VISION REPORT

TOWARDS AN ADAPTIVE INFRASTRUCTURE SYSTEM DECISION SUPPORT MODEL

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EXECUTIVE SUMMARY

For some infrastructure assets, maintenance practice has evolved from a reactive response at the point of failure to data-centred predictive and preventative measures. This is partially due to costly (societal and economic) consequences of unplanned maintenance but also embracing new capabilities in value generation through data exploitation. With climate change-induced shifts in load and environmental conditions, there is an increasing need to evolve risk and failure mitigation activities and adaptive strategies through effective telemetry and monitoring. Through a series of workshops and interviews, we have brought together a cohort of established national and international participants and collaborators to investigate the (R)evolution of maintenance and management practices in transport infrastructure and their effect on reliability, safety, and efficiency.

The vision report reflects the findings and discussions made throughout these activities, highlighting areas where strategic interventions could be directed.

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INTRODUCTION

The impact of inadequate maintenance and management practice in critical infrastructure is sadly evidenced regularly across the globe, for example: the breach of the Edenville dam in Michigan in May 2020, almost a century after its construction, caused major flooding and threatened hazardous chemical facilities forcing the evacuation of thousands of residents; the collapse of a barely ten-year old bridge in Mexico City in May 2021 resulted in at least 23 fatalities and dozens of injuries, in addition to significant disruption and loss of confidence in public transport safety. In both cases poor maintenance and management practice, namely deficiencies in risk assessment following an inspection and failure to detect and quantify construction defects, exacerbated both direct and indirect failure consequences. There are many other infrastructure failures that could be used to underscore the importance of good maintenance and management practice, but the above two are a reminder that such failures span the entire life of infrastructure assets, whether they are built from traditional or modern materials. Moreover, even when maintenance identifies safety concerns before accidents happen, as was the case in the Hitachi Class 800 trains on GWR/LNER lines in May 2021, the potential to act proactively rather than reactively to limit disruption and safeguard the public is of increasing importance in infrastructure systems operating at near-capacity levels in many countries around the globe. Achieving real-time, predictive maintenance and management practices, while satisfying demanding criteria for de-risked (in terms of human safety) and decarbonised activities and techniques encapsulates the vision for the future; the work of this commission, through the tasks described below, provides insights into current and future practice, and assists in identifying areas where strategic interventions could be directed in order to advance LRF's overarching aim "to ensure the future safety of complex physical infrastructure". Here, the term "infrastructure" refers to man-made structures and spatial networks that underpin energy, communications, and transport systems, as well as water and waste management. It also includes nature-based assets that absorb emissions, mitigate the impact of flooding and sea rise, and enhance the quality of both urban and rural landscapes. The complementary role of "hard" and "natural" infrastructure is increasingly being recognised as an essential attribute of sustainable infrastructure, i.e. infrastructure that is inclusive, resilient, resource-efficient, and cost-effective.

According to a number of influential reports (e.g. The Sustainable Infrastructure Initiative, 2016; Global Infrastructure Outlook, 2017), we are at a critical juncture with respect to investment in infrastructure, in terms of creating new, and fully utilising existing, networks. Globally, the need for infrastructure investment is forecast to reach $94 trillion by 2040; although four countries account for roughly half of that requirement (China, USA, India and Japan), the other half is spread widely and will impact on the economic growth and wellbeing of practically every country in the world. Investing in Sustainable Infrastructure is seen as key to tackling the three central challenges facing the global community: reigniting growth, delivering on the Sustainable Development Goals, and reducing climate risk. This investment will take place at a time of rapid change in technological advances and societal trends.

In this context, embracing new technologies for monitoring, maintenance and management of assets; responding to climate and demographic challenges; and recognising the societal drive towards safer and more resilient infrastructure must underpin the changes needed in how we plan, build, maintain and decommission individual assets and networks in different infrastructure sectors. Our ability to adapt in respect of need and purpose (i.e. is everything that is planned necessary or would other societal changes mitigate the perceived need?) and how the different sectors can work synergistically should promote efficiency and inform the way in which future maintenance and management practice is both formulated and implemented.

This report reflects on findings of a series of research activities which investigated the (r)evolution of maintenance and management practices in transport infrastructure. This particularly focused on the effect of these practices on reliability, safety, and efficiency.

In these activities, we brought together a cohort of established national and international participants and collaborators. These included transport asset owners and managers, leading consulting and contracting organisations, and research centres worldwide to reflect and explore current and future practices. A key aim was to identify areas where strategic interventions could be directed. [provide the list of organisations or involved people]

