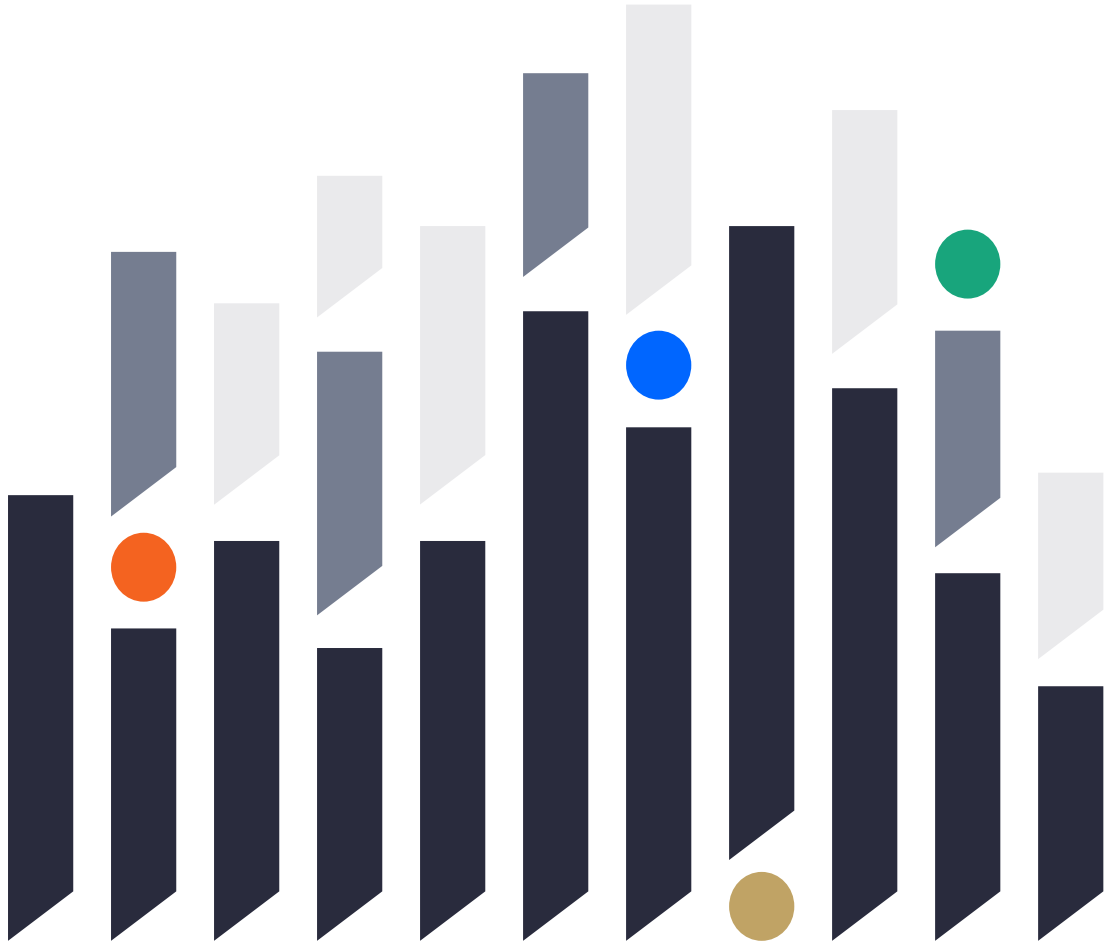


Research Agenda and Landscape



Workpackage 8: Integration and optimisation of services embedded in the built environment

V2.1 Released

Disclaimer

The views, thoughts, and opinions expressed in the report belong solely to the authors, and not the Centre for Digital Built Britain.

Executive summary

The world is undergoing a period of dramatic challenge and incredible opportunity. The planet is under stress from global warming, society is unbalanced where the few control the most whilst others starve, and we live in an economy where growth is seen as the primary goal. This is at a time where our ability to understand our natural and built environment is greater than ever, the computational power we have at our disposal is larger than anyone could have imagined, and the pace of technological change is ferocious. With this backdrop of challenge and opportunity, our country generates 80% of the GDP from the service sector, of which about half is dependent on the built environment. To respond to the challenges we now face, these services and the underlying infrastructure must use the opportunity presented to them.

This workpackage explores the capabilities required to specify, procure, design, deliver and manage services based on, and embedded in, the built environment in order to optimise effectiveness, efficiency and productivity for their stakeholders, whilst making best use of data and information through-life and across assets and infrastructure. It also looks to identify what new capabilities the UK will need; what research, development and demonstration is necessary to build, deploy and disseminate such capabilities; and where the basis for such development and demonstration exists today.

Focusing on surface transport and energy in the time horizon 2040-2050, it demonstrates the future themes to be addressed as follows:

Surface Transport	Energy
<ul style="list-style-type: none">• Reduction in air pollution• Decarbonisation• Changes in demand• Mobility-as-a-Service• Connected and Autonomous vehicles• Digitisation	<ul style="list-style-type: none">• Changes in demand• Decarbonisation• Decentralisation• Digitisation• Customer experience• Electrification of transport

The state-of-the-art was assessed. This illustrates that despite a considerable body of knowledge in this space, very little has been written about the capabilities needed to define, build and optimise the infrastructure needed to deliver the services and achieve the outcomes. The main areas identified requiring further research were:

- Derivation and description of the service outcomes.
- The relationship between service(s) and the underlying infrastructure.
- Describing the interdependency and behaviours between different services at a discreet level of abstraction such as a borough, small city, town or campus.
- Inclusion of perceptive, subjective and objective criteria into a system model.
- New services and associated business models.

A series of stakeholder interviews were conducted at different levels within the supply chain of both surface transport and energy to understand the current capability, where they see the sectoral challenges, and the ambition for development to address the challenges. This process illustrated that despite the pace of change overall and the specific challenges of both sectors, a capability gap was evident. The key areas identified requiring further capability development were:

- The need to establish and demonstrate the causal relationship between an asset and a service at a level below macro-strategic.
- There is a distinctive separation between the service provision to customers and the service provided to the assets.
- The business case for new methods of working needs establishing.
- Value is an overused but seldom understood term.
- The benefit of digital as a concept is understood and the translation to realising the benefit throughout the supply chain requires support.
- Despite the advances made with data and information literacy, and the adoption of BIM for Government projects which is starting to percolate through to the private sector, there is still an overall deficit in information capability across organisations.
- The need to ensure digital inclusion should be properly considered within the overall digital strategy for any implementation.

When the future needs of the UK are considered, alongside the state-of-the-art knowledge within these areas and reflecting on the current market capability, twenty candidate CDBB required capabilities were identified. These capabilities have been consolidated into four principal capabilities needing development for the UK to respond to the requirements in the time period 2040-2050, as follows:

- 1 The value of the technical, social, economic and environmental causal relationships between service outcomes and the underlying infrastructure are defined.
- 2 Service outcomes and underlying infrastructure can be measured and controlled with incentives to modify individuals patterns of behaviour and preferences resulting in improved personal and socioeconomic outcomes.
- 3 Value creation through new commercial relationships and business models for asset intensive services are established.
- 4 Organisations are able to provide digitally enabled services in an accessible form to enable all individuals to benefit from new services. All individuals have access, are able, and are digital equipped to benefit from the new services.

The UK has a considerable demonstration capability with over a hundred projects and centres in existence. When the required CDBB capability is mapped to the current demonstrator estate, the number of candidates reduces considerably. When the capability to support the requirements of CDBB of each potential demonstrator is further appraised, it illustrates that while there is some knowledge in existence, this is a new and potentially transformational area of development. This will need focus and funding if the future capabilities needed for the UK are to be realised.



For the Centre for Digital Built Britain to develop the national capability needed for 2040-2050, this workpackage recommends the following actions:

Create and hold the vision. This is a significant cross-sector cross-disciplinary challenge: it is not expected the answer will appear from within a traditional department or organisation, but at the edge and in combination with each other. As such it will be essential:

- For someone to create and hold the vision that can link and leverage the work of others.
- To creating new ecosystems to investigate, understand and implement these transformational changes.

Research. There is an established body of knowledge that can be built upon, but fundamental areas require further research to unlock the potential value, as follows:

- Establish the value of the technical, social, economic and environmental causal relationships between service outcomes and the underlying infrastructure.
- Determine how service outcomes and underlying infrastructure can be measured and controlled with incentives to modify individual patterns of behaviour and preferences that result in improved personal and socioeconomic outcomes.
- Demonstrate value creation through new commercial relationships and business models for asset intensive services.

Collaborate. This is a diverse subject area and will need existing organisations to work together in new ways and for new groups and ecosystems to be formed to provide the focussed outcomes. These include:

- The creation of an ecosystem to provide input, be a critical friend, share knowledge and create market advocates.
- To work with other centres of capability within academia and the private sector to address these challenges and develop knowledge.
- To support organisations who are or who wish to work in this area to find funding and gain access to knowledge, people, funding and organisations.

Demonstrate. One of the strong messages resonating from the stakeholder engagement and the analysis of demonstrable capability is that the need to show, prove and test a principle or concept at scale is an essential element of knowledge development and is market enabling. The required activities include:

- The demonstration of the causal links between service outcomes and the underlying infrastructure.
- The development of the business cases to demonstrate the possibilities.
- The selection or identification of one (or many) local authorities with the ambition and sufficient scale to: demonstrate impact; have the autonomy to implement change; have a supply chain with the willingness to change; and with access to academia to create a living lab or demonstrator to test our assumptions, gather evidence and prove a relationship.

Table of Contents

<i>Disclaimer</i>	2
<i>Executive summary</i>	3
1. Introduction	7
1.1. Research question	7
1.2. Method	7
2. What new capabilities the UK will need	8
2.1. Road transport future themes	8
2.2. Road transport required capabilities for CDBB	18
2.3. Energy future themes	21
2.4. Energy required capabilities for CDBB	25
3. Current Capabilities	30
3.1. Literature review	30
3.2. Research Landscape.....	54
3.3. Domain review	59
4. Gap analysis and capability development	69
5. Demonstrators	75
5.1. Summary of demonstrators	75
5.2. Observations	86
5.3. Capability development.....	87
6. Conclusions	89
7. Recommendations	92

1. Introduction

Services are core to the success of the UK with around 80% of our GDP generated in the service sector. Previous work by the Centre of Digital Built Britain has shown around half of the services creating the GDP are reliant on the infrastructure and built environment, which amounts to £600bn each year. The impact on the individual and the economy when the services falter is well documented: traffic congestion, poor air quality, rail delays, buildings not fit for purpose and requiring rework, increased burden to the NHS, and a negative impact on the environment. This is illustrated in Figure 1. It therefore follows that the ability to create and operate services and the underpinning infrastructure in a more effective and efficient manner targeted at delivering the right outcomes will be of considerable benefit to the UK.

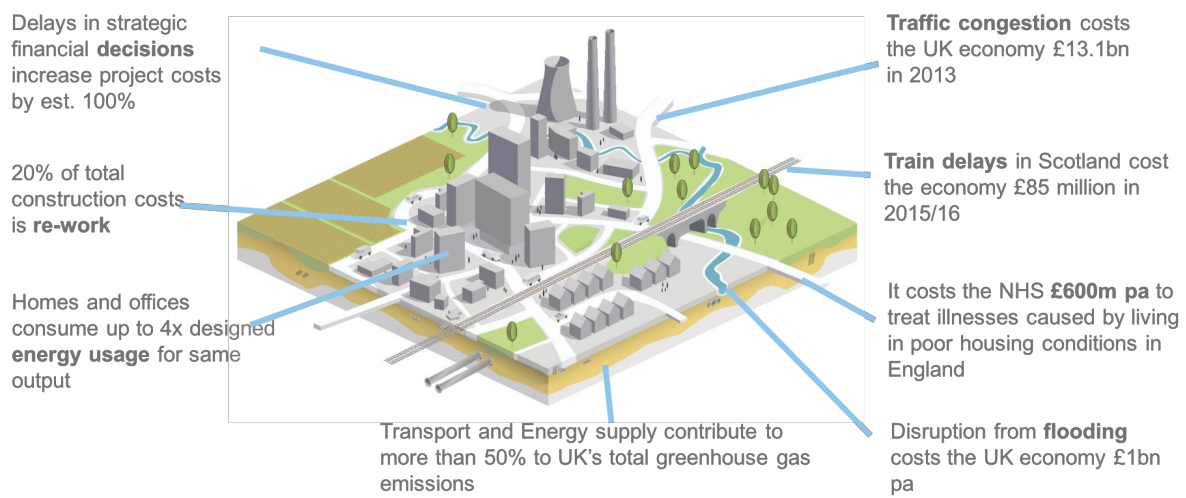


Figure 1 - Economic and social impact of poor infrastructure

1.1. Research question

This workpackage will explore the capabilities required to specify, procure, design, deliver and manage services based on and embedded in the built environment, in order to optimise effectiveness, efficiency and productivity for their stakeholders, whilst making best use of data and information through-life and across assets and infrastructure.

1.2. Method

The research will be structured around identifying:

- What new capabilities the UK will need.
- Where the basis for such development and demonstration exists today.
- The research, development and demonstration necessary to build, deploy and disseminate such capabilities.

Since the scope of the Centre for Digital Built Britain is broad, this research will focus on road transport and electrical energy. These have been selected as they are two sectors that are hypothesised to be converging due to the increased adoption of Electric Vehicles, the decentralisation of the energy networks, and the change in customers' attitude to ownership and outcomes. A sure basis for the investigation is provided by previous work completed for the Centre.

2. What new capabilities the UK will need

If the purpose of this workpackage is to:

explore the capabilities required to specify, procure, design, deliver and manage services based on and embedded in the built environment, in order to optimise effectiveness, efficiency and productivity for their stakeholders, whilst making best use of data and information through-life and across assets and infrastructure

it is therefore important to define what a service *is*, to be able to determine which capabilities are needed.

A 'service' is defined by the Cambridge Dictionary¹ as a "government system or private organisation that is responsible for a particular type of activity, or for providing a particular thing that people need."

Decomposing this definition further, a 'need'² is defined as "something that you must have in order to live a satisfactory life or to achieve a particular thing."

This section will focus on the time horizon 2040-2050. This period has been selected based on the combination of the forecasted timescales of the electrification of transportation, the expected change from personal transport and ownership, and the transformation of the energy consumer services.

2.1. Road transport future themes

Transport connects people, businesses and services. It enables people to access schools, jobs, food stores, hospitals and businesses to get their goods to market. But economic and population growth also brings an additional demand for transport.

Passenger transport in the UK recorded the highest volume ever with 801 billion passenger-kilometres and 201 billion tonne-kilometres of domestic freight moved within the UK³. Road has been the predominant mode in both passenger and freight transport for over 60 years and urban road freight movements (in van) increased at an average rate of 2% a year for the past 5 years⁴. The rise in internet shopping and home deliveries is likely to be one of the contributing factors to such trend.

UK airports handled a total of 268 million terminal passengers and 2.4 million tonnes of freight. Heathrow Airport is one of the busiest airports in the world with 76 million terminal passengers and 481 air transport movements⁵.

The Industrial Strategy⁶ has described infrastructure is one of the five foundations of productivity. Maintaining and upgrading the transport infrastructure can play a key role in enabling the delivery of the Government's plan⁷, and the Government is already acting on this priority, having allocated over £61 billion in capital investment for transport infrastructure up to 2020/21⁸.

¹ <https://dictionary.cambridge.org/dictionary/english/service>

² <https://dictionary.cambridge.org/dictionary/english/need>

³ Department for Transport: *Transport Statistics Great Britain: 2017*

⁴ Data computed by the authors from Department for Transport (2017): *Road Traffic Statistics*

⁵ Department for Transport: *Transport Statistics Great Britain: 2017*

⁶ https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/664563/industrial-strategy-white-paper-web-ready-version.pdf

⁷ Department for Transport (2017): *Transport Investment Strategy*

⁸ Department for Transport (2017): *Proposals for the Creation of a Major Road Network Consultation*

The impacts associated with current levels of transport activity are too well-known. A multi-departmental report of 2009⁹ referred to excess delays having the biggest economic cost of all transport externalities, followed by physical inactivity and the growing level of obesity, road accidents, and poor air quality. Currently, it is estimated that congestion costs the UK economy around £31 billion a year, and £6 billion in London alone¹⁰. Moreover, according to official BEIS data¹¹, transport accounts for the largest proportion of final energy consumption, and has done since 1988. At around 40% of total energy consumed in the UK, road transport accounted for the largest share of transport consumption, including being 74% of energy consumption in transport in 2016¹² and a quarter of UK domestic greenhouse gas emissions.

