the organisation's other functions. These moves are insufficient to warrant their inclusion as research pathways in this report.

Significant structured and funded research into modern digital asset lifecycle management business structures is required.

Agile Organisational Structures

STATUS: PRELIMINARY RESEARCH UNDERWAY

There is a need for significant change in the structural and cultural makeup of asset owner/operator organisations, as well as within organisations that sit within the asset lifecycle value chain. Some of the key considerations for a future state include the following structural and cultural reforms…

1. Organisations must recognise and protect their core ability to understand, curate and leverage the value of the asset. In line with emerging consensus across UK Government, Infrastructure Projects Authority and the Construction Leadership Council, the recognition and adoption of a whole-life cost model for asset investment and ownership is fundamental to the success of many of the capabilities identified within this report. Organisations and the accounting profession will need to change their operating models to reflect this new approach.

2. Organisations must have a robustly defined model business function for storing and managing data. The traditional Document Control department or function must evolve into a state where models, documents, metadata and data integrity are of managed on equal terms.

3. Contract management as a professional discipline is evolved and appropriate for a digitally managed asset. – Transfer of knowledge from the Fintech and Technology Giants on IP ownership, subscription-based supply and maintenance contracts and traceability in contract handover may be supportive. Transitioning of long-term contracts to these new, more agile contract models is critical.

4. Senior management behaviours and accepted boundaries of responsibility must be better defined. Senior ownership for key enabling functions (such as digital facility/asset management, collaborative platforms etc) in many supply chain and owner/operator organisations is currently unclear. Currently, ‘transformation teams’ and ‘digitalisation’ teams own the change. What happens when Transformation / Digitalisation completes?

5. Boards and senior management demonstrate short-termism, despite improvements in recognising the long-term fiduciary duty inherent in modern corporate social responsibility codes. Showing the link between CSR and long-term digital asset management and investment will be needed.

6. Reforms to the regulatory approach for many asset classes may be required. Regulatory oversight is currently discharged with minimal consideration for the role of digital in supporting a more robust method for controlling risk and decision making. Lessons can be learned from recent changes by the utility regulator (OFGEM) as it re-aligns its approach, considering the impacts of a new digital era of smart meters and European supergrids.

7. Adoption of single-point delivery and maintenance of the digital and physical asset. Precedent exists in other industries for suppliers to enter into agreements to keep the digital twin counterpart and physical goods supplied in current configuration. Unifying what is traditionally done by two different suppliers will change expectations at a contract level and lead to improvements in reliability and concurrency.

RESEARCH FOCUS

CONTACT

National Asset Records & Emergency Response

STATUS: ADVANCED RESEARCH AND PROTOTYPE UNDERWAY

OVERVIEW

The ability to leverage National database and knowledge resources for major asset classes across the UK. We are able to provide controlled visibility and access to digital asset information to support national planning and emergency response. We use it as a knowledge base for design acceleration, future research, AI algorithms and trend analysis, to support better commercial decision making, reduce design times and facilitate the management of legacy assets under a common national governance framework.

DRIVERS

- There is no centrally co-ordinated command and control hub for digitally-enabled built assets across the UK.
- Emergency and crisis response in the UK relies upon rapid availability of trustworthy, current information to assist in safe planning and on-the-ground responses. This provisioning is currently fragmented and lacks the required granularity.
- The asset and infrastructure industry lacks a central hub for knowledge sharing, digital libraries and information leadership.

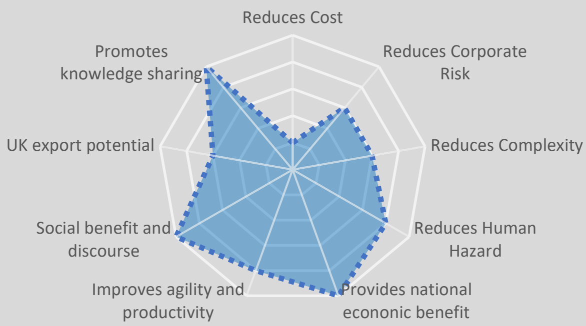
BARRIERS / ENABLERS

- Requires a common nationally-adopted ontology for primary UK built environment asset classes and equipment.
- Requires very clear governance on the nature, level of detail and validation of asset information to be housed.
- Requires significant investment in the integration of the platform with national emergency response and security tactical response systems.
- Requires robust cyber resilience capabilities to protect assets from attack.

BENEFITS

- Improved emergency response preparedness will lower the incidence and severity of major disasters such as Grenfell Tower and the Ponte Morandi motorway bridge collapse.
- Provides a common knowledge platform for the entire built environment sector to share best practice, accelerate design tasks and base further research and development upon.
- Transparency between commercial, academic and Government is improved, which sets valuable foundations for a more integrated digital economy. Dialogue between groups is improved.