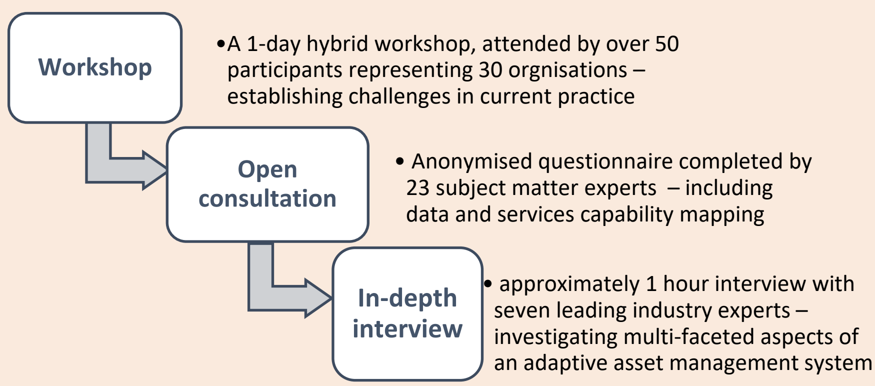


Figure 1 provides a schematic overview of the processes/factors involved within management practice and a simplistic view of their interdependencies. In the centre are the three key elements, namely data, processes and decisions. All discussion relating to these emphasised the importance of considering the human element in all aspects of project development and delivery. Additional elements considered were emerging technologies and net-zero issues.

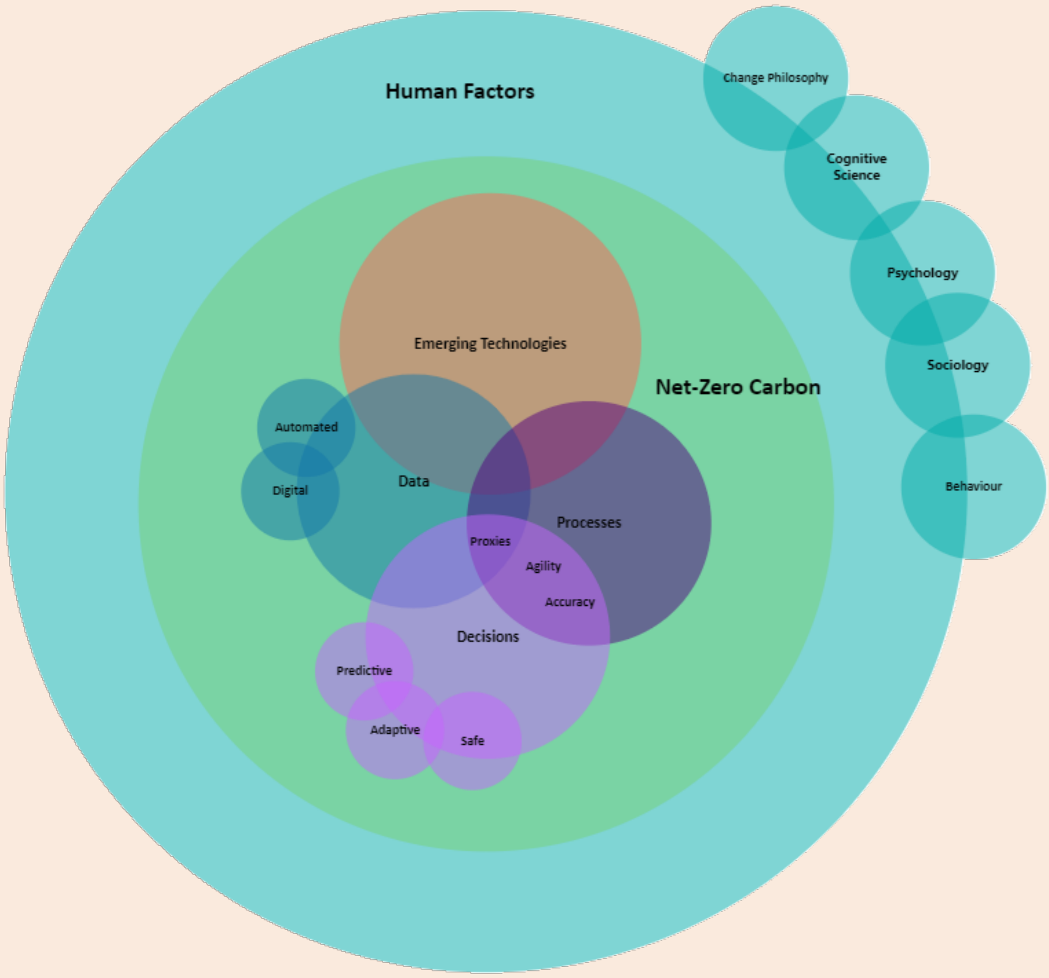

Human Factors
Change Philosophy
Cognitive Science
Psychology
Sociology
Behaviour
Net-Zero Carbon
Emerging Technologies
Automated
Digital
Data
Processes
Proxies
Agility
Accuracy
Decisions
Predictive
Adaptive
Safe

Figure 1

HUMAN FACTORS

KEY FINDINGS

- *Consider cognitive hierarchy and change psychology in educating and training personnel*
- *Coordinate human, technology, and machines in all levels of decision making*
- *Integrate specialists and technologists vertically and horizontally across the business*

CONTEXT

It is well understood that only part of the (r)evolution and transformation of decision-making systems is technical, while synthesis of other systemic dimensions such as people, education, ethics and legal matters are critical to the decision-making process. According to the UK Ministry of Defence's DLOD framework (Defence Lines of Developments), any meaningful implementation of a capability requires parallel co-ordinating in training, equipment, personnel, information, concepts & doctrine, organisation, infrastructure and logistics.