Alongside socio-economic and environmental challenges, ongoing changes in the administration of transport infrastructure will present new challenges to the way the infrastructure will need to be managed and maintained. Notably, the devolution of transport powers - a process that intends to give more control to English local authorities by transferring powers historically centralised to local government - will enable the latter to have more say over strategic transport investment on their local transport network. And, if on one hand, it will enable integration at the local level, for instance through smart ticketing, the risk is that this decentralisation will hinder an integrated approach to infrastructure and data management at network level.

Given the increasing pressure on existing transport networks as a consequence of the additional demand for transport that comes from economic and population growth, it is of the utmost importance to understand how to achieve higher levels of performance of the existing and future transport infrastructure.

The transport needs for the UK in 2050 continue to change as society evolves: as human kind responds and mitigates the damage inflicted on the planet and as economies develop around the World. Focusing on the UK transport needs, the UK population is predicted to grow from 64 million to 77 million by 2050¹³. A greater proportion of these people will live in cities and the population over 65 is expected to almost double. This will increase pressure on existing transport infrastructure and create additional mobility needs. The economics of society will change. The emerging markets and developing countries now account for more than half of global economic growth and this is increasing their demand for resources and affecting global trade patterns. The trends in behavioural patterns among young adults (18-34 years) continue to evolve. These include higher participation in further education and a delay in marriage and traditional household formation. As the global climate continues to change, the UK is expected to see increasingly unpredictable weather with more extreme events, thus continuing to test the resilience of the UK's transport infrastructure. The major themes identified for the surface transport sector are:

Reduction in air pollution. Ambient (outdoor) air pollution is a major cause of death and disease globally. The health effects range from increased hospital admissions and emergency room visits, to increased risk of premature death. An estimated 4.2 million premature deaths globally are

⁹ Cabinet Office et al: *The wider costs of transport in English urban areas 2009*

¹⁰ INRIX: *INRIX 2016 Traffic Scorecard – U.K.*; <http://inrix.com/resources/inrix-2016-traffic-scorecard-uk/> [last accessed 28 March 2018]

¹¹ Department for Transport: *Transport Statistics Great Britain: 2017*

¹² Data computed by the authors from Department for Business, Energy & Industrial Strategy: *Energy Consumption in the UK (2017)*

¹³ <https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates>

linked to ambient air pollution, mainly from heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and acute respiratory infections in children.

Pollutants with the strongest evidence for public health concern, include particulate matter (PM), ozone (O₃), nitrogen dioxide (NO₂) and sulphur dioxide (SO₂). The health risks associated with particulate matter of less than 10 and 2.5 microns in diameter (PM₁₀ and PM_{2.5}) are especially well documented. PM is capable of penetrating deep into lung passageways and entering the bloodstream causing cardiovascular, cerebrovascular and respiratory impacts. This has been classified as a cause of lung cancer by the World Health Organisation's (WHO) International Agency for Research on Cancer (IARC). It is also the most widely used indicator to assess the health effects from exposure to ambient air pollution¹⁴.

To mitigate the creation of these pollutants, the transportation sector will reduce the number of internal combustion engine powered vehicles and move to electric. These produce zero emissions directly, although they may cause indirect emissions through the electricity they use for their manufacturing process and during generation. The UK Government's UK plan for tackling roadside nitrogen dioxide concentrations¹⁵ announced to end the sale of all new conventional petrol and diesel cars and vans by 2040. This has a large impact on the transport and energy sectors from all aspects. There are an anticipated 34 million Electric Vehicles (EV) on the road requiring 60TWh of electricity per year by 2040. Dependant on the method of electricity generation, it will also have an impact on the decarbonisation of the transportation sector.

Decarbonisation. Transportation is responsible for 14% of the global greenhouse gas emissions¹⁶, as illustrated in Figure 2. In order to achieve the Paris Agreement¹⁷, decarbonisation of the transport sector will be essential.

¹⁴ <https://www.who.int/airpollution/ambient/health-impacts/en/>

¹⁵ https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/633270/air-quality-plan-detail.pdf

¹⁶ https://wriorg.s3.amazonaws.com/s3fs-public/resources/world_greenhouse_gas_emissions_flowchart.pdf?_ga=2.151633145.1379760340.1542995307-739773925.1542995307

¹⁷ <https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement>

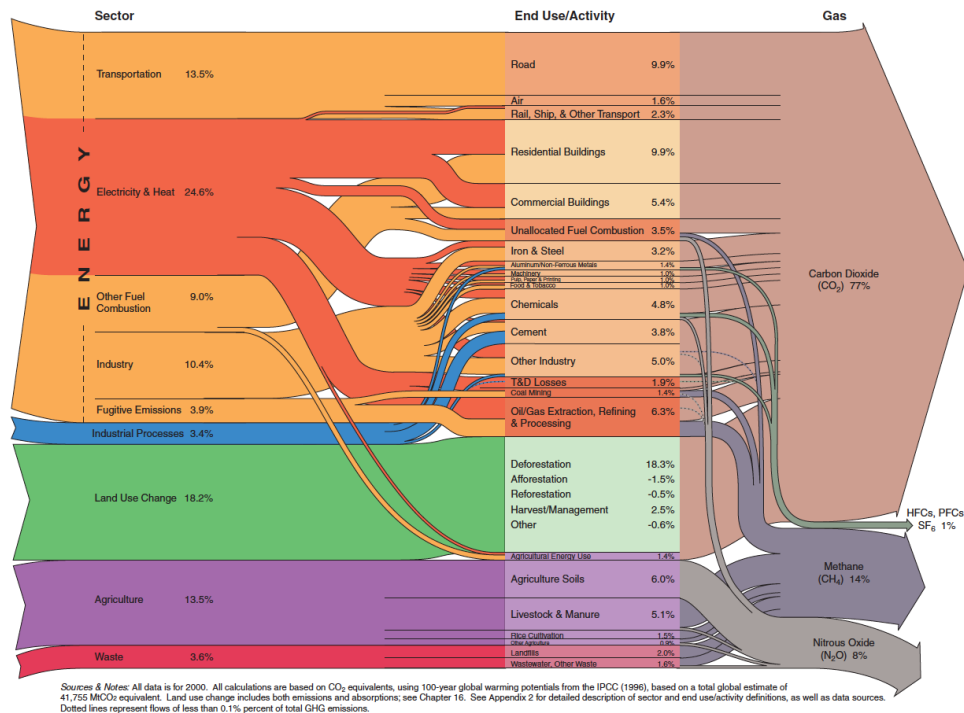


Figure 2 - Global greenhouse emissions

The main levers for decarbonisation are¹⁸:

Electrification. The reduction in the carbon produced to transport people and goods through the use of electric vehicles. This also addresses the road side air pollution challenge described earlier. The increase in electrification will require the infrastructure to support vehicle charging: it is forecast that the majority of private vehicles will be slow charged overnight at home, whilst an increase in mobility-as-a-service and high demand vehicle users will require faster distributed charging networks around centres of urban and sub-urban density. For commercial use, whether this is cars, vans or trucks, there is a need to have a wider extra-urban network to enable greater distances to be travelled with confidence.

Demand reduction. The reduction in demand through changes in patterns of behaviour, or an increase of density in people and goods. This is explored in further detail later in this section.

Modal shift. Switching to transport modes that are inherently more carbon efficient than others. This includes moving from private to public transport, using high speed rail rather than air for medium distance journeys, and the use of cycles and walking to cover short distances.

Changes in demand. There is an ever-increasing shift of populations to cities and large towns. This is driven by a combination of greater employment opportunities, and the increased access to services and leisure options¹⁹. This is being seen for both young adults attracted by opportunity and the old driven by the access to services. However, this desire to be located in the centres of conurbation is tempered by affordability which impacts travel patterns, especially for families who tend to move to suburban areas. Over the past twenty years the distance that people commute to work has increased slightly. However, there has also been a decrease in the number of commuter trips made. This combination of fewer, but longer, commutes is likely due to several

¹⁸ https://ec.europa.eu/transport/sites/transport/files/themes/strategies/doc/2001_white_paper/lb_com_2001_0370_en.pdf

¹⁹ <https://www.weforum.org/agenda/2018/10/this-is-why-people-live-work-stay-leave-in-growing-city/>

factors, including more opportunities to work from home and increasing suburban house prices which force commuters further from city centres.

The proportion of jobs located in city centres continues to rise as the number of jobs in knowledge-based industries that are typically located in or near city centres increases²⁰. This process is 'agglomeration'²¹. Agglomeration economies or external economies of scale refer to the benefits from concentrating output and housing in particular areas. If an area specialises in the production of a certain type of good, all firms can benefit from various factors such as established supply networks, supply of trained workers, infrastructure built specifically for the industry, and good transport links. As a consequence of agglomerated economies, people and companies often concentrate in particular areas. For example, people tend to move to cities where there is a greater choice of jobs, social activities and specialist services. This puts increasing demand on public transport in and to and from cities. If public transport is not a viable or preferred option, there is a risk of increasing congestion on the roads without using levers like road user charging and low emissions zones. Furthermore, once the vehicle is within the urban space it needs to be parked, which increases competition for land for car parking²².

Mobility-as-a-Service. There is a recognition that personal transportation is an unsustainable, but often necessary extravagance. As the trend continues away from an ownership to a service culture, the need to own your means of transport will diminish. An analysis of the maturity and performance of mobility systems has shown that, due to the complex nature of the problems at hand, separate optimisation at sub-system level has strong limitations, and only system-level improvement will significantly improve overall mobility performance. However, in most of today's mobility systems, means of transportation are often still divided, and public and private stakeholders do not work together sufficiently closely on the development of seamless and networked mobility ecosystems.

The concept of Mobility-as-a-Service (MaaS) aims to provide consumers with integrated, flexible, efficient and user-oriented mobility services. It implies a shift away from the personal ownership of individual motorised transportation modes and non-integrated means of transportation, towards the use of integrated multimodal mobility solutions consumed as services. This shift is enabled by combining transportation services from public- and private-transportation providers through an integrated mobility platform, combining services, technology and business layers, managing the journey and integrating planning and payment, based on mobility packages tailored to the needs of each customer segment, on a one-stop-shop principle.

The high expectations of the concept of MaaS are fuelled by the anticipated evolution from ownership of a personal car towards consuming mobility through a combination of on-demand mobility services, which are expected to become significantly more affordable once autonomous vehicles are widely available. Until recently, whilst the concept of MaaS has been largely applied to individual mobility, it can be applied for the same reasons to the movement of goods. Full development and implementation of Mobility-as-a-Service at city or national level requires the presence of several components, as illustrated²³ in Figure 3.

²⁰ <https://www.centreforcities.org/blog/why-do-businesses-flock-to-certain-areas-of-britain/>

²¹ <https://dictionary.cambridge.org/dictionary/english/agglomeration>

²² <https://phys.org/news/2018-01-cities-dominance-space.html>

²³ http://www.adlittle.com/futuremobilitylab/assets/file/ADL_UITP_Future%20of%20Mobility3.0-min.pdf

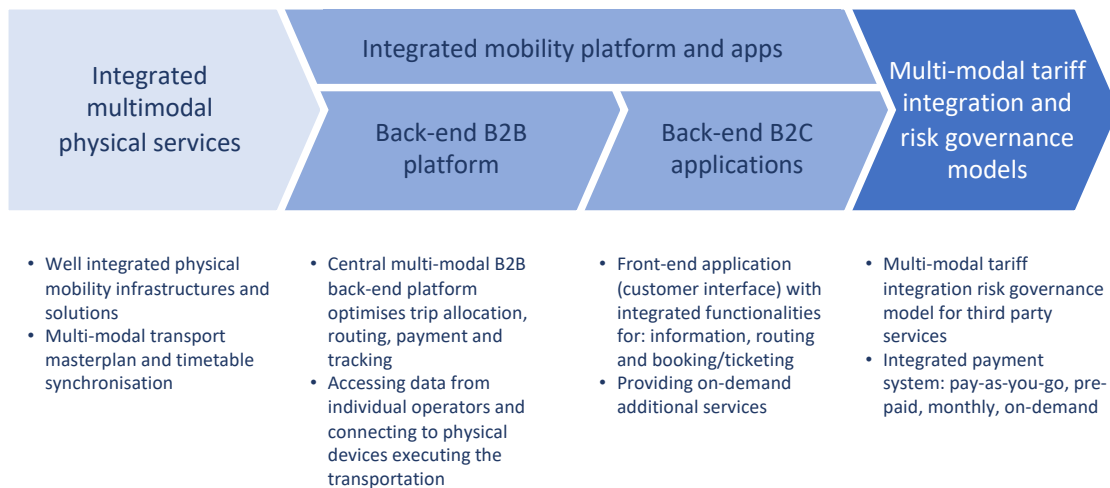


Figure 3 - Example multimodal platform

Well-integrated physical multimodal mobility infrastructures and solutions are a prerequisite to a well-functioning MaaS concept. This requires long-term alignment between mobility stakeholders on a shared mobility vision and strategy, and a coordinated approach to investments. The development and implementation of a multi-modal transport master plan, ensuring the optimal allocation of transport modes in space and in time, will benefit the system as a whole.

The integrated mobility platform and application(s) lies at the core of MaaS. These will allow for the creation and management of journeys and act as the user-interface with consumers, along with the tariff model, which includes the service governance and risk sharing. This is of particular relevance when the model is evolving and the likelihood of a misalignment between revenue and return is high, and the commitment by the service provider is significant.

The public transport authorities are key stakeholders and actors in the enablement of the MaaS concept at city, regional or national level, and the following conditions are anticipated to be necessary:

- Defining integrated and multimodal mobility plans and making the arbitrage for investment in public- and road-transport infrastructures.
- Providing access conditions and guidelines for new mobility solutions providers through regulation, which have a critical role to play in the implementation of MaaS.
- Defining rules of an open-data policy for public transport and the provision of access to the application programming interface (API) required for the development of back-end platforms.
- Establishing the right governance mechanisms to ensure MaaS operators strive for the best system possible, allowing optimisation of the mobility system as a whole by taking an agnostic approach to different transport modes.

The mobility solutions providers, such as train, bus, car share, taxi, bike share, parking, active travel and autonomous vehicles (discussed in next section) also have a vital role to play. It is critical that public and private providers converge to enable the gradual evolution towards Mobility-as-a-Service. The key areas are:

- Contributing to the development of integrated and multimodal mobility visions and an integrated transport master plan.

- Collaborating with other solutions providers to better manage relevant mobility data; as an input for the defining of mobility offerings in-line with mobility demand; and contributing along with public transport authorities to creating and enacting a data policy and information exchange agreements.
- Creating an ecosystem for innovation and inclusion by taking a leading role or participating as a third party in the development and implementation of integrated mobility platforms and applications.

Connected and Autonomous Vehicles. The forecasts for the number of connected and autonomous vehicles on our road varies considerably depending on the study and the level of optimism. What is evident is that they are coming, and this will impact our existing mobility services and infrastructure. Table 1 summarises the level of market penetration for different scenarios.