BENEFIT RADAR



RESEARCH FOCUS

The Urban Observatory at Newcastle University broadcasts itself as the largest set of publicly available real time urban data in the UK. Capturing thousands of points of information in real-time from built assets around the Newcastle area as a central, accessible platform for asset information. The Observatory is working with researchers from the University and Northumbrian Water to assess the application of a digital twin for real-time performance management of the utility company's asset base. This project is being undertaken as part of the University's Innovation Festival 2019 programme and is a short-term sprint to scope the potential for further funding and development.

- https://www.ncl.ac.uk/press/articles/latest/2018/06/digitaltwins/
- https://innovationfestival.org/

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National Asset Records & Emergency Response

STATUS: ADVANCED RESEARCH AND PROTOTYPE UNDERWAY

We are aware of the progress made by CDBB and its industry and academic partners in scoping the development of the national digital twin platform and related asset record base. Whilst the maturity of this capability is perhaps far more advanced than others discussed in this report, its impact on the viability and value of a future digital lifecycle state ensured its inclusion in the final document.

Several national databases and knowledge stores are already open to public and private access and have been lauded as visible examples of the increase in transparency of public-facing Government departments. The creation of the databases themselves is not subject to any immediate barriers, barring availability of Government funding and support. However, what is lacking in the current state is the clarity of purpose behind how these national asset datasets are leveraged for the good of the social and economic fabric of the country. This will require dedicated focus, investment and research over the next decade.

A risk exists that without careful planning and structuring, the content of these asset libraries could become unmanageable; without a clear purpose, ontology, and without robust governance around the quality and quantity of data brought onto the platform.

In our vision for through-life asset management, a national digital twin platform exists that has a robust governance framework in place. It is hosted on a secure cloud environment that provides graded access to a range of stakeholders across the private, academic and public sectors, and has effective cybersecurity protocols in place to protect from malicious attack.

The functionality of the platform is expected to cover the following core elements at a minimum:

1. Digital modelled content is made available to a range of stakeholders in open formats to support the development and delivery of new infrastructure projects. Developers will be able to use current, validated geospatial information to base designs from, and reduce the risk of poorly co-ordinated designs.

2. National emergency response teams will have access to curated, validated information on the spatial, material and hazard profiles of assets across the UK without the need to contact the asset owner. The database will be linked directly with emergency response planning systems, with rapid response units briefed on critical hazards and characteristics before arrival at the site.

3. Software and hardware developers will have a rich seam of asset information and characterisation data to support the training of machine learning algorithms, machine vision systems, and trend analytics.

4. The platform could become the basis for an integrated national asset command and control platform, where live feeds on utilisation, availability, return on investment, consumer/tenant feedback and safety monitoring and responsive automation for publicly-owned assets are brought together and managed centrally.

RESEARCH FOCUS

The UK Nuclear Decommissioning Authority has recently developed and released a private cloud system that represents a First of a Kind for secure Infrastructure as a Service that is able to host information at high levels of security classification and national criticality, over and above the current provision within the Government G-Cloud. It will be a national platform, used by project developers, regulators, safety specialists and site owners to co-ordinate major projects, asset information and data, unifying delivery systems into one central hub.

The platform is intended to be developed further, in collaboration with UK Government, major supply chain partners and academic institutions to explore its use as a central data spine for the nuclear industry, able to serve applications, workflows, knowledge databases and information exchange.