Fundamentally, 'change' needs to be embraced at all levels from management board though to end-user, in industry and by both local and national regulators and government. Change is challenging, but both necessary and continuing; acceptance and understanding of the need for change are critical. For a change to occur, it is paramount to appreciate the cognitive, physical, psychological and emotional aspects of the change at different levels of decision making. Otherwise, any form of change and modification of the status quo will face resistance.

Whilst the western military and technology industry have strongly implemented OODA-like (observe-orient-decide-act) process, the transport industry has lagged behind. This is partly an educational challenge in which **cognitive hierarchy (explaining insights and deriving value from insights) is often overlooked**. However, the other main factor is a **lack of understanding of the psychology of change**. This is also a combined effect of the sector not being geared up or understood as a system of systems and a network of networks; i.e. change needs to be coordinated across the system and its contributory elements (e.g. personal, tools and equipment and organisation). It is important to get everyone around the table early in the whole conceptualisation of the ultimate goal and purpose, which can lead to effective engagement. It is not important to get the people around the table just at the beginning; it is key to keep them at the table for all the formative times in developing the decision-making system

Barriers

- Lack of appreciation of cognitive hierarchy and change psychology
- Resistance to change at all levels of decision making
- Gap between technology advancements and upskilling at all levels.
- Language gap between generations and skill sets
- Loss of knowledge and know-how of experienced workforce after they leave

Opportunities

- Upskilling the workforce
- Recruiting trained psychologists in different levels of decision making
- Effective use of social media and citizen science

Priorities

- Humanised decision-making systems.
- Integration of specialists throughout the business
- Effective communications on new technology, context and background at all levels

<u>A human-centred focus in translating data to actionable information is critical</u>, as is understanding the skills required in applying and using it. data scientists, psychology specialists and technologists should be integrated through the business, vertically and horizontally, with appropriate autonomy in decision making. This is particularly relevant where thresholds and parameters of decision variables have a more complex interpretation. Specialists can help untangle these nonlinear relationships. However, despite the rapid growth in digitisation, the proliferation of SMEs and start-ups providing speedy developments in tools and technologies, our industry has failed to keep up with the skills required to make use and sense of these advancements.

The view of the system and feed-in information also needs to be humanised. Data scientists are commonly perceived as introverted and uninvolved in the implications of their work. Integrating specialists in different decision-making levels will help clarify communications in the use of technology and enable meaningful engagement (of what/who) in decisions. The inclusion of trained psychologists in different levels of decision-making can also help in bridging the gap in communication and language used. This helps to build a knowledge-based environment that can help shift decision-making from a binary outcome (threshold-dependent) to more context-based decisions.

DECISIONS AND DECISION-MAKING SYSTEMS

Barriers

- Lack of clear definition of purpose and objectives at the outset
- Lack of end-to-end narrative describing boundaries between assets, systems, networks and people
- Silo thinking across the system and network
- Different versions of ‘truth’

Opportunities

- Implementing minimum viable product principles in decision making
- Maximising opportunities to learn from user experience and small pilot (e.g. small city without siloed governance) projects

KEY FINDINGS

- Deliver outcome-focused decision through end-user-centred objectives
- Consider adaptive and modular capabilities in decision system design
- Utilise demonstrator tools for customising narrative and maximising opportunities to understand end-user perspectives
- Acceptance criteria are largely binary rather than graded

CONTEXT

The design of any decision-making system should start by **defining its purpose and objectives**. Decisions are often informed by indicators and factors such as time to failure, remaining service life, structural strength, condition, net-zero carbon, risk, consequences of failure, welfare, service efficiency, and reduced risk of failure. The design of a decision support system needs to consider these indicators alongside the key decision objectives and the context in which a decision is made. The level of accuracy and agility should also be defined at this stage

The definition of objectives should be followed by the description and **definition of system characteristics** (e.g. boundary, actors, performance variable etc.). In this process, a systems-of-systems approach should be employed. Given the diversity of infrastructure assets, the definition of asset ontology and system-of-systems formulation are easier said than done. Whilst the day-to-day activities of an asset within a system are relatively well-established and data-driven, the relationships between demands and capacity become more complex and nonlinear when going outside business-as-usual performance, particularly in response to ‘freak’ events. This highlights the importance of small pilot (small city) projects that help in better understanding potential ‘uncommon features and behaviour’, subtle interdependencies and building disruptive thinking culture.

The context of time needs to be captured in defining objectives. Asset management should **drive through life-business benefits**; hence objectives need to be considered strategically over the short, medium and long term.

The objectives should be co-defined in closer collaboration with the stakeholder and end-users. This will lead to decisions focus on outcome rather than output. Ultimately an asset management system should deliver value and

Priorities

- Design and develop flexible adaptive systems
- Multi-dimensional (beyond financial implications) rebalancing and re-evaluating value propositions
- Use well-designed digital twins as enablers for stress-testing future scenarios

manage risk. In this process, linking the objectives to clear, measurable and quantifiable performance indicators can help in the meaningful performance-based assessment and sifting through of the right processes, information and data.