Table 1 - Estimates of CAV market penetration

Scenario	Description and reference points	CAV uptake (share of new vehicle sales)		
Progressive	<p>Follows global uptake projections from Goldman Sachs, 2015²⁴ and high global uptake projections from McKinsey, 2016²⁵</p> <ul style="list-style-type: none"> - Safe and reliable technical solutions fully developed and introduced by mass market leaders before 2025. - Significant cost reductions to hardware (following similar trends to smartphones) achievable in the next 10 years. - Levels of scepticism can be reduced in a short time frame, supported by the regulatory environment and the rapid solution of remaining technological challenges. 	2025	2030	2035
		L3: 11%	L3: 29%	L3: 54%
		L4/5: 0.4%	L4/5: 8%	L4/5: 30%
Central	<p>Follows global uptake projections set out in BCG, 2015²⁶</p> <ul style="list-style-type: none"> - Assumes that uptake is governed predominantly by consumer willingness to pay; possible effects of regulations (e.g. those mandating autonomy) are not accounted for. - Uptake is based on comparing projections of cost reductions (which are based on extensive industry consultation and cost trends for existing ADAS technology) with consumer willingness to pay (based on survey results). 	2025	2030	2035
		L3: 11%	L3: 18%	L3: 15%
		L4/5: 0.3%	L4/5: 3%	L4/5: 10%
Obstructed	<p>Follows low global uptake projections from McKinsey, 2016</p> <ul style="list-style-type: none"> - Technical and cost challenges for L5 are not addressed in the next 10 years. - Regulations (excluding those in the UK) do not enable sufficient use of CAVs in varied environments. - Negative publicity following incidents; consumers take longer to trust the technology. 	2025	2030	2035
		L3: 0.2%	L3: 3%	L3: 5%
		L4/5: 0%	L4/5: 0.2%	L4/5: 3%

²⁴ http://pg.rj.com.cn/acc/Res/CN_RES/INVEST/2015/9/17/f70472c6-f4ad-4942-8eab-3c01f3c717a7.pdf

²⁵ <https://www.mckinsey.com/~media/mckinsey/industries/high%20tech/our%20insights/disruptive%20trends%20that%20will%20transform%20the%20auto%20industry/auto%202030%20report%20jan%202016.ashx>

²⁶ <https://www.bcg.com/en-gb/publications/2015/automotive-consumer-insight-revolution-drivers-seat-road-autonomous-vehicles.aspx>

The functionality provided by the level of connection and autonomy ranges from providing traffic updates at the elementary level through to making operational assistance. The SAE²⁷ has defined 6 levels of connection and automation: this illustrates the adjacency of connected and autonomous vehicles along with the differing levels of control exercised. Table 2 summarises these definitions, with Table 3 illustrating the use case for each of the levels of connectivity and automation.

Table 2 - SAE definition of connected and autonomous levels

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/Deceleration	Monitoring of Driving Environment	Fallback Performance of Dynamic Driving Task	System Capability (Driving Modes)
Human driver monitors the driving environment						
0	No Automation	the full-time performance by the <i>human driver</i> of all aspects of the <i>dynamic driving task</i> , even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the <i>driving mode</i> -specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the <i>human driver</i> perform all remaining aspects of the <i>dynamic driving task</i>	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the <i>driving mode</i> -specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the <i>human driver</i> perform all remaining aspects of the <i>dynamic driving task</i>	System	Human driver	Human driver	Some driving modes
Automated driving system ("system") monitors the driving environment						
3	Conditional Automation	the <i>driving mode</i> -specific performance by an <i>automated driving system</i> of all aspects of the <i>dynamic driving task</i> with the expectation that the <i>human driver</i> will respond appropriately to a <i>request to intervene</i>	System	System	Human driver	Some driving modes
4	High Automation	the <i>driving mode</i> -specific performance by an automated driving system of all aspects of the <i>dynamic driving task</i> , even if a <i>human driver</i> does not respond appropriately to a <i>request to intervene</i>	System	System	System	Some driving modes
5	Full Automation	the full-time performance by an <i>automated driving system</i> of all aspects of the <i>dynamic driving task</i> under all roadway and environmental conditions that can be managed by a <i>human driver</i>	System	System	System	All driving modes

Table 3 - Use cases for different levels of autonomous control

No automation	1 Driver assistance	2 Partial automation	3 Conditional automation	4 High automation	5 Full automation
Human driver performs part or all of the dynamic driving task; in particular, the driver is responsible for monitoring the environment and any action taken by the automation system	System performs entire dynamic driving task while engaged, including monitoring and response as well as steering and acceleration				
Human driver performs all aspects of dynamic driving tasks	System can perform either steering or acceleration	System can perform both steering and acceleration	Human driver may be requested to intervene (fallback)	Full automation in some driving modes	Full automation in all driving modes
e.g. Park Assist, Adaptive Cruise Control	e.g. Traffic Jam Assist		e.g. Intersection Pilot, Platooning		e.g. Urban automated driving

It is expected that the majority of connected and autonomous vehicles (CAV) systems will need a combination of detailed mapping of the road network and real-time information received from sensors to safely navigate the road network. This presents a series of considerations for the future infrastructure requirements. A study for the Department of Transport about future-proofing

²⁷ https://www.sae.org/misc/pdfs/automated_driving.pdf

infrastructure for connected and autonomous vehicles²⁸ identified the following categories as areas for further consideration:

Traffic Management Measures. Roadworks may alter the road layout, changing where vehicles are expected to travel. For human drivers, intuition and ability to interpret road signs allows them to navigate these areas. However, CAVs may not have the intelligence to interpret a new environment correctly, and therefore may have difficulty navigating through these areas. Due to these difficulties, consideration needs to be given to future design, implementation, and the operation of traffic management measures. This includes planned and unplanned roadworks. Planned roadworks might be scheduled weeks or months in advance and information about their design and implementation could be foreseen and included in the network model through close co-operation between contractors and local authorities. However, emergency roadworks, including broken-down vehicles in the carriageway, occur on an ad-hoc basis and cones are placed on the carriageway by the first responders to the scene. This will require special consideration within the network model, sending alerts via the infrastructure to vehicle systems, and transmitting to the CAVs to adopt the appropriate control.

Road markings. In addition to the detailed network maps, a number of CAV technologies rely on situational awareness from the road markings for guidance. These include lane markings and other on-road indication such as stop lines or signage. The challenges that need to be addressed to enable CAVs to tackle road markings include: old road markings not completely obscured even if blacked out, bitumen lines used to seal cabling or drainage in the roadway, faded indistinct lines on asphalt surfaces, slightly faded lines on concrete road surfaces which present poor contrast, lane markings not in normal use, and discontinuous markings. Whilst road signage is not safety critical and the information contained within should be part of the detailed network model, any control systems relying on this infrastructure for visual information will be impaired. Inclement weather such as rain, fog and snow may also impair the visibility of marking, as will direct sunlight causing saturation of sensors.

For the safe operation of CAVs, the quality of the road surface and marking will need to be improved and maintained, with alerts to the operational teams to remedy degradation captured through a series of sensors in the surface and LiDAR imagery captured to condition monitoring. The roadside infrastructure will need to be able to visually interpret the situation in order to send set transmission messages, providing real-time information to the CAV through a series of beacons throughout the network.

Safe harbour areas. It is likely that in full autonomy, the driver vehicles will be travelling at speed with the driver disengaged from driving the vehicle with no awareness of the situation. It is also possible the driver may not be in a fit condition to take control of the vehicle before a planned exit point due to an incident ahead, CAV vehicle malfunction, inclement conditions or if the driver is incapacitated. Here the CAV will need to find a safe harbour ready for conditions to revert to a state where automatic running can resume, or where manual control is taken. This is analogous to the emergency refuge areas seen on the Smart Motorway

²⁸ <https://s3-eu-west-1.amazonaws.com/media.ts.catapult/wp-content/uploads/2017/04/25115313/ATS40-Future-Proofing-Infrastructure-for-CAVs.pdf>

network or exiting the network at the next departure point and resting at a suitable location such as a service station.

Service stations will provide off-network high-capacity safe harbours, locations for charging electric vehicles, and mode interchange locations within the network. It is anticipated that the majority of CAV will be electric vehicles and a proportion of these vehicles will be used for distances greater than the capacity of a single charge, therefore requiring replenishment at rapid charging points. The mode interchange is of particular relevance when the CAV is being used as part of a MaaS network, where there is a pool of CAVs for use on routes not served by public or mass transit.

Car parking. Whether the CAVs are private and shared, there are locations where the vehicles will need to reside. The benefit of CAV is the space required between vehicles for access and egress is significantly less as the driver and passengers do not need the space. In addition, techniques adopted from the logistics sector can be adopted to shuffle vehicles to enable access. This enables the existing car parks to have increased capacity and reduce the size of new car parks for the same number of vehicles.

Automated Demand Response Public Transport. It is anticipated that the modes within the MaaS system will include lower capacity automated demand response public transport, or autonomous taxis or mini-buses to provide network in-fill or point-to-point solutions. These enable new services to be provided and optimised as demand/supply routings are determined.

Crossings and junctions are a key feature of our road networks, especially urban and suburban. These include pedestrian crossings such as uncontrolled, zebra or signalled; junctions, which are marked, signalled (operational or in a failure state), or priority controlled; and level crossings. Non-signalised junctions may prove to be challenging for CAVs and it is anticipated that a greater number of signalised junctions will be needed. These signalised junctions, like other visual indicators like road signage, will require infrastructure to vehicle and vehicle to infrastructure communication to inform the network of classification, priority, presence and destination, along with the network communicating instructions to manage localised demand. It is foreseen that a significant development of the CAV visual analytics will be required if CAVs are permitted to operate in areas where other road users will be present. The network resilience will be highly dependent on the performance of these crossings and junctions. This will increase the need for sensing of the performance of infrastructure and monitoring of the operational spaces.

Impact on bridge structures. Bridges are features of significant importance within the network, unlocking social progression and economic growth when built. The design guidelines for bridges in the UK are described in the Design Manual for Bridges and Roads²⁹. This assumes that the lorries are dispersed along the route and interspersed with cars and light vehicles. Platooning of CAV lorries is a popular use case that will reduce fuel economy and increase network capacity. Alongside control logic to disperse lorries crossing a bridge, the bridge loading will need monitoring to ensure design parameters are not exceeded and any degradation closely monitored.

²⁹ <http://www.standardsforhighways.co.uk/ha/standards/dmrb/>

Digitisation of sector. The actions identified to address air pollution and reduce the level of carbon from transport, along with new services like MaaS and CAV all rely on data and information to provide the service. The impact on infrastructure of these advancements require information about the asset's usage and performance to inform the planning process, which in turn are described in the design and subsequently realised through construction. The asset usage and performance are an essential element of feedback that will assist in the predictive maintenance and, where necessary, rapid diagnostic in the event of an incident, essential to maintain high levels of availability.

The information used for transportation will need to be handled in accordance with the relevant data privacy regulation as it will be possible to derive considerable insight into individual patterns of behaviour. With the increased dependency on a tightly coupled system, the security classification of the network and nodes within will require evaluation to ensure the appropriate oversight and governance is in place. The resilience of the network and the services they depend on (either directly or indirectly) will need evaluation to ensure neither assets, services nor the beneficiaries of the services are stranded.

Closer coupling of sector with infrastructure providers. The transport sector itself will become more closely coupled. This increases the number of touch-points or adjacencies with other infrastructure providers.

The transportation sector will become more closely coupled with the energy sector, as the reliance on electricity as a power source increases. This will require the management of supply and demand to be considered across the traditional sectoral boundaries. Potential will be unlocked as the quantity of electricity storage (with on-board batteries) will increase dramatically, whilst needing careful management to ensure demand requests are balanced. The respective system operators of the energy networks and transport networks will therefore be required to collaborate in new methods of working and develop agreements for co-operation.

Both the transportation and the energy sector will individually and collectively need to serve the housing demand that will develop. The shortfall in housing will continue to be addressed with new developments in accordance with the housing strategy. This will put additional demands on the already stretched sections of the networks in terms of capacity, but also to create linkages so that communities are formed rather than dormitory towns.

2.2. Road transport required capabilities for CDBB

The capability requirements for the UK relevant for the CDBB agenda and mandate are summarised in Table 4. These consider the major trends for the road transport sector in the time horizon 2040-2050.

Table 4 - Road transport capabilities required for CDBB

Theme	National Requirement	CDBB Capability Required
Reduction in air pollution	<ul style="list-style-type: none"> • Electrification of vehicles. • Creation of clean air zones. 	<ul style="list-style-type: none"> • Integrated system modelling at varying levels of geographical focus and with focus on service outcomes. • Impact on transport and energy network of electrical demand. • Socioeconomic evaluation of infrastructure impact and capability. • Methods to trigger behavioural change.
Decarbonisation	<ul style="list-style-type: none"> • Electrification of vehicles. • Reduce demand. • Modal shift to low carbon solutions. 	<ul style="list-style-type: none"> • Integrated system modelling at varying levels of geographical focus and with focus on service outcomes. • Socioeconomic evaluation of infrastructure impact and capability. • Methods to trigger behavioural change.
Changes in demand	<ul style="list-style-type: none"> • Increased demand for public transport capacity in urban areas. • Increased demand for public transport transit time capability in suburban/extra-urban areas. 	<ul style="list-style-type: none"> • Integrated system modelling at varying levels of geographical focus and with focus on service outcomes. • Socioeconomic evaluation of infrastructure impact and capability. • Methods to trigger behavioural change.
Mobility-as-a-Service	<ul style="list-style-type: none"> • Physical integration of transport modes. • Schedule integration of transport modes, including demand regulated. • Digital integration of transport modes. • Increased surety and resilience in service provision. • Creation of new services. • Creation of new service platforms. 	<ul style="list-style-type: none"> • Integrated system modelling at varying levels of geographical focus and with focus on service outcomes. • Socioeconomic evaluation of infrastructure impact and capability. • Inclusion of perceptive, subjective and objective criteria into system model. • Define service outcomes, capability and capacity, linked to the elements of the infrastructure and service required. • Exploration of new service offering, associated business models, supply chain formation and contractual structures. • Methods to trigger behavioural change. • Methods to increase surety and resilience in complex systems. • Development of methods to present complex information and manage choice for the digitally emerging or excluded members of society. • Data privacy and security.

Theme	National Requirement	CDBB Capability Required
Connected and Autonomous vehicles	<ul style="list-style-type: none"> • Vehicular automation technology. • Improvements in road and road-side infrastructure to facilitate CAV. • Managing ad hoc events and emergencies. • Modal shift to CAV. • Integration into MaaS. 	<ul style="list-style-type: none"> • Ongoing determination of asset condition for the suitability of CAV operation. • Use of asset information to optimise CAV operation within existing infrastructure. • Define service outcomes, capability and capacity, linked to the elements of the infrastructure and service required. • Use of assets information to mitigate and respond to incidents on the network, and integrate with CAV vehicle control systems. • Risk, liability and commercial impact for asset information availability, accuracy, integrity, relevance, completeness and timing.
Digitisation	<ul style="list-style-type: none"> • Digital skills and capability. • Digital access, especially for the vulnerable or excluded. • Availability and access to required data sources. • Definition of integrated data models for asset and service information. • Standards, guidelines and codes of practice for data integration. • Protection of national and personal information. 	<ul style="list-style-type: none"> • Awareness, training and development in an accessible and consumable form throughout the supply chain and society. • Development of methods to present complex information and manage choice for the digitally emerging or excluded members of society. • Integration of 'slow' and 'fast' data models. • Standards, guidelines and codes of practice for data integration. • Data privacy and security.
Closer coupling of sector with infrastructure providers	<ul style="list-style-type: none"> • Integrated system modelling at varying levels of geographical focus and with focus on service outcomes. • Inclusion of perceptive, subjective and objective criteria into system model. • Understand the impact of system disturbances. 	<ul style="list-style-type: none"> • Integrated system modelling at varying levels of geographical focus and with focus on service outcomes. • Inclusion of perceptive, subjective and objective criteria into system model. • Methods to increase surety and resilience in complex systems. • Data privacy and security.

2.3. Energy future themes

The global energy system has remained unchanged from its inception for many years and consists of a hierarchical and linear system of central generation, high voltage transmission to regions and distribution to medium/low voltage consumers. With the introduction of renewables at various points in the existing system, the decentralisation of the network increased and the term smart grid was born.