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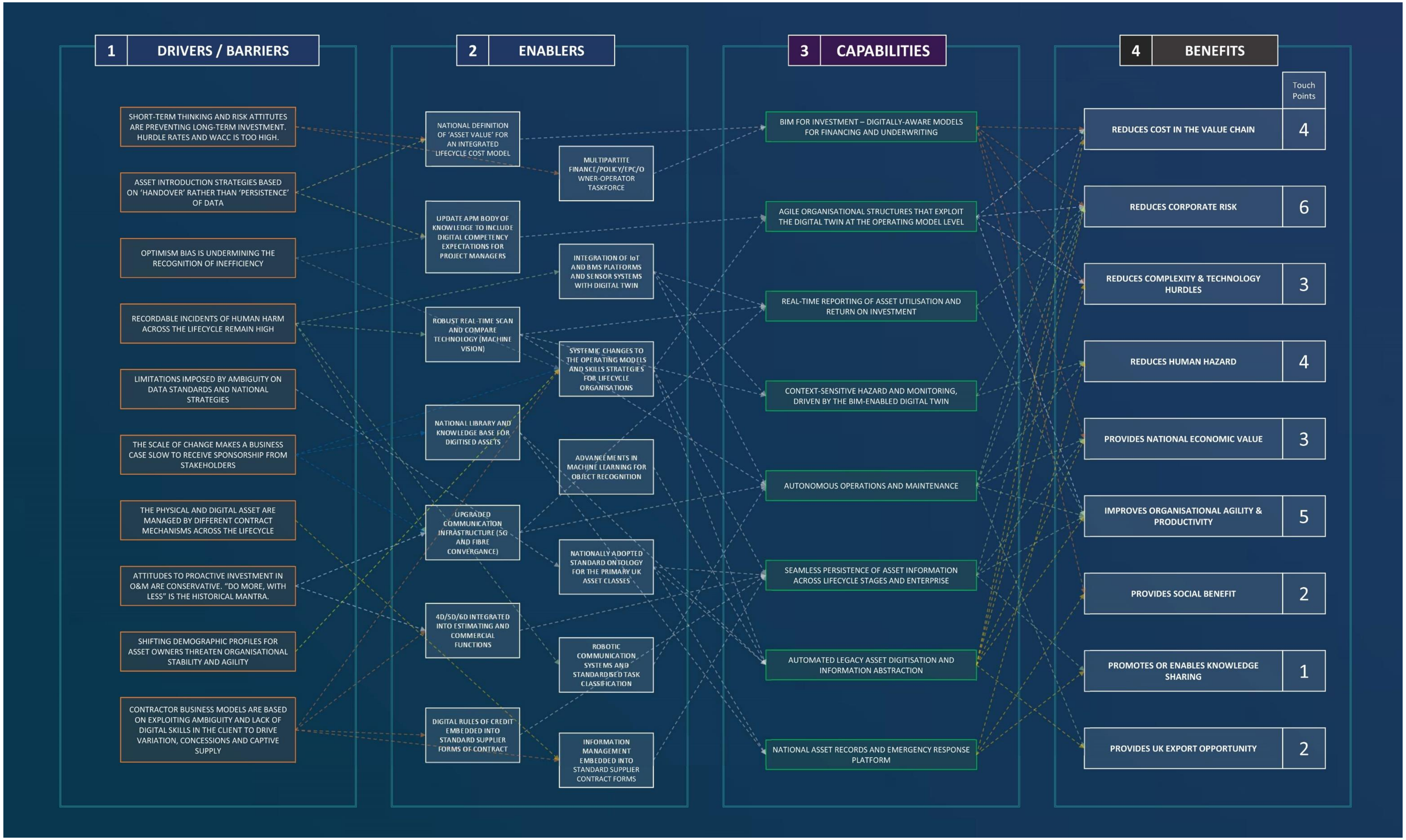
Overarching Full Capability Benefits Dependency Map

An A3 guide to understanding the drivers, barriers and benefits associated with the future capability landscape to 2030



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CONCLUSIONS

Conclusions

In preparing this report, and researching its content, the authors were encouraged by the breadth and calibre of research that is underway across the UK and internationally in relation to moving our built environment to a new digital era.

Pleasingly, there is great consensus and momentum both within academic circles, but also within Government support for the transition. A raft of working groups, project demonstrators and collaborative initiatives are generating ideas and exemplars for the future.

Private sector organisations are poised to follow suit, but the cost/benefit argument which was so readily adopted by front-end project delivery teams has yet to be made compellingly for asset owners and operators. The risks are great, and the cost uncertain. ‘When’ investments are made is perhaps more important than in ‘what’ they made. Even cautious adoption of some of the more mundane capabilities and underlying enablers highlighted in this report would show a material positive impact in the way we use the valuable assets and infrastructure we are privileged to have access to in the UK.

What is perhaps most important to the viability of the future vision is that the real value of the lifecycle can be understood by more than just a select few. In particular, it is imperative that the investor and insurance communities come together with industry stakeholders to open a dialogue in how their traditional risk models have been, and will be affected by the journey we are on. Only by doing this will commercial organisations be at greater liberty to make investments that would historically been challenged by boards and shareholders alike as misguided, long-term vanity projects.

Certainly, there is work to be done to advance the maturity and confidence in technology to make change happen. The digital twin concept means a lot of things to a lot of people, and initiatives like the CDBB National Digital Twin programme will add a level of clarity and enable broader dialogue that is sorely needed. However, there are also more structural issues around organisational structures, readiness, cyber security and the skills gap that may yet add headwinds to the journey.

We hope that in compiling this report, we have provided you with a valuable viewpoint from the lifecycle perspective. We are grateful for the opportunity to produce this report for CDBB and look forward to being part of the conversation into the future.

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This report was written and reviewed by James Harris, Jeremy Harris, Mike Turpin and Philip Isgar, with contributions from Kris MacCrory and John MacDonald:

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By way of broader recognition, we are grateful for the support provided by other analysts and reviewers from Turner Harris, and for the valuable contributions of our external partners and colleagues from industry and academia, including CDBB, who have taken part in our consultations, and provided us with their insights.

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ANNEX

Capabilities and Research Matrix (appended)

Bibliography and Data Sources (appended)