Furthermore, different characteristics of a decision-making system should be considered in the context of the circumstances and needs, i.e., risk-based and performance-based decision-making should not be a means to an end.

An ideal decision-making system should allow **flexibility via the use of modular and adaptive capabilities** where different models can be added, updated or removed depending on changes in decision needs. Integrating data and information into a digital twin of the system can enable stress testing under different scenarios. Whilst digital twins can be seen as a panacea; they will have to be purposively designed to model the right systems to solve the right problem A federated approach and inherent flexibility in the whole system design would offer adaptability to changes in decision needs but should not compromise the focus needed in order to fulfil specific objectives.

The design process should also incorporate frequent value-proposition when considering emerging technologies: e.g. extending service life via maintaining existing assets versus building new ones. In other words, in addition to operational cost, short, medium and long-term value creation assessment is required. Whilst 'value' has a wide-ranging definition and scope in different organisations and businesses, the description should not be from the financial and monetary perspective only but should also consider other aspects such as ethics and societal values. The value propositions need to be re-balanced to also assess progress on services delivered and user needs satisfaction.

Traditionally, 'safety' and total cost are seen as key driving factors in decisions and value definition, however recent years have seen a shift towards net-zero as key driving factors in solution choices (Figure 2) . It is critical to balance mitigation by minimising carbon use and adapting to future climate. The systems that are designed today must be adaptive to future environmental parameters.

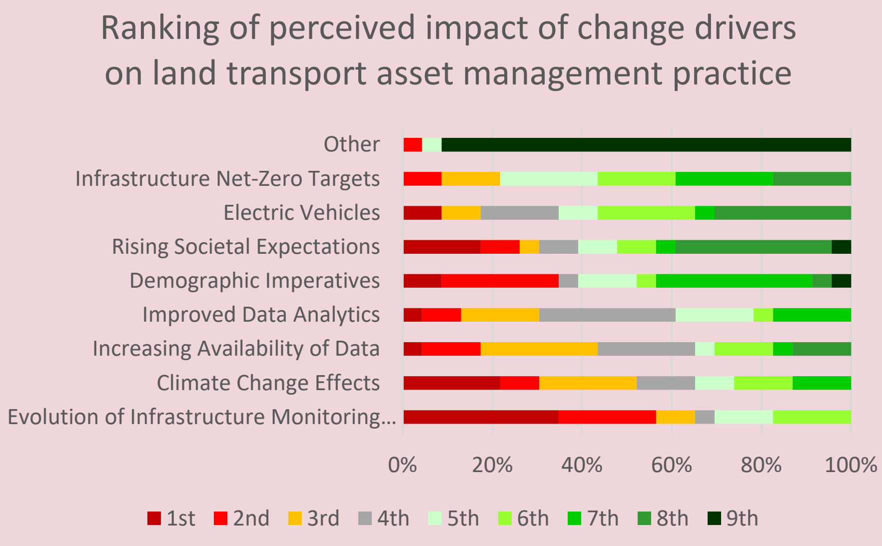


Figure 2

PROCESSES

KEY FINDINGS

- Move towards a 'predict and prevent' rather than 'find and fix'.
- The objective or purpose of the decision should define the level of macro and micro analytics

Barriers

- Too complex or over-simplistic decision tools
- Lack of data and information on non-linear behaviour.
- Lack of trust in complex models.

Opportunities

- Producing demand and nonlinear impact assessment models as a function of weather scenarios
- Move from hindsight to foresight and predicting and planning for potential future scenarios

CONTEXT

The processes and decision-making tools utilised/available are quite wide-ranging. Often the modelling techniques are either too over-simplified or too complex, which limits the application and broader adaptation of the approach. The balance between the micro and macro-state of the analysis and processes needs to be observed in conjunction with the decision purpose, and the accuracy required.

The experience of the recent pandemic has further highlighted the importance of a paradigm shift from hindsight and what can be learnt from the past to foresight. **Moving from hindsight to foresight** requires a shift in thinking from 'what happened, 'why did it happen', to 'what will happen (insight)' and 'how can we control things to make the right decision' (cognitive analytics). This requires a cultural change in different levels of the decision-making process as discussed in the HUMAN FACTORS section.

Whilst recent advances in computational powers and modelling tools have facilitated the building and developing of complex models, appropriate maturity and hence trustworthiness in these approaches is yet to be achieved. This is mainly due to the difficulty in validating and calibrating such models. This is of particular concern for predictive modelling (as demonstrated in the questionnaire response in Figure 3). In other words, "a model is trusted when the model itself and the data that it feeds on are accurate and authoritative".