Today we are on the cusp of major changes to this traditional sector provoked by a combination of customer demand, technological enablement, network upgrade and the economic balance of the current model. Exactly what this future will look like and when, is a subject of considerable discussion in the sector, but what is clear is the direction of travel, which is subject to opposing forces in places. This will be unpacked in this section. The major themes identified are:

Changes in demand. In the Evolving Transition scenario which assumes that government policies, technologies and societal preferences evolve in a manner and speed similar to the recent past, world GDP more than doubles by 2040, driven by increasing prosperity in fast-growing emerging economies, as more than 2.5 billion people are lifted from low incomes. This rising prosperity drives an increase in global energy demand, although the extent of this growth is offset by accelerating gains in energy efficiency: energy demand increases by only around one third over the next 25 years³⁰. Figure 4 illustrates this growth: driven by China, India and the developing countries, and across the sectors of transport, industry and buildings.

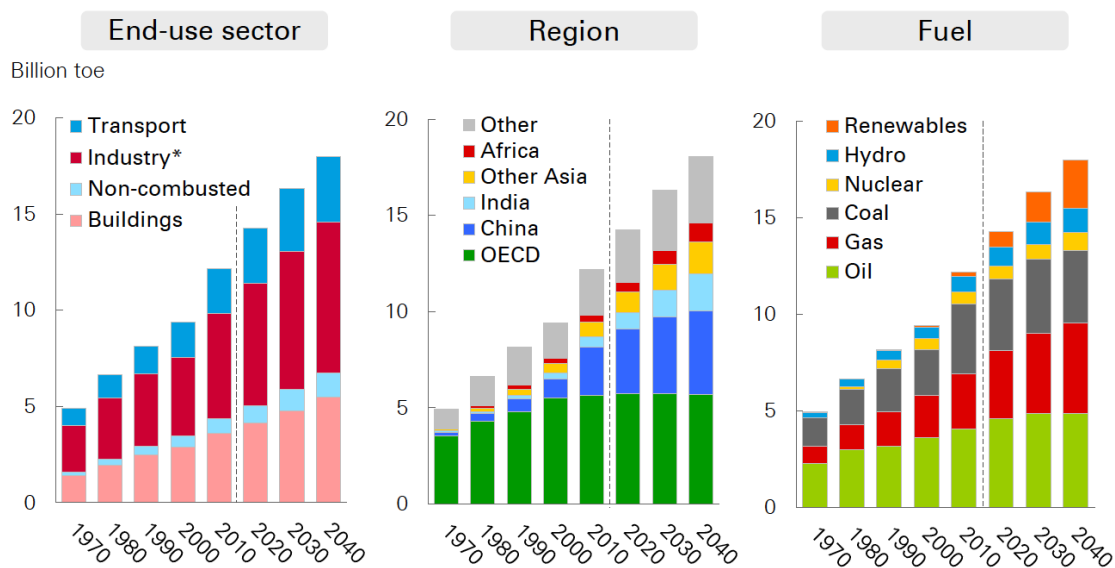


Figure 4 - World future energy demand

Forecasts focusing on the electricity sector suggest the demand will peak in 2032³¹ and decrease thereafter as shown in Figure 5.

³⁰<https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/energy-outlook/bp-energy-outlook-2018.pdf>

³¹<https://eto.dnvgl.com/2018>

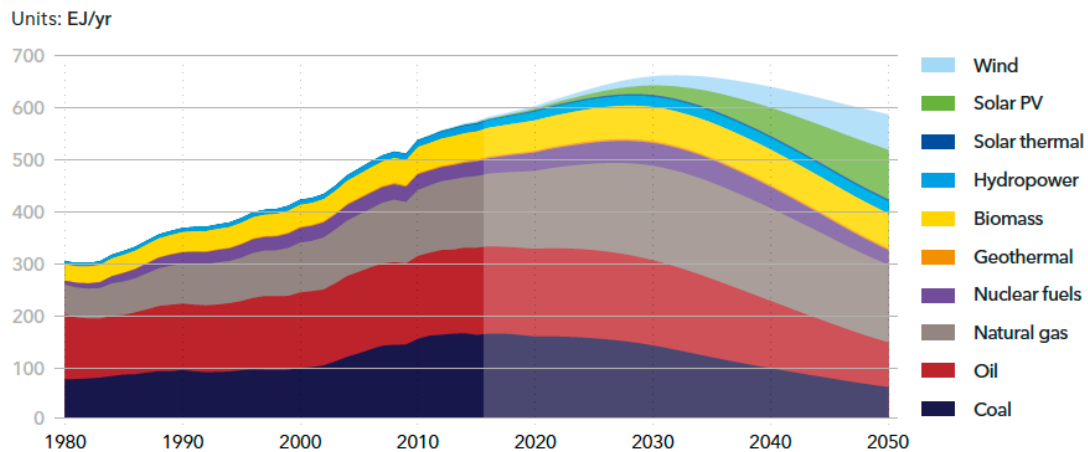


Figure 5 – Forecast global electricity production by source

The decrease is a function of forecast improvements. Energy efficiency is a key feature in the observed trend of the energy transition. The world's energy intensity (the units of energy per unit of GDP) has been declining by 1.1% per year on average for the last two decades. This is anticipated to increase to an average annual decrease of 2.3% due to the accelerating electrification of the energy system, which is more efficient than fossil fuels.

This situation is accentuated by more solar PV and wind generation capacity being installed, with only negligible energy losses. This efficiency trend will be further boosted by Electric Vehicles becoming mainstream in automotive markets, as they consume about a quarter of the energy used by Internal Combustion Engine Vehicles, and the annual energy efficiency improvement in the road sector is boosted by strong electrification, to 3.4% per year over the forecast period.

The other transport sub-sectors and the building and manufacturing sector, will electrify more slowly than the road sector, hence they will not experience a similar additional boost in energy efficiency. Nevertheless, the average annual energy efficiency improvement is forecast to vary between 0.9 and 2.0% per year for these sectors as well.

Decarbonisation. The historic energy mix has been a significant contributor to climate change. With around 30% of installed capacity³², the replacement of fossil fuel generation with renewable energy is beginning to make an impact: reduction in consumption per capita continues to reduce and the change to low carbon vectors all help. Yet more is required if the targets of the Paris Agreement are to be achieved. The world's energy system is expected to decarbonise, with the 2050 primary energy mix split equally between fossil and non-fossil sources. Oil demand will peak in the 2020s and natural gas is expected to take over as the biggest energy source in 2026.

Environmental legislation has been an important driver in reducing the UK's carbon emissions. The UK is currently committed to a number of environmental targets, particularly the Climate Change Act 2008³³. This is the UK contribution to the Paris Agreement that seeks to hold the increase in global temperatures to less than 2°C above pre-industrial levels.

The Climate Change Act legally binds the UK to reduce carbon emissions by at least 80% from 1990 levels by 2050, (the '2050 carbon reduction target') via a series of carbon budgets. This is

³² <http://fes.nationalgrid.com/media/1363/fes-interactive-version-final.pdf>

³³ <https://www.legislation.gov.uk/ukpga/2008/27/contents>

underpinned by further legislation and policy measures. Many of these have been consolidated in the UK Clean Growth Strategy³⁴.

The European Union's 2030 Climate and Energy Framework³⁵ also includes a number of decarbonisation targets for 2030, namely:

- At least a 40% reduction in greenhouse gas emissions (from 1990 levels).
- Renewable energy to make up at least 27% of energy consumption in the EU.
- Energy efficiency – reducing energy use by at least 27% (when compared to the projected use of energy in 2030).

The EU 2030 targets will continue to be binding on all EU member states. Although the UK's future relationship with the EU is being determined (and is in a state of flux at the point of writing), the UK's current energy and climate policy is in line with the EU's 2030 targets, and in some cases is more ambitious.

Decentralisation. Generating closer to the point of use not only increases overall resilience, it reduces the large capital costs of central generation and transmission by having smaller scale production and storage closer to the point of consumption, which in itself is more efficient. The flexibility improves as the methods deployed in the energy supply chain can be optimised to local conditions and profiles.

The point in time when the amount of decentralised energy production exceeds centrally grid-delivered energy is in the near future. It is forecast that in Oceania off-grid energy reaches cost and performance parity with grid-delivered energy as early as 2021, dominated by solar energy. Whereas the cost of transporting electricity is anticipated to exceed the cost of generating and storing it locally in the US Northeast region first in 2039.

Digitisation is expected to have a major impact on the sector. With power systems becoming more connected, intelligent, efficient and reliable. Smart Grids are already improving the safety, productivity, accessibility and sustainability of the power systems, enabling supply and demand to be more closely matched. The introduction of more analytics and intelligence into the value chain is expected to yield further benefits enabling new business models and services to be developed.

Digitisation has and will continue to lower the cost of monitoring and control of all methods of energy generation. In transmission and distribution networks it is expected to improve efficiency and lower losses by operating closer to the optimum conditions. In asset intensive value chains, the insight surfaced through digitisation will drive improvements in planning, predictive maintenance and operations.

In the power sector, digitisation is an important enabler of the energy transition that is upon us. Smart Metering and demand response will provide a better way of matching demand with supply. This will help manage the intermittency and variability that is increasing with the higher levels of renewable sources in our energy mix. It is anticipated this improved level of control will contribute

³⁴ https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/700496/clean-growth-strategy-correction-april-2018.pdf

³⁵ https://ec.europa.eu/clima/policies/strategies/2030_en

to a 4% reduction in the peak load capacity reducing the need to build expensive energy generation capacity around the globe.

The greater adoption of digitisation in itself will increase the energy required to operate the digital devices, albeit the impact is negligible compared to other dominant sources.

From a customer perspective it enables personalisation of service based on preferences and choice. This focus on the outcome or output has the potential to change the relationship between the individual and energy they use.

Customer experience. The customer experience of the energy sector is not at the same level as other services, with examples such as ScottishPower being fined by Ofgem for poor service hitting the headlines³⁶. The Competitions and Markets Authority³⁷ issued a report into the state of the market which concluded there are low levels of customer service provided, the level of trust with consumers is low, and the level of choice is limited. The scale of vertical integration within the sector from generation to supply may be a factor with organisations having a culture of heavy engineering and complex market economics at the core, rather than a true customer focus. Yet the appetite of the consumer to make a change is not high, even though the level of engagement with the service is reducing.

Market deregulation allows new service providers to enter the market. As this continues, there is an expectation of change analogous to the telecoms market. Here there is a clear and growing distinction from the infrastructure and the service as the market matures. Whilst there are still pockets of mobile 'black spots' generally, coverage which is intricately linked to the infrastructure is no longer a distinct point of differentiation. The energy sector is more mature than the telecoms sector and the regulation preventing this decoupling is anticipated to change.

This change will enable organisations to emerge and develop, using the other dominant trends in the market such as information and enabling technology to create new offerings and services. The details of the services are yet to emerge, and where many are speculating what they may be, these include³⁸ the concept of Energy-as-a-Service. Energy consumers do not value a kWh of electricity or a BTU of gas. They value the warmth that it provides, or the light that it enables. Energy-as-a-Service models are starting to appear where consumers might buy warmth, lighting and power rather than units of electricity and gas. The service would be provided by a business that competes for customers by delivering that warmth, lighting and power most efficiently – perhaps by helping improve home insulation, supplying the best equipment to deliver the required service, sourcing the best energy supplies and optimising any local generation or storage. Traditionally, consumers have purchased their energy from one of the big six energy suppliers yet, with the rise of microgeneration, people will generate their own power and can sell it back to the grid enabling everyone to also be their own energy supplier.

Electrification of transportation. The UK Government has recently announced in its UK plan for tackling roadside nitrogen dioxide concentrations³⁹ to end the sale of all new conventional petrol and diesel cars and vans by 2040. This has a large impact on the transport and energy sectors from

³⁶ <https://www.ofgem.gov.uk/publications-and-updates/scottishpower-pay-18m-customer-service-failings>

³⁷ https://www.ofgem.gov.uk/sites/default/files/docs/2014/03/assessment_document_published_1.pdf

³⁸ <https://innovateuk.blog.gov.uk/2018/03/06/predictions-the-future-of-energy/>

³⁹ https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/633270/air-quality-plan-detail.pdf

all aspects. There is an anticipated 34 million Electric Vehicles (EV) on the road requiring 60TWh of electricity per year.

Ofgem report on the implication of the transition to electric vehicles⁴⁰. The impact of EV on the electricity network is not as simple as the substitution of petrol or diesel vehicle for an EV, as our relationship with the mobility is expected to change in the coming generations as detailed in the previous sections. The network for vehicle charging is expected to require enhancement to manage capacity and demand cycles, whether these are private owned and charged at home with the majority using an overnight slow charge or on-street rapid charging solutions. An increase in mobility-as-a-service will require rapid charging around the city and regions if these vehicles are not to be stranded. Meanwhile, commercial use, whether this is car, van or a truck will need locations across the network where rapid charging of large numbers of vehicles are possible.

This EV demand is anticipated to impact the distribution network the greatest, via the overall increased capacity of high demand consumption at a local level and the impact of the control logic used to determine the best place and price to charge the EV. The latter point will need integration of the capability and capacity of the electricity network with the new services delivered for electricity provision and charging to ensure unintended consequences of power demand spikes do not occur.

2.4. Energy required capabilities for CDBB

The capability requirements for the UK relevant for CDBB agenda and mandate are summarised in Table 5. This considers the major trends for the energy sector, in the time horizon to 2040-2050.

⁴⁰ <https://www.ofgem.gov.uk/ofgem-publications/136142>

Table 5 – Energy sector capabilities required for CDBB

Theme	National Requirement	CDBB Capability Required
Changes in demand	<ul style="list-style-type: none"> • Long term reduction in overall demand driven by efficiency, with short term increase driven by growth. • Greater contribution of renewable energy. • Methods for improving the relationship and consideration of energy. 	<ul style="list-style-type: none"> • Integrated system modelling at varying levels of geographical focus and with focus on service outcomes. • Methods to trigger behavioural change.
Decarbonisation	<ul style="list-style-type: none"> • Reduced reliance on fossil fuels and transition to renewables. • Electrification of vehicles, heat and processes. • Long term reduction in overall demand driven by efficiency and behavioural change. 	<ul style="list-style-type: none"> • Integrated system modelling at varying levels of geographical focus and with a focus on service outcomes. Socioeconomic evaluation of infrastructure impact and capability. • Methods to trigger behavioural change.
Decentralisation	<ul style="list-style-type: none"> • Higher levels of generation closer to the point of use. • Balancing supply and demand at national and local levels. • Greater insight and access to demand data. • Control of demand. • New business models to decouple infrastructure and service provision. • Integrated system modelling at varying levels of geographical focus and with focus on service outcomes. • Inclusion of perceptive, subjective and objective criteria into system model. • Understand the impact of system disturbances. 	<ul style="list-style-type: none"> • Integrated system modelling at varying levels of geographical focus and with focus on service outcomes. • Inclusion of perceptive, subjective and objective criteria into system model. • Methods to increase surety and resilience in complex systems. • Measurement, control and nudging of demand at different levels of abstraction. • Greater insight and access to demand data.
Digitisation	<ul style="list-style-type: none"> • Greater insight and access to demand data. • Greater insight and access to supply data. • Digital skills and capability. • Digital access, especially for the vulnerable or excluded. • Availability and access to required data sources. 	<ul style="list-style-type: none"> • Awareness, training and development in an accessible and consumable form throughout the supply chain and society. • Development of methods to present complex information and manage choice for the digitally emerging or excluded members of society. • Integration of ‘slow’ and ‘fast’ data models.

Theme	National Requirement	CDBB Capability Required
	<ul style="list-style-type: none"> • Definition of integrated data models for asset and service information. • Standards, guidelines and codes of practice for data integration. • Protection of national and personal information. 	<ul style="list-style-type: none"> • Standards, guidelines and codes of practice for data integration. • Data privacy and security. • Understanding the 'give and get' at an individual and consolidated level.
Customer experience	<ul style="list-style-type: none"> • Improved customer experience. • Change of relationship with energy to enabled outcomes. • New business models to decouple infrastructure and service provision such as Energy-as-a-Service. • Greater insight and access to demand data. • Greater insight and access to supply data. 	<ul style="list-style-type: none"> • Integrated system modelling at varying levels of geographical focus and with a focus on service outcomes. • Socioeconomic evaluation of infrastructure impact and capability. • Define service outcomes, capability and capacity, linked to the elements of the infrastructure and service required. • Exploration of new service offering, associated business models, supply chain formation and contractual structures. • Methods to increase surety and resilience in complex systems. • Development of methods to present complex information and manage choice for the digitally emerging or excluded members of society.
Electrification of transport	<ul style="list-style-type: none"> • An extra 60TWh of demand for EV. • Charging infrastructure. • Integration of EV batteries into national and local energy vectors. • New transport services, such as MaaS. 	<ul style="list-style-type: none"> • Infrastructure impacts of change in demand. • Integrated system modelling at varying levels of geographical focus and with a focus on service outcomes. • Socioeconomic evaluation of infrastructure impact and capability. • Define service outcomes, capability and capacity, linked to the elements of the infrastructure and service required.