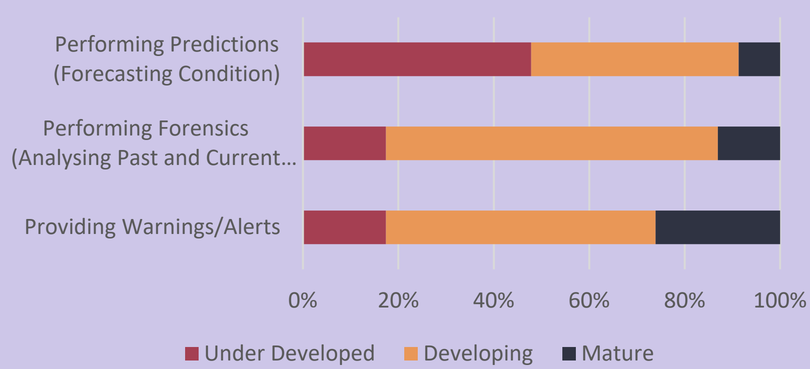


Figure 3

Priorities

- Consider processes in the context of decisions that need to be made
- Improve understanding of the processes and the related theory at all levels

One of the main contributory factors to developing effective predictive modelling is limited data and information on the complex and nonlinear behaviour of assets and systems. This is further exacerbated by the lack of one single source of truth in data and information. Communication gaps between analysts and decision makers is another major factor, as highlighted in the HUMAN FACTORS section. This can also explain the difference in the response to the level of maturity between model-based and physical analytics and data-driven analytics in the questionnaire (Figure 4).

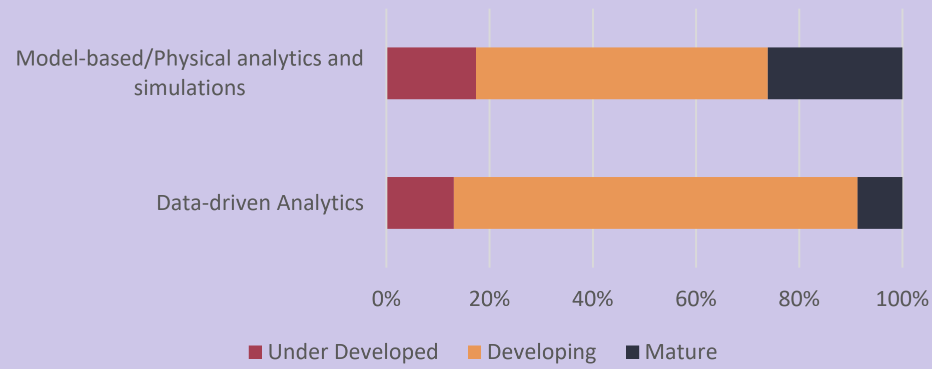


Figure 4

Whilst the last two decades have seen significant advancements in modelling approaches, these have not been able to keep up with the characteristics of the data (volume, variety, reliability). One example of an apparent gap in processes is the translation of weather predictions to infrastructure loading and demand models and capturing linear and nonlinear impacts of different weather scenarios. Another example is the lack of acquisition and processing protocols in obtaining asset performance, leading to heterogeneous and potentially incompatible datasets being used in model analytics.

Any process and analytics should be led by the decision question and purpose. The definition of decision questions will also influence the type, level and complexity of data to be collected and used.

Understanding the context and theory behind the processes is crucial for effective implementation. Often the processes are used as a blackbox without full appreciation of the technical background of the process, which impacts trust in results by the end-user. It may also cause a lack of reflection on outputs using domain knowledge.

Whilst the industry is richly supplied by scores of data and information management systems, the majority of these systems are often described as '*vanilla systems*', referring to their difficult user interfaces and lack of customisation to what end users may need. Lack of **integration of user experience** and a common 'top-down' approach in creating these systems have led to poor adoption. This ultimately prevents meaningful change in the way data is stored and managed within an organisation.

DATA

Key Barriers

- Data quality and variety
- Challenges with data sharing and ownership

Opportunities

- Understanding data inter-dependencies and their effect on system performance
- Exploiting technology for creating data that does not exist (e.g. nonlinear behaviours)

Priorities

- Adaptation of a standardised data quality assurance system
- Creating usable and actionable integrated single source of truth
- Rethinking contractual obligations and frameworks for secure data sharing

KEY FINDINGS

- Collect accurate and correct data rather than a large volume of incomplete and unreliable data
- Avoid collecting data for the sake of collecting data - Before collecting data, challenge why it needs capturing, how it will be used, and what is its value for different assets, systems and networks
- Consider end-user experience at the heart of any data and information management system.

CONTEXT

A significant volume of data currently exists for different assets and purposes – Figure 5 shows a snapshot of different types of data collected and used by the participants in our open consultation.