The capabilities required for CDBB in the previous section are summarised in Table 6. This illustrates there are some dominant capabilities that will support the future national challenges.

Table 6 - Summary of CDBB required capabilities

CDBB Capability	Road Transport							Energy					
	Reduction in air pollution	Decarbonisation	Changes in demand	Mobility-as-a-Service	Connected and Autonomous vehicles	Digitisation	Closer coupling	Changes in demand	Decarbonisation	Decentralisation	Digitisation	Customer experience	Electrification of transport
Integrated system modelling at varying levels of geographical focus and with a focus on service outcomes.	●	●	●	●			●	●	●	●		●	●
Impact on transport and energy network of electrical demand.	●	●											●
Socioeconomic evaluation of infrastructure impact and capability.	●	●	●	●								●	●
Methods to trigger behavioural change.	●	●	●	●				●	●				
Define service outcomes, capability and capacity, linked to the elements of the infrastructure and service required.				●	●							●	●
Inclusion of perceptive, subjective and objective criteria into system model.				●			●		●				
Exploration of new service offering, associated business models, supply chain formation and contractual structures.				●								●	
Methods to increase surety and resilience in complex systems.				●		●			●			●	
<ul style="list-style-type: none"> Development of methods to present complex information and manage choice for the digitally emerging or excluded members of society. 				●								●	
Determination of ongoing asset condition for the suitability of CAV operation.					●								

CDBB Capability	Road Transport						Energy						
	Reduction in air pollution	Decarbonisation	Changes in demand	Mobility-as-a-Service	Connected and Autonomous vehicles	Digitisation	Closer coupling	Changes in demand	Decarbonisation	Decentralisation	Digitisation	Customer experience	Electrification of transport
Use of asset information to optimise CAV operation within existing infrastructure.					●								
Use of assets information to mitigate and respond to incidents on the network, and integrate with CAV vehicle control systems.					●								
Risk, liability and commercial impact for asset information availability, accuracy, integrity, relevance, completeness and timing.					●								
Awareness, training and development in an accessible and consumable form throughout the supply chain and society.						●					●		
Development of methods to present complex information and manage choice to the digitally emerging or excluded members of society.						●					●		
Integration of 'slow' and 'fast' data models.						●					●		
Standards, guidelines and codes of practice for data integration.						●					●		
Data privacy and security.					●	●	●				●		
Understanding the 'give and get' at an individual and consolidated level.											●		
Measurement, control and nudging of demand at different levels of abstraction.										●			
Greater insight and access to demand data.										●			

3. Current Capabilities

This section will review the current capabilities from a broad research perspective and the application within the transport and energy sectors.

3.1. Literature review

3.1.1. Requirements and capability

Taking a global perspective, the United Nations has identified 17 goals for sustainable development. These are the anchor points to which national and local Governments can specify, instruct and validate the economic and societal outcomes. These are illustrated in Figure 6.



Figure 6 - United Nations Sustainable Development Goals

The goals applicable to the research agenda are goal 9 and goal 11, however, we recognise not all aspects of the target descriptor are applicable to the UK or the objectives of CDBB.

Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation.⁴¹

The global indicator framework was developed by the Inter-Agency and Expert Group on SDG Indicators (IAEG-SDGs) and agreed to as a practical starting point at the 47th session of the UN Statistical Commission held in March 2016. The report of the Commission, which included the global indicator framework, was then taken note of by ECOSOC at its 70th session in June 2016. The targets as indicators are summarised in Table 7.

⁴¹ <https://sustainabledevelopment.un.org/sdg9>

Table 7 - Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation

Target	Indicators
Develop a quality, reliable, sustainable and resilient infrastructure, including regional and trans-border infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all.	Proportion of the rural population who live within 2km of an all-season road. Passenger and freight volumes, by mode of transport.
Promote inclusive and sustainable industrialization and, by 2030, significantly raise industry's share of employment and gross domestic product, in line with national circumstances, and double its share in least developed countries.	Manufacturing value added as a proportion of GDP and per capita. Manufacturing employment as a proportion of total employment.
Increase the access of small-scale industrial and other enterprises, in particular in developing countries, to financial services, including affordable credit, and their integration into value chains and markets.	Proportion of small-scale industries in total industry value added. Proportion of small-scale industries with a loan or line of credit.
By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities.	CO ₂ emission per unit of value added.
Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, including, by 2030, encouraging innovation and substantially increasing the number of research and development workers per 1 million people and public and private research and development spending.	Research and development expenditure as a proportion of GDP. Researchers (in full-time equivalent) per million inhabitants.
Facilitate sustainable and resilient infrastructure development in developing countries through enhanced financial, technological and technical support to African countries, least developed countries, landlocked developing countries and small island developing States.	Total official international support (official development assistance plus other official flows) to infrastructure.
Support domestic technology development, research and innovation in developing countries, including by ensuring a conducive policy environment for, inter alia, industrial diversification and value addition to commodities.	Proportion of medium and high-tech industry value added in total value added.

Target	Indicators
Significantly increase access to information and communications technology and strive to provide universal and affordable access to the Internet in least developed countries by 2020.	Proportion of population covered by a mobile network, by technology.
Increase the access of small-scale industrial and other enterprises, in particular in developing countries, to financial services, including affordable credit, and their integration into value chains and markets.	Proportion of small-scale industries in total industry value added. Proportion of small-scale industries with a loan or line of credit.

Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable.⁴²

As with goal 7 above, the global indicator framework was developed by the Inter-Agency and Expert Group on SDG Indicators (IAEG-SDGs) and agreed to, as a practical starting point at the 47th session of the UN Statistical Commission held in March 2016. The report of the Commission, which included the global indicator framework, was then taken note of by ECOSOC at its 70th session in June 2016. The targets and indicators are summarised in Table 8.

Table 8 - Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable

Target	Indicators
By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums.	Proportion of urban population living in slums, informal settlements or inadequate housing.
By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons.	Proportion of population that has convenient access to public transport, by sex, age and persons with disabilities.
By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries.	Ratio of land consumption rate to population growth rate. Proportion of cities with a direct participation structure of civil society in urban planning and management that operate regularly and democratically.
Strengthen efforts to protect and safeguard the world's cultural and natural heritage.	Total expenditure (public and private) per capita spent on the preservation, protection and conservation of all cultural and natural heritage, by type of heritage (cultural, natural, mixed and World Heritage Centre designation), level of government (national, regional and local/municipal), type of expenditure (operating expenditure/investment) and type of

⁴² <https://sustainabledevelopment.un.org/sdg11>

Target	Indicators
	private funding (donations in kind, private non-profit sector and sponsorship).
By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations.	Number of deaths, missing persons and persons affected by disaster per 100,000 people. Direct disaster economic loss in relation to global GDP, including disaster damage to critical infrastructure and disruption of basic services.
By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.	Proportion of urban solid waste regularly collected and with adequate final discharge out of total urban solid waste generated, by cities. Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population weighted).
By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities.	Average share of the built-up area of cities that is open space for public use for all, by sex, age and persons with disabilities. Proportion of persons victim of physical or sexual harassment, by sex, age, disability status and place of occurrence, in the previous 12 months.
Support positive economic, social and environmental links between urban, peri-urban and rural areas by strengthening national and regional development planning.	Proportion of population living in cities that implement urban and regional development plans integrating population projections and resource needs, by size of city.
By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015-2030, holistic disaster risk management at all levels.	Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with the Sendai Framework for Disaster Risk Reduction 2015-2030. Number of countries with national and local disaster risk reduction strategies.
Support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilizing local materials.	Proportion of financial support to the least developed countries that is allocated to the construction and retrofitting of sustainable, resilient and resource-efficient buildings utilizing local materials.

In response to the UN Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable, the ISO project committee 268⁴³ has developed and recently updated a

⁴³ <https://www.iso.org/committee/656906.html>

standard 37102:2018⁴⁴. This standard provides indicators for city services and quality of life and defines and establishes methodologies for a set of indicators to steer and measure the performance of city services and quality of life. This framework is suited for comparing macro socioeconomic factors within a city space at a global level and has been useful to consolidate the proliferation of indices that exploded between 2000 and 2012. During this time just about every major organisation and NGO had developed their own set of indices that purported to be definitive.

An example of this is created by Wu et al⁴⁵ who, along with a global research team, analysed the 38 most acclaimed evaluation systems with the aim of identifying and creating a super-set of indices that would provide the best evaluation of a particular city. This would provide a basis for further analysis on the characteristics of that city that contribute to a rating and set out how these factors could be considered in city planning. This methodology is called City IQ. The research is both broad and deep providing another perspective on the indices selected by the ISO standard 37120, and proving a useful reference to compare cohorts. The City IQ index identifies 220 attributes that are grouped into five categories: environment and construction, Government and public service, economy and industry, level of connectivity (internet), and innovation potential. The approach does suggest that more of something is better than less (or vice versa dependant on the measure), stopping short from describing 'what good looks like', what is the purpose of something or how the interdependencies of attribution can be described.

Gibberd et al⁴⁶ noted a dissociation between the UN and other indicators and the city planning processes. This included the development of Integrated Development Plans (IDPs) and Spatial Development Frameworks (SDFs) that plan infrastructure, such as energy, water, sanitation, road and public transport systems, which determine sustainability performance of a city. Here it is argued that in order to improve sustainability performance of cities, it is important that sustainability indicators and targets are effectively integrated, and inform, city strategy, planning and implementation processes. It proposes a City Capability Framework that strengthens the relationship between sustainability strategy, targets and indicators and city planning and implementation processes. This is shown in Figure 7.

⁴⁴ <https://www.iso.org/obp/ui/#iso:std:iso:37102:dis:ed-1:v1:en>

⁴⁵ <https://doi.org/10.1016/J.ENG.2016.02.009>

⁴⁶ [/doi.org/10.1016/j.proeng.2017.07.084](https://doi.org/10.1016/j.proeng.2017.07.084)

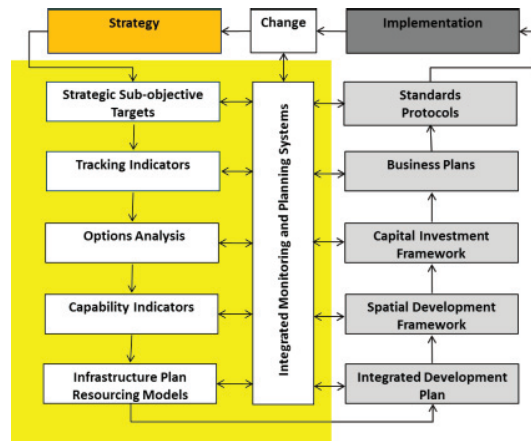


Figure 7 - City Capability Framework

Gibberd noted that whilst the framework provided the relationship between the indicators and the different investment or planning frameworks, it needs developing to identify the decision-making process or logic and the information needed to inform the frameworks.

The approach taken by Gibberd is analogous to a systems engineering approach using the V-Model. The V-Model was recognised in the 1980s within software and system development. Subsequently it has been used extensively across all sectors. The classical V-Model has been developed further to include consideration of modelling and simulation creating a digital twin. The Systems Engineering V-Model is a framework which links the requirement decomposition, with the method of assurance verified through simulation and validated through physical assessment. This provides a 1:1 association between the requirement, the method of testing the requirement is fulfilled, verification the outcome will be achieved before the detail is developed and the asset is built, and finally validation of the outcome in the physical world with a feedback to the model for subsequent simulation.

The Systems Engineering V-Model is a framework is ideally suited to complex systems and assets where traceability of requirements to outcomes are needed, and where the ability to confirm an outcome can be achieved using simulation or modelling is possible. It also provides a structure where different tests can be run through the lifecycle to triangulate results and assess repeatability. When applied to the built environment it provides a framework where the capabilities of a service can be defined, the enabling infrastructure in the fulfilment of the service associated, and the decomposition of the requirements to achieve the infrastructure. Since the framework seeks to link the definition with test and verification, if the relationship can be established, it allows the output and outcome to be tested. If not, it illustrates where there are deficiencies that need addressing or there is a risk the outcome will only be known at a later date and often after considerable investment.

The framework does not have any standards associated to define the requirements or information structure, and therefore relies on this to be defined elsewhere. The design of the assurance methods is key to framework. In some cases, it is not possible to define a measurable test until quite late in the lifecycle, and this prompts the developer to decompose requirements, assess as a sub-set to build confidence and mitigate risk. This is illustrated in Figure 8.

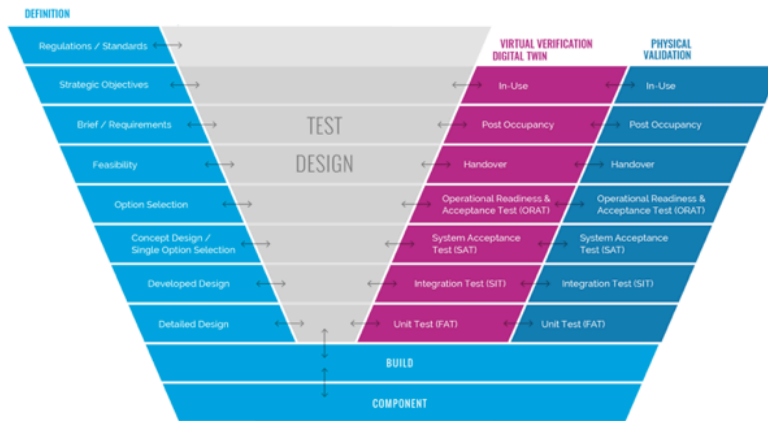


Figure 8 - Systems Engineering V-Model

Amartya Sen⁴⁷, the Nobel Prize winner, developed a capability approach through studies of well-being and quality of life in a multidimensional model focusing on people's freedom. Sen states the approach measures the individual advantage associated with the capability an individual has to decide and the value associated with that process. This is simplified to the profound questions 'what the individual can do or can be'.

Baldascino et al⁴⁸, who use this approach within an urban context, develop this research further. They propose that, rather than using the traditional methods of 'how many ...', suggest describing the wellbeing services offered by a city as a series of capabilities aligned to International Classification of Functioning of Disability and Health (ICF) from the World Health Organisation (WHO)⁴⁹. This, it is argued, would provide better alignment to the outcomes than a traditional count of services. The work by Baldascino has hypothesised a concept and an approach but has yet to publish.

Leach et al⁵⁰ noted that despite the attention sustainability-related urban measurement and assessment methods have received it is still not well understood how accurate (or not) the various methods are; their limitations in holistic city performance assessment; or, how they can be effectively used to better the design of the urban environment, city services and policies. The research focussed on Birmingham, UK, to determine whether the relationships between the different factors could be established and proposed using a forces diagram to represent the impact of the different variables on achieving an outcome. The analysis used 341 indicators selected from a variety of different sources. The work demonstrated that the relationship, and therefore balance, between different outcomes can be established with quantitative and qualitative logic supporting the evaluation. With the observation that visualisation of the results in a form consumable by the recipient is a key aspect that is understood and can be implemented. This is illustrated in Figure 9.

⁴⁷ Sen A. (1999) The development as freedom, Oxford University Press, 1999.