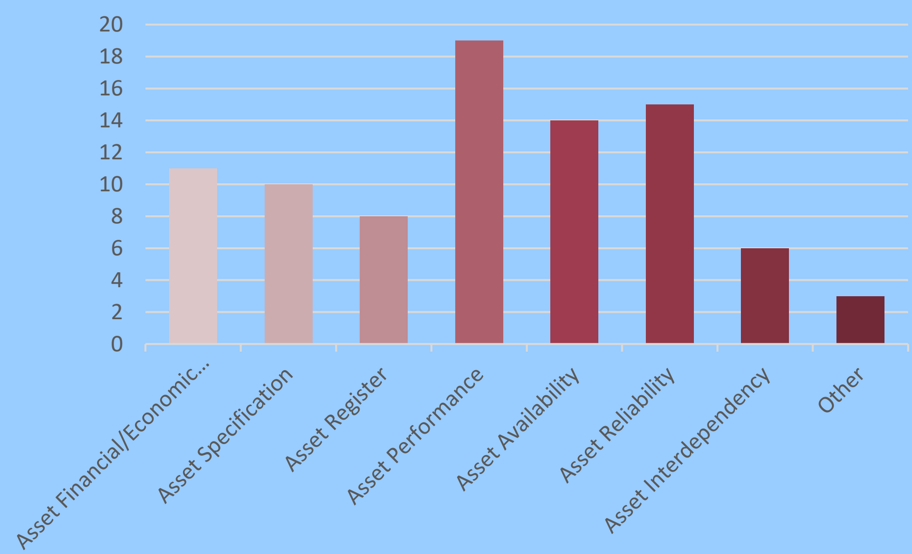


Figure 5

There are different types and sources of data, ownership, (isolated) legal entities, frameworks for collecting and storing, with different value-assignment to data by owners. There is also a wide range of skillset requirements to analyse and interpret the data to produce useful information. Our open consultation has demonstrated (Figure 6) that whilst the capabilities in data acquisition design, collection and storage on asset register and performance can be characterised as relatively mature and/or in the developing stage, data capture capabilities for asset interdependencies are categorically under-developed. This is often due to challenges with compliance and stewardship of interdependency. Lack of clear understanding of ownership and accountability leads to unclear interfaces and often overlooking interdependencies and means to capture these relationships.

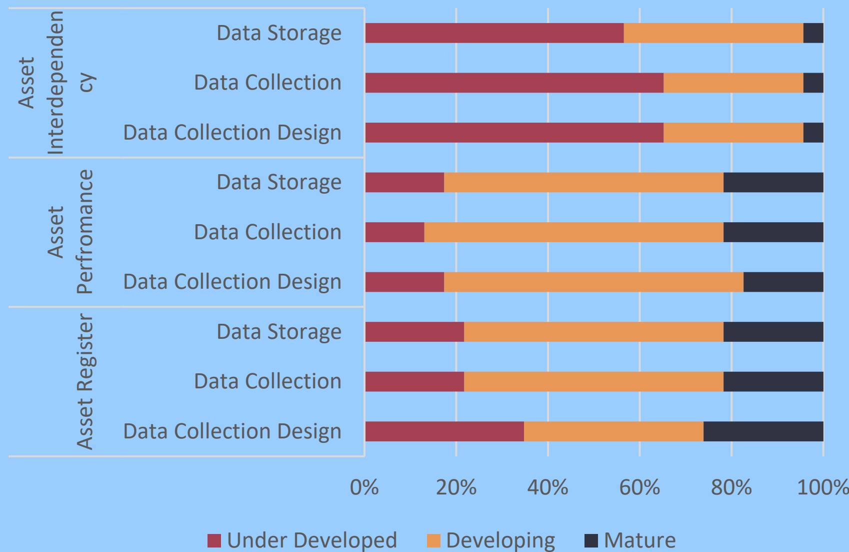


Figure 6

The value of data is predominantly assessed by their importance in asset and system safety and functionality; however other factors such as environmental and social impacts and cost of collection and storage may influence the perceived value of data (Figure 7). Data should be collected if they provide insight and collection of data for the sake of collection should be avoided. The common technique in assessing and quantifying the value of data is through performing targeted analysis and experience and census of experts, however, pilot projects and trials have also proven to be effective in this regard (Figure 8).

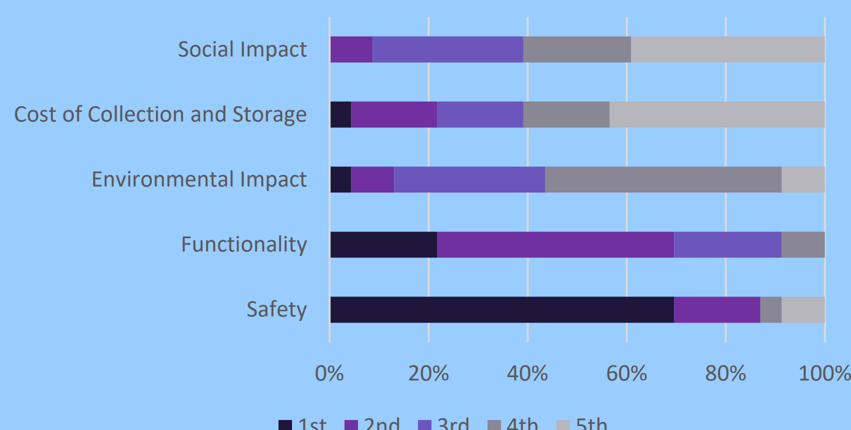


Figure 7

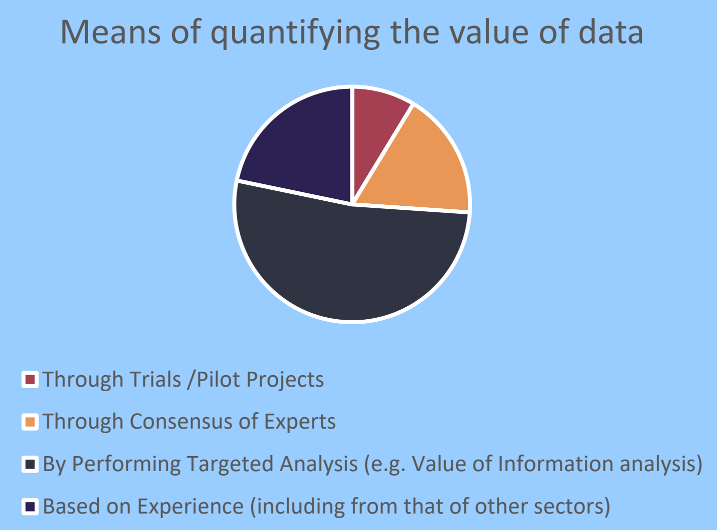


Figure 8

Whilst factors such as data ownership, challenges in security and sharing have hindered the attempts to derive value from data (Figure 9), the main barriers are identified as data quality and variety. Despite the ever-growing variety and volume of data, many organisations seem to be data-rich but information-poor. Technological advancements may improve the quality and quantity of data. Emerging technologies can also be used for the complete digitisation of what has been built and what can be built and answering the questions of how it is used and how it responds to a wide range of events, scenarios and changes. Advancements in the tech industry should also be exploited to build data that does not exist (e.g. interdependency-based information). This can also be used in 'virtual rehearsals' and 'simulators.

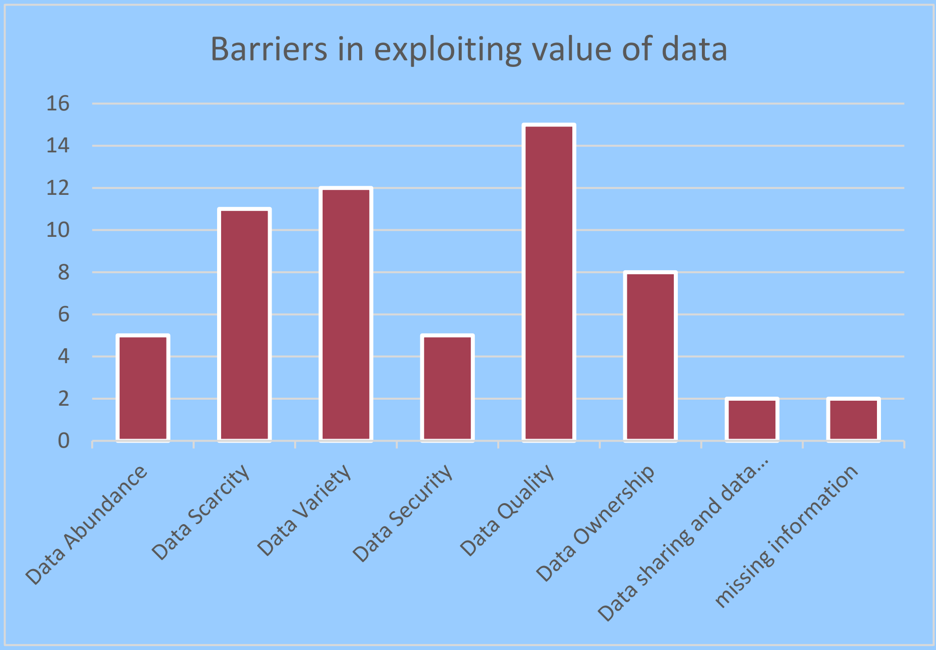


Figure 9

In addition to poor quality data, the metadata, the context in which the data was collected and real-time environment assessment are often lacking. This leads to continuous catching up with whatever happened and trying to learn from it (hindsight), instead of influencing the decisions (potential foresight). The word influence is deliberately used as opposed to controlling because sometimes the circumstance is beyond control, but what can be done is to limit the impact of the uncertainty.

Mastering the digital world can be a key factor in maximising the value offered by extreme data. Digitisation of the data and models are pivotal in providing the skeleton for an information management system. Many organisations have a myriad of systems where they store the data and they often store the same data in different versions. One of the main challenges in deriving value from such data and information management systems is the lack of a **systematic and systemic data management and quality assurance** system that is able to bring different data management systems into one place to provide one single source of truth. Data quality assurance and the data validation process is critical. Integration of different sources of data streams to form a **single version of truth** and consistency and standardisation of data capture and storage is key to enabling value. Given the conservative nature of the industry, often the 'no data' state is preferred to inaccurate, poor-quality data. This is mainly due to the high cost associated with untrustworthy data. Ideally data should be collected once, stored in one place and its use should be exploited at different levels and for different purposes.