⁴⁸ <https://doi.org/10.1016/j.sbspro.2016.05.306>

⁴⁹ <http://www.who.int/classifications/icf/en/>

⁵⁰ <https://doi.org/10.1016/j.cities.2017.06.016>

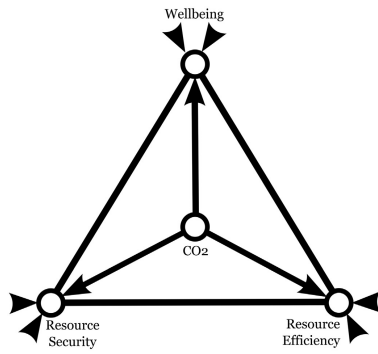


Figure 9 - Forces model developed by Leach

Bolar et al⁵¹ investigated the use of Quality Function Deployment (QFD) and the Hidden Markov Model (HMM) as a method of evaluating customer expectation of infrastructure performance and maintenance efficiency. This is an exciting investigation as it builds on a method used extensively in other sectors ranging from automotive to process engineering to health care. It has not been broadly adopted within civil engineering and infrastructure in particular. It is suggested this is an opportunity that can be easily realised and would help in the establishment of the relationship between perception and features of an infrastructure system or a service offering. The House of Quality, central to the QFD process, is illustrated in Figure 10.

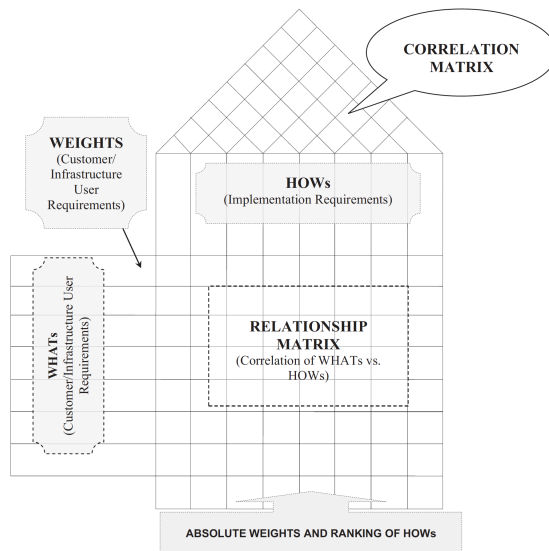


Figure 10 - House of Quality

The introduction of the Markov process enables different states dependant on the outcome or condition to be considered within the analysis. This is particularly useful when an asset lifecycle and degradation of service is to be considered. The approach was tested on highway asset maintenance during its operational lifecycle and assessed the importance of different scenarios on the customer perception of the service quality. This demonstrated the customers objective and subjective needs during the operation of an asset can be associated

⁵¹ <https://doi.org/10.1016/j.ijsbe.2017.02.002>

to discrete interventions which can be translated into design or maintenance or service design requirements.

Capability based planning and assessment of infrastructure is a method used at a national or organisational level for risk management and emergency planning. Lindbom et al⁵² observed that few scientific descriptions of capability exist and when infrastructure capability assessments are undertaken, only a third of all assessments included a description of task and consequence. Lindbom noted that from a review of 25 capability models five trends emerge:

- Capability is equated to resources.
- Resources constitute an important component to capability.
- Capability describes the ability to do something.
- Capability has a capacity.
- Capability is a factor affecting an outcome or goal.

The research used the ACU Framework⁵³ which defines risk, vulnerability and resilience as:

- Risk is the uncertainty about and severity of the consequence of an activity.
- Vulnerability is the uncertainty about severity of the consequences of the activity given the occurrence of the initiating event A; vulnerability = (C, U A).
- Resilience is the uncertainty given the occurrence of any type of initiating event A: resilience = (C, U any A).

This framework is developed further to include the association of capability with an actor or object - for our area of research infrastructure or a service - expanded further to included consideration of what it intended to provide, the task (T), the uncertainty of outcome (Q) and finally, its ability to deal with consequences (C_T). This creates the equation:

$$\text{Capability (definition)} = (C_T, U A, Q, T)$$

This is a useful insight and linkage between the factors that can impact the Capability and the Task (or Service). The descriptions of the elements of Capability provide a useful test to whether all aspects are considered.

3.1.2. Interdependencies

Alsulami et al developed an approach by creating a model of an infrastructure system considering the economic, environmental, technical and social factors. Each element of the network has these factors as characteristics, and all have a dependency and interaction. When the relationship of the nodes is established, the behaviour of each node has an impact on the rest of the system. Alsulami used a fuzzy cognitive mapping technique to establish the impact of the relationships.

French⁵⁴ observed that considerable work has been conducted about the relationships of the major hard infrastructure such as water supply, energy and transportation. They hypothesised that the development of an integration model with the relationships

⁵² <https://doi.org/10.1016/j.res.2014.11.007>

⁵³ https://www.acu.edu.au/policies/governance/risk_management/risk_management_policy

⁵⁴ <https://www.witpress.com/Secure/elibrary/papers/SC14/SC14042FU1.pdf>

established between the systems would be beneficial to address the limited knowledge in this area.

The National Infrastructure Commission⁵⁵ published a report on Digitally Connected Infrastructure System Resilience. Although the report is focussed on resilience, the relationship between different infrastructure systems and their ability to provide a service is believed to be of equal relevance.

The report draws upon work by Perrow⁵⁶ who introduced the concept of system interaction and coupling. An example is shown in Figure 11.

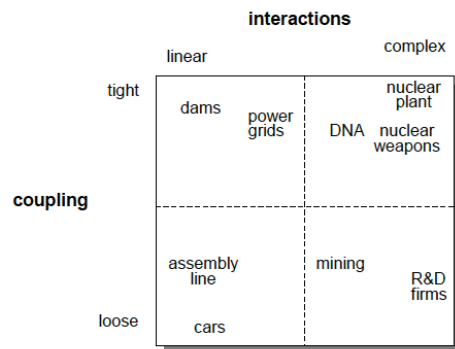


Figure 11 - Concept of system interaction and coupling

It was noted through this analysis that infrastructure systems, particularly digitally connected infrastructure systems, have the properties of high-risk systems (complex interactivity and tight coupling). Therefore, any intervention in an infrastructure system that, intentionally or otherwise, increases the complex interactivity of, or tightens coupling between infrastructure system components and the broader socio-technical system within which infrastructure systems are embedded will increase the likelihood of a 'normal accident'. Furthermore, any intervention that increases human reliance on a specific infrastructure system to enable the outcomes on which individuals, communities, organisations, societies, nations, international bodies, global humanity depend, then that intervention will also increase the likelihood of a 'normal accident'. As we become increasingly dependent on digitally connected infrastructure systems to enable the outcomes we expect infrastructure systems to deliver, or if use of digital connectivity tightens coupling or increase complex interactivity the risk of an incident increases. Perrow argues that the complexity and dynamic nature of interdependencies that unfold during an incident are only comprehensible in retrospective.

The NIC report reviews the concepts and practice behind High Reliability Organisations, especially those who are dependent on infrastructure to perform their service. The genesis of this branch of investigation was in 1987 with the work of Weick and Sutcliffe which has been developed by many in the High Reliability community⁵⁷ including van Stralen. Van

⁵⁵ <https://www.nic.org.uk/wp-content/uploads/CCCC17A21-Project-Literature-Review.pdf>

⁵⁶ *Normal Accidents living with high-risk technologies* (Perrow, 2011)

⁵⁷ High-Reliability.org

Stralen summarised the characteristics of a High Reliability Organisation: believed to be analogous for organisations who rely on infrastructure to provide a service. These include:

1. Prioritisation of both safety and performance are shared goals across the organisation.
2. A culture of reliability (or, better, attitude toward reliability) that simultaneously decentralizes and centralises operations allowing authority decisions to migrate toward lower ranking members.
3. A learning organisation that uses trial-and-error learning to change for the better following accidents, incidents, and, most importantly, near misses.
4. A strategy of redundancy beyond technology but in behaviours such as one person stepping in when a task needs completion.

This work was developed by Hollnagel⁵⁸ who succinctly described the abilities of a resilient built system:

The ability to address the actual . (respond)	Knowing what to do: how to <i>respond</i> to regular and irregular disruptions and disturbances either by implementing a prepared set of responses or by adjusting normal functioning.
The ability to address the critical . (monitor)	Knowing what to look for: how to <i>monitor</i> that which is or can become a threat in the near term. The monitoring must cover both events in the environment and the performance of the system itself.
<i>The ability to address the factual.</i> (learn)	Knowing what has happened: how to <i>learn</i> from experience, in particular how to learn the right lessons from the right experience – successes as well as failures.
The ability to address the potential . (anticipate)	Knowing what to expect: how to <i>anticipate</i> developments, threats, and opportunities further into the future, such as potential changes, disruptions, pressures and their consequences.

To understand these interdependencies, HM Treasury commissioned work to develop a process to Value Infrastructure Spend⁵⁹, building on the work of Rosenberg et al⁶⁰. This developed the Interdependency Planning and Management Framework (IP&MF). This, in turn, used the concept developed by RAEng⁶¹ of interdependency matrices to describe the interaction between the different actors.

The Anytown project lead by the London Resilience Partnership⁶² has developed and executed several multi-day workshops to understand the ripple effect of system

⁵⁸ <http://erikhollnagel.com/ideas/resilience-engineering.html>

⁵⁹ https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/685903/The_Green_Book.pdf

⁶⁰ Rosenberg, G., Carhart, N., 2014. Review of Potential Infrastructure Interdependencies in Support of Proposed Route HS2 Phase 2 Consultation. International Centre for Infrastructure Futures, London. doi:10.14324/20141455383

⁶¹ Royal Academy of Engineering (Great Britain), Engineering the Future (Organization), 2011. Infrastructure, engineering and climate change adaptation: ensuring services in an uncertain future. Royal Academy of Engineering, on behalf of Engineering the Future.

⁶² https://www.london.gov.uk/sites/default/files/london_resilience_partnership_strategy_2016.pdf

dependencies on the major city scale systems. An example of the output is illustrated in Figure 12.

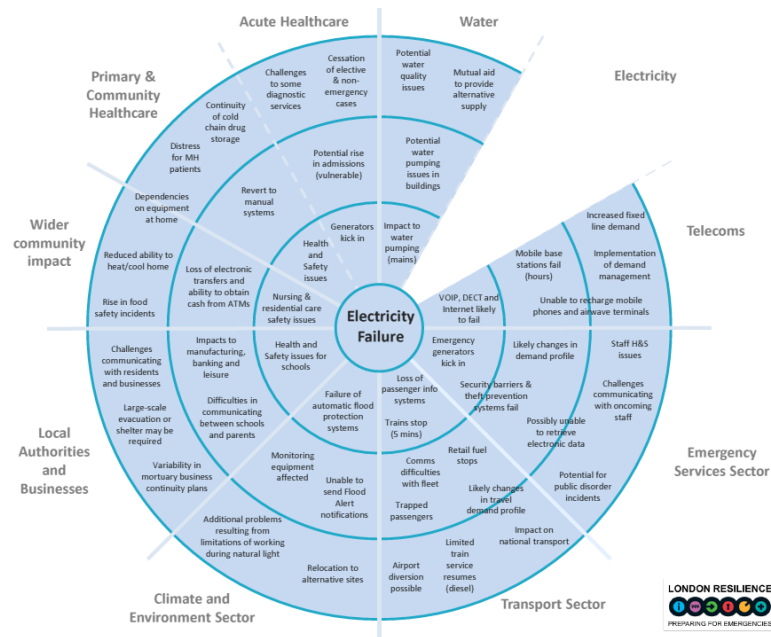


Figure 12 - Example of interdependence from the London Resilience Partnership

Beckford⁶³ has developed a practical approach to showing the relationship between the infrastructure, services and society. He argues that the integration of digital connectivity to the systems enables the information about the need and performance to be traded.

Bloomfield⁶⁴ et al provided an overview of the different models to be considered when modelling the interactions between systems and highlighted the key capabilities considered for development:

- To provide specialised security analysts with a means for the assessment of interactions and interdependencies.
- To provide off-line support for risk assessors, both aggregators of risk and also individual infrastructure owners, in order to evaluate the impact of dependencies and interdependencies.
- To provide off-line support for risk assessors, both aggregators of risk and also individual infrastructure owners, to evaluate the impact of dependencies and interdependencies during incidents (soft real-time).
- To provide real-time, decision support integrated command and control systems (hard real-time) that takes fully into account the impact of dependencies and interdependencies.

In the UK, the Engineering and Physical Sciences Research Council formed a consortium called the Infrastructure Transitions Research Consortium (ITRC)⁶⁶. This is a collaboration of seven universities and over 50 partners from infrastructure policy and practice. ITRC's

⁶³ Beckford Consulting, 2009. An Overview of Systemic Interdependencies of the UK National Infrastructure. Available at: Beckford Consulting <http://beckfordconsulting.com/wp-content/uploads/2008/10/Modernising-National-Infrastructure-Draft-2009.pdf>.

⁶⁴ https://www.adelard.com/assets/files/docs/d422v10_review.pdf

⁶⁵ <https://pdfs.semanticscholar.org/a6ea/1856397e6711c8de01a1c31a97792a4bc819.pdf>

⁶⁶ <https://www.itrc.org.uk>

research provides concepts, models and evidence to inform the analysis, planning and design of national infrastructure (NI). The consortium investigates infrastructure and its interdependencies in energy, digital communications, solid waste, transport, waste water, water supply and infrastructure governance. They have developed the world's first national infrastructure system-of-systems model, NISMOD, which has been used to analyse long-term investment strategies.

The current work programme, Multi-Scale Infrastructure Systems Analytics (MISTRAL), builds on NISMOD to develop an integrated analytics capability to inform infrastructure decision-making across scales, from local to global. Part of this programme is the development of the Data and Analytics Facility for National Infrastructure (DAFNI)⁶⁷ launched in July 2017. This facility is focused on the challenges of:

- Computational limits on the ability to simulate and optimise large complex systems.
- Interpretation of results from complex simulations through visualisation.
- Establishing high quality datasets of infrastructure systems.
- Coupling of models for system-of-systems analysis.

For the transport sector, the MISTRAL programme has developed a new strategic transport assessment model for Britain, modelled as 144 interconnected zones, with transport demand for road and rail being generated in each zone. Usage and average speeds are modelled for travel within and between zones, along with the examination of demand for ports and airports over the next fifty years. The work of the programme is comprehensive and directly relevant to the work of CDBB and this workstream.

Lovric⁶⁸ has used the transport model and the UK road network to illustrate how the pinch points can be established. This work has been expanded to include the interaction of the other systems, such as electricity: a fundamental component of future transport vectors.

Thacker⁶⁹ wrote that re-orientation towards a decentralised arrangement of infrastructure (both in terms of technology and governance) could result in national infrastructure performance increases. The energy sector analysis, for example, revealed that the decentralisation transition strategy resulted in the greatest diversification of energy supply options. Decentralisation also has the potential to capitalise upon interdependencies (e.g. via local waste to energy conversion or combined heat and power plants). However, the evaluation of the cross-sectoral performance of decentralised options indicated that there are significant front-loaded capital investment requirements to enable the transition.

Oughton et al⁷⁰ analysed the economic impact of disruptions to the energy network in the USA. The work showed that the direct economic impact was only 49% of the potential macroeconomic cost. The remainder of the impact is within the supply chain and actors reliant on that service.

A similar programme to MISTRAL is run in the USA by the National Science Foundation⁷¹. This work is being undertaken as part of the National Infrastructure Protection Plan, under

⁶⁷ <https://www.itrc.org.uk/dafni-data-and-analytics-facility-for-national-infrastructure/dafni-launch/>

⁶⁸ <http://isngi.org/wp-content/uploads/2017/10/Milan-Lovric.pdf>

⁶⁹ <https://www.itrc.org.uk/assessing-the-impacts-of-increasing-levels-of-decentralized-energy-in-the-united-kingdom/>

⁷⁰ <https://doi.org/10.1002/2016SW001491>

⁷¹ https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=13545

Executive Order 13010⁷². This work has two lenses: the understanding of the impact of interdependencies on future system-of-systems events, and the socioeconomic value of the interdependencies. The result of this work is not widely reported but supports the National Infrastructure Protection Programme⁷³.

In Switzerland, there is another centre at the ETH Zurich⁷⁴ focussing on future resilient systems. This centre works closely with Nanyang Technological University in Singapore⁷⁵. The research is centred around the common themes of modelling the interdependence, impact of interruption and sociotechnical consequences. The work by the centre is part of the FP7 and Horizon 2020 EU portfolio, with key projects including STREST⁷⁶ and GRRASP⁷⁷ supporting the Disaster Risk Management Knowledge Centre⁷⁸ (DRMKC), launched by the European Commission in 2015.

Other comparable work for reference include the EU project IRRIS (Integrated Risk-Reduction of Information-based, Infrastructure Systems)⁷⁹, Idaho National Laboratory, US Department of Energy⁸⁰ [40], and the National Infrastructure Simulation and Analysis Centre (NISAC) at the US Sandia National Laboratories (SNL) and Los Alamos National Laboratory (LANL)⁸¹.

Lui et al⁸² argue that previous studies on multilayer network robustness model cascading failures via a node-to-node percolation process assumes ‘strong’ interdependence across layers – once a node in any layer fails, its neighbours in other layers fail immediately and completely with all links removed. It is suggested this assumption is not true of real interdependent infrastructures that have emergency procedures or natural hysteresis to buffer against cascades. They considered a node-to-link failure propagation mechanism and establish ‘weak’ interdependence across layers via a tolerance parameter which quantifies the likelihood that a node survives when one of its interdependent neighbours fails.

Cavalcante et al⁸³ continued this theme to understand the development challenges of city scale system-of-systems. They concluded the principle areas are:

- Scale and inherent complexity.
- Multi-disciplines and domains.
- Heterogeneity and interoperability.
- Effect of emergent behaviours.
- Unification on information.
- Data granularity.
- Data analytics.

⁷² <https://fas.org/jrp/offdocs/eo13010.htm>

⁷³ https://www.dhs.gov/xlibrary/assets/nipp_consolidated_snapshot.pdf

⁷⁴ <https://www.ethz.ch/content/specialinterest/dual/frs/en.html>

⁷⁵ <http://www.ntu.edu.sg/Pages/home.aspx>

⁷⁶ <http://www.strest-eu.org>

⁷⁷ <https://ec.europa.eu/jrc/en/grrasp>

⁷⁸ <https://drmkc.jrc.ec.europa.eu>

⁷⁹ [IRRIIS.org](http://www.rris.org)

⁸⁰ <https://www.inl.gov>

⁸¹ <https://www.sandia.gov/nisac-ssl/>

⁸² <https://www.nature.com/articles/s41598-018-20019-7.pdf>

⁸³ <https://doi.org/10.1145/3131151.3131189>

Varga⁸⁴ wrote that as the system-of-systems becomes less diverse and interdependencies increase, we expect to see more frequent occurrence and more prolonged time before recovery after disruption. In essence, a critical slowing down found in natural systems as they approach threshold/transition points, suggesting worsening resilience. Vice versa, with greater diversity and less inter-dependence, we expect to see greater resilience but less overall usage of available capacity: in other words, efficiency might be greater with newer technology, but it may take longer to achieve payback on investment.

Rezgui at Cardiff University has developed an urban analytics platform called CUSP⁸⁵. This platform is built using a systems engineering approach using a combination of BIM data, semantic information and interdependency models. These are integrated with simulations of behaviours and scenarios to create a digital twin of the use case under consideration. The platform has been used for analysing single and multi-vector district services, with the most developed areas being energy and water. Work on the inclusion of subjective and behavioural is underway. This model sits in the current void below the large national scale models such as MISTRAL and above single building and single vector solutions.

The model is developed to TRL 7 and has been used as basis for the investigations by Rezgui⁸⁶⁸⁷, Petri et al⁸⁸ and Howell et al⁸⁹ on integrating building and urban semantics with water solutions. The investigation demonstrated a semantic knowledge management service and domain ontology which support a novel cloud-edge solution. By unifying domestic socio-technical water systems with clean and waste networks at an urban scale it was possible to deliver value-added services for consumers and network operators. This is particularly relevant for demand regulated approaches used in the utilities sector and also applicable for other sectors such as transport.

3.1.3. Service

Harris et al⁹⁰ conducted a comprehensive evaluation of available material to define a service and to cross-check the findings to an US based study by Hartman et al⁹¹. The work concluded the finds of the US based study are consistent and that the literature supported the characterisation framework of a service as:

Intangibility. The literature highlights intangibility as one of the key characteristics of services. Regan⁹² introduced the idea of services being activities, benefits or satisfactions which are offered for sale, or are provided in connection with the sale of goods.

⁸⁴ <http://discovery.ucl.ac.uk/1469381/1/131-135.pdf>

⁸⁵ <https://www.cardiff.ac.uk/bre-trust-centre-sustainable-engineering/research>

⁸⁶ <https://www.brebookshop.com/samples/327975.pdf>

⁸⁷ <https://www.brebookshop.com/samples/327976.pdf>

⁸⁸ <http://dx.doi.org/10.1109/TII.2017.2782338>

⁸⁹ <http://dx.doi.org/10.1016/j.autcon.2017.02.004>

⁹⁰ <https://www.empgens.com/wp-content/uploads/1998/06/4-Characteristics-Services.pdf>

⁹¹ Hartman D.E. and Lindgren J.H. Jr (1993). "Consumer Evaluations of Goods and Services - Implications for Services Marketing", *Journal of Services Marketing*, 7, 2, 4 - 15.

⁹² Regan W.J.. The Service Revolution, *Journal of Marketing*, 47, 57 - 62.

Degree of intangibility has been proposed as a means of distinguishing between products and services (Levitt⁹³). Darby et al⁹⁴ and Zeithaml⁹⁵ highlight the fact that the degree of tangibility has implications for the ease with which consumers can evaluate services and products. Other studies suggest that intangibility cannot be used to distinguish clearly between all products and services. Bowen⁹⁶ and Wycham et al⁹⁷ suggest that the intangible-tangible concept is difficult for people to grasp. Onkvisit et al⁹⁸ state the importance of intangibility is over-emphasised, with the view the service provider's offer is their 'productive capacity' and not the (in)tangible nature of the offer.

Inseparability. This is taken to reflect the simultaneous delivery and consumption of services and is believed to enable consumers to affect or shape the performance and quality of the service. (Regen, Wycham et al and Grönroos⁹⁹.)

Heterogeneity reflects the potential for high variability in service delivery. This is a particular problem for services with a high labour content, as the service performance is delivered by different people and the performance of people can vary from day to day. (Rathmell¹⁰⁰; Carman et al¹⁰¹ and Langeard, Zeithaml.) Onkvisit et al consider heterogeneity to offer the opportunity to provide a degree of flexibility and customisation of the service, whilst Wyckham suggests that heterogeneity can be introduced as a benefit and point of differentiation.

Perishability: The fourth characteristic of services highlighted in the literature is perishability. In general, services cannot be stored and carried forward to a future time period. Onkvisit et al suggest that services are 'time dependent' and 'time important' which make them very perishable. Hartman et al claim that the 'issue of perishability is primarily the concern of the service producer' and that the consumer only becomes aware of the issue when there is insufficient supply and they have to wait for the service.

This is summarised in Table 9.

Table 9 - Service description

Characteristic	Criteria Used in Study
Tangibility	Item is highly tangible (touchable). Item is easy to evaluate prior to purchase.
Inseparability	Item requires high quality customer contact personnel. Item is easily customised to meet the customers' needs.

⁹³ Levitt T. Marketing Intangible Products and Product Intangible, Harvard Business Review, 81, 94 - 102.

⁹⁴ Darby, M.R. and Karni, E. Free competition and the optimal amount of fraud, Journal of Law and Economics, 16, 67-86

⁹⁵ Zeithaml V.A. How Consumer Evaluation Processes Differ between Goods and Services, reprinted in Lovelock, C, Services Marketing, 2nd Edition, Upper Saddle River, New Jersey: Prentice Hall.

⁹⁶ Bowen, J. Development of a Taxonomy of Services to Gain Strategic Marketing Insights, Journal of the Academy of Marketing Science, 18, 1, 43-49

⁹⁷ Wyckham R.G., Fitzroy P.T. and Mandry G.D. Marketing of Services - An Evaluation of the Theory, European Journal of Marketing, 9, 1, 59 - 67.

⁹⁸ Onkvisit S. and Shaw. Is Services Marketing "Really" Different?, Journal of Professional Services Marketing, 7, 2, 3 - 17.

⁹⁹ Grönroos C. A Service Oriented Approach to Marketing of Services", European Journal of Marketing, 12, 8, 588 - 601.

¹⁰⁰ Rathmell J.M. What is Meant by Services?, Journal of Marketing, 30, 32 -36.

¹⁰¹ Carmen J.M. and Langeard E. Growth Strategies of Service Firms, Strategic Management Journal, 1, 7 - 22.

Characteristic	Criteria Used in Study
Heterogeneity	Item has a great deal of variability from purchase to purchase. Item is highly standardised.
Perishability	Item is readily available when needed. There are times when a customer must wait in line to purchase this item.

Previous work for the CDBB¹⁰² highlighted the broken pathways between the definition of a service provided, the outcomes required and the asset. This work proposed the void could be bridged if the capability, capacity and state were described. This has been successfully tested with a number of other clients (under NDA).

Service quality is widely measured using a tool called SERVQUAL¹⁰³. This is a multidimensional research instrument (i.e. questionnaire or measurement scale) designed to measure service quality by capturing respondents' expectations and perceptions along the five dimensions of service quality. This is summarised in Table 10.

Table 10 - SERVQUAL dimensions

Dimension	Definition
Reliability	The ability to perform the promised service dependably and accurately.
Assurance	The knowledge and courtesy of employees and their ability to convey trust and confidence.
Tangibles	The appearance of physical facilities, equipment, personnel and communication materials.
Empathy	The provision of caring, individualised attention to customer.
Responsiveness	The willingness to help customers and to provide prompt service.

The analysis provides an indication in the gaps between the expectation and the received service which can be used to diagnose and optimise the service delivery. This is illustrated in and summarised in Figure 13 and described in Table 11.

¹⁰² <https://www.cdbb.cam.ac.uk/BIMLevels/BIML2c>

¹⁰³ Parasuraman, A., Berry, L.L. and Zeithaml, V.A., "Refinement and Reassessment of the SERVQUAL scale," Journal of Retailing, Vol. 67, no. 4, 1991, pp 57-67

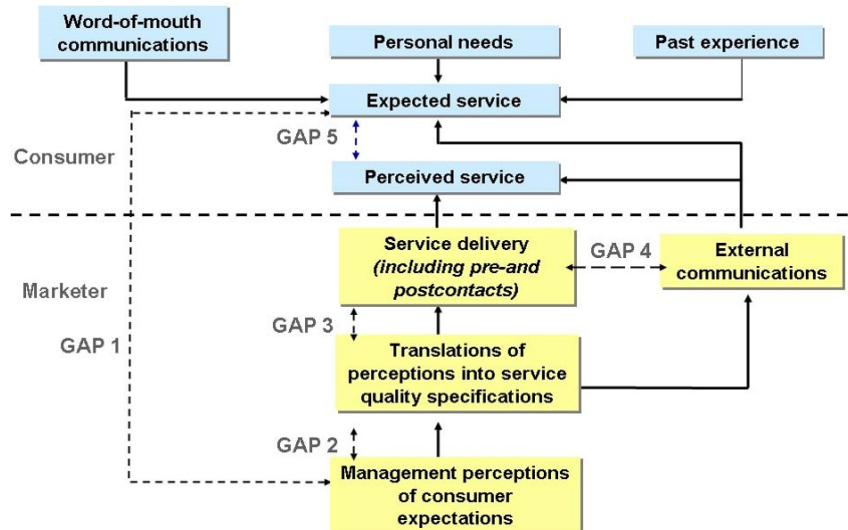


Figure 13 - Illustration of gap analysis

Table 11 - Description of gap analysis

Gap	Brief description	Probable Causes
Gap 1 The Knowledge Gap	Difference between the target market's expected service and management's perceptions of the target market's expected service.	<ul style="list-style-type: none"> • Insufficient marketing research • Inadequate upward communications • Too many layers of management
Gap 2 The Standards Gap	Difference between management's perceptions of customer expectations and the translation into service procedures and specifications.	<ul style="list-style-type: none"> • Lack of management commitment to service quality • Employee perceptions of infeasibility • Inadequate goal setting • Inadequate task standardisation
Gap 3 The Delivery Gap	Difference between service quality specifications and the service actually delivered.	<ul style="list-style-type: none"> • Technical breakdowns or malfunctions • Role conflict/ambiguity • Lack of perceived control • Poor employee-job fit • Poor technology-fit • Poor supervision or training
Gap 4 The Communications Gap	Difference between service delivery intentions and what is communicated to the customer.	<ul style="list-style-type: none"> • Lack of horizontal communications • Poor communication with advertising agency • Inadequate communications between sales and operations • Differences in policies and procedures across branches or divisions of an entity • Propensity to overpromise

Although the SERVQUAL instrument has been widely applied in a variety of industry and cross-cultural contexts, there are many criticisms of the approach. Buttle¹⁰⁴ published one of the most comprehensive criticisms of the model of service quality and the associated SERVQUAL instrument in which both operational and theoretical concerns were identified. In spite of these criticisms, the SERVQUAL instrument, or any one of its variants (i.e. modified forms), dominates current research into service quality¹⁰⁵. In a review of more than 40 articles that made use of SERVQUAL, a team of researchers found that few researchers concern themselves with the validation of the measuring tool¹⁰⁶. SERVQUAL is not only the subject of academic papers, but it is also widely used by industry practitioners¹⁰⁷.

Mansoor et al¹⁰⁸ conducted a study into systems approaches to public service delivery focusing on lessons from health, education, and infrastructure. This concluded there is considerable research in how individual sectors or vectors operate and system-of-systems interdependency and risk; however, there is an absence in detailed research into the relationship between infrastructures.

The Carnegie Mellon University Capability Maturity Model (CMMI)¹⁰⁹ is well established in the software industry. In 2010, the CMMI for Service¹¹⁰ was launched as a process for assessing the maturity of best practice application within the service sector, irrespective of whether the service is provided in finance or rail. The model provides the framework to assess an organisations service function. The case studies and references do not indicate its application for infrastructure dependant services.

3.1.4. Transport

The transport sector is broad and extensive research has been undertaken at a wide range of research institutes and organisations. The landscape is reduced when the relationship between the infrastructure, the service provided, and the underpinning data is considered. This section reviews the landscape within the subset of the transport research.

A report was commissioned by the Transport Systems Catapult to understand the data required to support and drive intelligent mobility¹¹¹. The investigation identified 20 new services that would emerge before 2024, ranging from real-time demand management to autonomous vehicles. The report illustrated how the transport sector is data rich¹¹²¹¹³ and information about journey planning and journey times are now common place with new innovative applications continuing to evolve. The report details how demand and route management, along with information about exceptions, offers opportunity for capacity

¹⁰⁴ Buttle, F., "SERVQUAL: Review, Critique, Research Agenda," European Journal of Marketing, Vol. 30, no. 1, pp. 8-32 1996

¹⁰⁵ Ladhari, R., "A review of twenty years of SERVQUAL research", International Journal of Quality and Service Sciences, Vol. 1 no. 2, pp.172 - 198

¹⁰⁶ Nyeck, S., Morales, M., Ladhari, R., & Pons, F., "10 Years of Service Quality Measurement: Reviewing the use of the SERVQUAL Instrument," Cuadernos de Difusion, Vol. 7, no 13, pp 101-107.

¹⁰⁷ Asubonteng, P., McCleary, K.J. and Swan, J.E., "SERVQUAL revisited: a critical review of service quality", Journal of Services Marketing, Vol. 10, no 6, 1996, pp 62-81

¹⁰⁸ <https://www.bsg.ox.ac.uk/sites/default/files/2018-06/Background%20Paper-Systems%20Approaches%20to%20Public%20Service%20Delivery%2014-15%20May%202018.pdf>

¹⁰⁹ <https://cmiiinstitute.com>

¹¹⁰ <https://cmiiinstitute.com/cmii/svc>

¹¹¹ <https://ts.catapult.org.uk/wp-content/uploads/2016/04/The-Transport-Data-Revolution.pdf>

¹¹² http://www.deloitte.com/view/en_GB/uk/market-insights/deloitte-analytics/bfb570a79416b310VgnVCM1000003256f70aRCRD.htm,

¹¹³ <https://www.gov.uk/government/publications/transparency-and-open-data-progress-against-commitments>,

maximisation. This is particularly relevant for service providers who rely on the network performance such as logistics companies, public transport operators and providers of innovative car clubs like ZipCar¹¹⁴ or DriveNow¹¹⁵ along with organisations charged with the maintenance of free-flowing traffic such as Highways England, Transport for Scotland, the local authorities and their term maintenance contractors and system operators.