There is also a need to identify the key data streams that are repeatable in different types of assets (often due to data segregation between different sectors and within one organisation). To combine data from various systems, the data standards need to be clear to both the source system and the analytic tool. In other words, the assets do not need to be standard but the rules for describing assets and their elements need to be clear (and transferable) .

Data and analytics need to be designed holistically with an appropriate quality control system, considering people, system-of-systems processes, mission and objectives, and timescales. Where possible, 'federation' needs to be incorporated to keep the systems generic enough to afford flexibility and application for different assets and systems. The adaptability is also a key characteristic for these systems to allow change for future structures and infrastructures.

The key in maximising the value of the data is to anticipate how this data can be used in future, which will help in having a clear approach to the type of data that is needed e.g. data on actions and loading vs data on response and resistance. In other words, the data capture design needs to be challenged at the outset to describe why the data needs capturing, how it will be used, and the value of the data. This will ensure the usability and **actionability of data** beyond one asset or system.

Standards for interoperability between other owners and users, stakeholders and beneficiaries (e.g., academia, commercial, and customers of varying nature) will support maximising the value of data by focusing the efforts in deriving value rather than re-inventing means to collect similar data. The value of data increases through collaborative works on data. Hence the data acquisition and analytic system design need to be considered in an open or co-developed platform.

The **context of the time** in data is critical, as having on-time data with immediate insight is key for rapid response systems. However, also having any data at any time can be highly valuable. Hence, the collection and storing system of data needs to consider its short, medium and long-term usage. Appreciation of different timescales for real-time monitoring, forecasting and prediction can be reflected in the difference of data required for each timescale and purpose.

Furthermore, the frequency of data collection and use to support information flow, thresholds and decision parameters and level of alerts need to be defined at the design level. The linear and non-linear impacts should be anticipated by thinking of the system as a whole. Using indirect, third party and secondary data may improve the understanding of indirect relationships but may lead to data reliability and ownership issues.

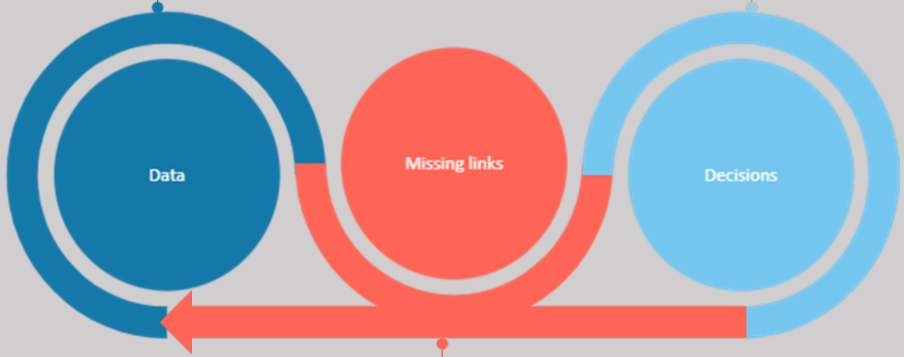
Security of data storage and sharing mechanisms are important to avoid potential misuse. Data is often linked to revenue and commercial sensitivity which inhibits the potential for sharing. Standards need to be agreed between operators, managers and owners to facilitate the transferability and use of data. In addition to changing mindset on security matters, the sharing culture also requires attention as often the interoperability of data is overlooked. To promote sharing, interfaces and connectedness needs to be considered.

A paradigm shift is required in rethinking contractual obligations and frameworks in relation to sharing data . The data acquisition system should also consider the flexibility required in any contracts by capturing shared perspectives and contradictions. It is key to consider the whole life cycle of data in the design process: build-design-operate-dispose/reuse and the ownership transfer/sharing in its lifetime and to incorporate the short-term and long-term maintenance and handing-over process.

GOING FORWARDS

- ✓ Collect and store data once and maximise its use (keep one single source of truth)
- ✓ Prioritise quality over quantity and variety
- ✓ Purpose-based data collection (avoid collecting for the sake of collection)
- ✓ Implement contractual obligations for secure data sharing

- ✓ Develop decision making systems with clear and right questions, triggers, reactions and processes
- ✓ Design and adapt outcome-focused and end-use-centred decision-making systems
- ✓ Exploit demonstrator tools and pilot studies as means of capturing end-user perspectives
- ✓ Incorporate flexibility and adaptability in the decision-making system design
- ✓ Avoid bottom-up design systems.



- ✓ Upskill asset management workforce with data analytics and emerging technologies
- ✓ Incorporate trained psychologists and sociologists with data science backgrounds in different levels of decision making
- ✓ Train and educate the workforce to better understand the technical background behind decisions and corresponding processes
- ✓ Incorporate means of retaining institutional know-how of the experienced workforce

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- David White (High Speed 2)
- Dr Linh Truong (Loughborough University)
- Dr Payam Zargarzadeh (Connected Places Catapult)
- Joel Zbinden (LeanBI)