A briefing to Parliament¹¹⁶ reflected many of the earlier observations, whilst drawing attention to the importance of understanding the asset condition or state, as well as its actual or predicted loading for capacity management.

Whilst roads and road vehicles are well instrumented and are the major user of the network, they are not the only ones. Active travel is a key element to a healthy transport plan, promoting both physical and mental wellbeing. Yet it is a transport vector with little sensing to understand the demand, patterns of behaviour and requirements. The Urban Big Data Centre¹¹⁷ reported on the use of crowd sourcing using Apps such as Strava to successfully inform the research and provide quantitative data.

This theme continues with the London Assembly future transport strategy¹¹⁸ as part of the healthy street and data sharing initiatives. The healthy streets theme aims to create an environment where active travel is a mode of choice by improving the air quality and guiding the consumer of the public realm to areas conducive with this mode of transport. This is informed, along with other modes, by the data available from the sensor around the transport network.

In the report Future Highways by Arup, they refer to the inevitable need to consider the highway network as part of an integrated multi-mode system. The report addresses the need for data to be a core of this enablement and a key element of adoption will depend on the quality of the information created to inform the decision-making process of the system operators throughout the lifecycle of travellers who benefit from the service. Similar themes emerge from similar reports on other transport modes such as rail¹¹⁹ or bus¹²⁰.

The universities and research centres working in the specific area of the interface between the infrastructure and transportation include:

The Centre for Transport Studies (CTS) at Imperial College¹²¹ is looking at a range of applicable themes which include the travel demand, supply of public transport, integrated urban transport modelling, transport economics and large-scale transport data.

The Centre for Transport Studies (CTS) at University College London has the Accessibility Research Group, looking at how people navigate transport, and the Pedestrian Accessibility Movement Environment Laboratory which brings together clinicians, clinical and medical researchers, geriatricians, neurologists, neuroscientists, psychology, architecture, biology,

¹¹⁴ <https://www.zipcar.co.uk/>

¹¹⁵ <https://www.drive-now.com>

¹¹⁶ POSTnote 472 July 2014 Big and Open Data in Transport

¹¹⁷ <https://www.ubdc.ac.uk/news-media/2017/september/using-social-media-app-and-sensor-data-to-inform-transport-planning/>

¹¹⁸ https://www.london.gov.uk/sites/default/files/future_transport_report_-_final.pdf

¹¹⁹ <https://www.driversofchange.com/projects/future-of-rail-2050/>

¹²⁰ <https://www.driversofchange.com/projects/rethinking-urban-mobility/>

¹²¹ <http://www.imperial.ac.uk/transport-studies/>

ophthalmology and orthopaedics to explore issues in a real environment. Both of these programmes will inform how an individual will interact with a service provision.

Transport resides in the energy initiative at the University of Cambridge¹²² and is investigating at the intersection between energy and transport. This includes the development and deployment of smart networks for urban transport monitoring systems, and modelling transport in cities to investigate the system-wide impact of technological interventions such as electric and fuel cell vehicles.

Research at the University of Oxford is at the intersection of the relationship and impact of transport, society and the built environment. The work focuses on the relationships between the multiple dimensions of people's every day coordination activities and the complexity of moving into, and through, urban space.

The Institute for Transport Studies (ITS), at the University of Leeds have a number of applicable research areas which include choice modelling¹²³. This seeks to understand and model why particular choices are made ranging from long-term choices like residential location, to medium-term choices like car ownership, and short-term choices such as mode, route and even lane choice while driving on a motorway, along with understanding the policy and governance around investment decisions for infrastructure¹²⁴.

The Transport Operations Research Group (TORG), at the University of Newcastle have researched across the domain with a particular interest in road user charging, use of smart cards, traveller information systems and traveller safety and security.

The Transportation Research Group (TRG), at the University of Southampton¹²⁵ are researching transport as a socio-economic system and the impact on the outcomes of this system.

The Transport Systems Catapult¹²⁶, now incorporated with the Future Cities Catapult, are active in the area and have the potential to draw together the transport, infrastructure and social aspects.

3.1.5. Energy

Within the energy sector the research suggests the greatest transformational intersection between the service and the infrastructure is Demand Side Regulation (DSR). DSR is a change in the power consumption of a customer to better match the demand for power with the supply. Operators have traditionally matched demand and supply by throttling the production rate by taking generating units on or off line, or importing power from other suppliers. There are limits to what can be achieved on the supply side, because some generating units can take a long time to come online, may be expensive to operate, and demand can at times be greater than the capacity of all the available supply sources put together. Demand response seeks to

¹²² <https://www.energy.cam.ac.uk/directory/research-themes/demand/transport>

¹²³ <https://environment.leeds.ac.uk/transport-choice-modelling>

¹²⁴ <https://environment.leeds.ac.uk/transport-social-political-sciences>

¹²⁵ https://www.southampton.ac.uk/engineering/research/groups/transportation_group.page#group_overview

¹²⁶ <https://www.ts.catapult.org.uk>

adjust the demand for power instead of adjusting the supply. This approach will become more challenging as the percentage of renewable (availability time skewed) sources increases.

Demand side management is the ability of customers to have a greater role in load shifting their demand for electricity during peak periods and reducing electricity use overall. Load shifting or Demand Response (DR) allows transfer of customer loads to off peak periods of supply whilst energy efficiency and conservation encourage users to use less energy (through active monitoring) and through choosing more energy efficient appliances.

However, it is not just consumers that have a role to play. Large industrial and commercial customers, medium and small enterprises, and aggregators are part of a solution landscape increasingly providing on-site generation and storage and by reducing demand.

The Figure 14 from the Ofgem report - 'Creating the right environment for demand-side response: next steps'¹²⁷ - identifies a number of areas within the disaggregated supply chain that can be positively impacted by DSR.

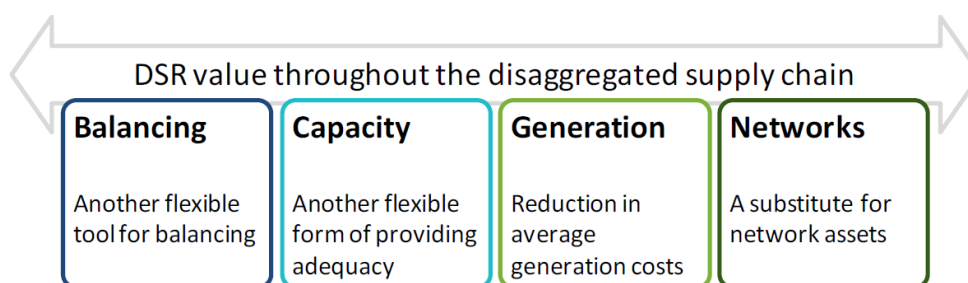


Figure 14 - DSR value throughout supply chain

- The McKinsey report¹²⁸ - 'The Smart Grid and the promise of Demand Side Management' - identifies the following as key levers to an effective DSR:
- Tariffs: the ability to offer attractive tariffs which drive behaviour. For example, Time of Use (TOU), Critical Peak Pricing (CPP), or Real Time Pricing (RTP).
- Incentives: to encourage participation in demand side programs.
- Access to information: to inform energy use decision-making, real time and historical usage data.
- Automation systems: to directly control loads such as air conditioning during critical periods of peak demand or directly control energy storage and release.
- Education and marketing: making the case for DSM.
- Customer insight and verification: the ability to close the loop when operating DSR.

A key part of enabling effective DSR will also be the development and evolution of the Smart Grid. Ofgem's Smart Grid Vision and Route Map¹²⁹ highlights increasing digitalisation of the network with ever greater use of smart technology in building and home automation and, just as importantly, in monitoring both the grid edge, transmission, distribution, storage and generation elements.

¹²⁷ Ofgem 2013 - Creating the right environment for demand-side response: next steps

¹²⁸ McKinsey 2010 - Smart grid and the promise of demand side management

¹²⁹ Ofgem 2014 - Smart grid vision and route map

A further key element to enabling DSR is the effective and near real time exchange of large volumes of data. The report by the THEMA group – ‘Data Exchange in Electric Power Systems: European State of Play and Perspectives’¹³⁰ – identifies that by far the most common approach to data exchange between TSOs and DNOs in Europe is currently decentralised. It seems likely that closer integration of both TSO’s and DSO’s data will be needed through the use of Data Exchange Platforms (DEPs). Furthermore, this data will be needed to be securely shared with third party service providers such as aggregators and energy service companies.

The universities and research centres working in the specific area of the interface between the infrastructure and transportation include:

Energy Research at the University of Cambridge, researching energy demand reduction in the urban environment by integrating new technologies for energy efficient cities, with links to economic, policy and regulatory considerations¹³¹.

The University of Nottingham Energy Systems¹³² group explore the use of mathematical modelling to predict how different energy technologies will work together in a complete system. The research also explores how people interact within their environment and how human behaviour patterns impact on energy use.

The University of Manchester has a number of groups of interest. The Manchester Urban Institute¹³³ is working with a diverse network who are impacted by energy policy and service deployment on energy use and sustainable behaviour, particularly around networked and autonomous solutions. The Smart Distribution Networks Research Group is researching the distributed energy systems and its interaction with other vectors such as transportation¹³⁴.

The University of Leeds¹³⁵ have a series of applicable research programmes on the intersection of the low carbon transportation sector through electrification of the system. This provides a body of work that may be built upon for this study.

The University of Reading¹³⁶ has developed Agents in the Grid. This is an approach that responds to the distributed generation (DG), energy storage and responsive demand, with a focus on the low voltage network having the potential to benefit distribution network operators in improving network security and reliability and potentially to positively impacting network users. This is relevant to work of the Demand¹³⁷ project seeking to influence demand requirements that combines Lancaster, Leeds, Reading and EDF.

The University College London¹³⁸ also has a broad energy system capability. The research areas of interest include the socioeconomic perspective on energy as an enabler and the MaasLab. The Maas Lab¹³⁹ has developed from this core research to develop research groups

¹³⁰ [Thema Consulting Group 2107 – Data exchange in electric power systems: European state of play perspectives](#)

¹³¹ <https://www.energy.cam.ac.uk/directory/research-themes/demand/buildings>

¹³² <https://www.nottingham.ac.uk/research/groups/etri/themes/energysystems/index.aspx>

¹³³ <http://www.energy.manchester.ac.uk/research/cities/>

¹³⁴ <http://www.energy.manchester.ac.uk/research/energy-networks/>

¹³⁵ https://www.leeds.ac.uk/info/130564/energy/590/transport_energy_systems

¹³⁶ <https://www.reading.ac.uk/energy/ene-energy-demand.aspx>

¹³⁷ <http://www.demand.ac.uk>

¹³⁸ <https://www.ucl.ac.uk/bartlett/energy/research/themes/transport/maaslab>

¹³⁹ <https://www.maaslab.org>

across the different departments to understand the future impact of Mobility as a Service, including the impact on the energy sector and service provision.

The University of Salford Applied Buildings and Energy Research Group¹⁴⁰ is focusing on the reduction of energy consumption. This work provides an insight into the influence of human behaviours and the impact on adoption of building improvements and the influence on end use energy demand.

The UK Energy Research Centre¹⁴¹, funded by UKRI, is the focal point for UK energy research and the gateway with international communities. They have a number of focal themes with 1) future energy system pathways and 4) energy, economy and societal preferences being of most interest.

The Energy Systems Catapult¹⁴² has a diverse research and application portfolio. Areas of interest include the whole system modelling, impact on EV on the network, the use of vehicles as a node in the energy system and leading the Energy Data Task Force. This Task Force¹⁴³ sits alongside the other Government data initiatives and will complement the work of the CDBB. The Task Force is charged with improving data flows to optimise the operation of the energy system; improving the handling of real-time data and forecasting capabilities, to efficiently integrate solutions such as demand response, electric vehicles and storage; and improving data visibility and better access to data for both existing and new players in the system, to increase competition in existing markets and enable the creation of new markets and addressing barriers, where parties holding data for commercial purposes prevent market opportunities for other participants.

¹⁴⁰ <https://www.salford.ac.uk/research/uprise/research-groups/applied-buildings-and-energy>

¹⁴¹ <http://www.ukerc.ac.uk>

¹⁴² <https://es.catapult.org.uk>

¹⁴³ <https://es.catapult.org.uk/news/energy-minister-announces-energy-data-taskforce-led-by-catapult/>

3.2. Research Landscape

The literature review and research assessment highlights a number of key themes, as follows:

Outcomes

- There is considerable focus on metrics from a global to local perspective to describe an outcome. These are well developed and cover many perspectives. The definition of the UN SDG provides a global reference that can be used to align the activities at a large scale. At a local level, having an established relationship and comparison at this scale can provide insight into relative performance but more importantly identify where lessons may be learned.
- There are many frameworks in existence, each with a slightly different perspective but essentially providing the same message. It is suggested that rather than develop further derivations of essentially the same thing, refinement of the existing work and focus on the insight developed from the analysis would be of greater value.
- There is an implicit suggestion that more of something is better than less (or vice versa depending on the measure) and the interdependency is not considered.
- The relationship between the outcome and the individual is not always clear leaving reader questioning 'why is it better to have?'

Linking performance with requirements

- Defining the question is often the most challenging task. A surprisingly small number of researchers have taken the outcomes and decomposed these using a variety of methods to determine what is needed to achieve the outcome at varying degrees of abstraction.
- The methods used all seek to close the loop between the input and the outcome which can be verified through modelling or validated by assessment.
- Work in the built environment tends to be addressing output rather than outcome.
- There is little research into methods to derive and describe outcomes.

Interdependency between systems and system-of-systems

- There is considerable work at a national level and within research institutions to understand the interdependency between systems and systems-of-systems.
- The research connected to infrastructure is predominately regarding the key hard asset network resilience and large-scale socioeconomic impact. The scale of the research is predominately for a country or large city. This work is underpinned by a number of national centres in most developed countries.
- There are fewer examples of borough, small city, town or campus assessment of the impact of infrastructure, the services they support and the societal impact.
- The concept of tight and loose coupling of systems and impact on resilience is well documented.

Service definition

- The idea of a service as an abstract concept is well documented, as are the components that contribute to a service and how to determine the quality of service.
- Methods for service design applied in a variety of different sectors is documented. The use of objectives and subjective feedback in the processes control is understood.

- The link between service delivery and infrastructure is not well researched.

Service maturity

- Frameworks are established based on proven methods to describe service maturity. The application case studies for the built environment tend to focus on the information technology elements rather than the service itself.

Standards

- There is recognition of the importance of standards and there are many standards, guidelines and codes of practice in existence relevant for the scope of CDBB. There is some work that frames the importance of service definition and describing the elements that will contribute to the service fulfilment.
- Apart from the work by CDBB, there is still a deficit in both understanding and the standardisation of how a service is described and related to the built environment.

Data

- The importance and value of data in all aspects of life is well described. The concept of measurement and feedback within infrastructure and service is gaining increasing attention, whilst the combination of service AND infrastructure is yet to emerge.
- The use of data to develop new service models is of particular interest and the two sectoral focus of transport and energy are both seeing an explosion of interest in recent years. The use of data to define requirements and understand the behaviour of the infrastructure is increasing in prominence. There is an emerging recognition that an understanding of state can assist in the management of both the infrastructure and service.

The research identified is illustrated in Figure 15. This illustrates the research landscape for the aforementioned categories and shows that while there is considerable activity in this area, there are some white spots emerging that will require further research. A mapping of the research gaps against the CDBB required capability and industry drivers is shown in Table 12. This illustrates the key areas to consider for further research as follows:

- Derivation and description of the outcome of a service.
- The relationship between service(s) and the underlying infrastructure.
- Describing the interdependency and behaviours between different services at a discreet level of abstraction such as a borough, small city, town or campus.
- Inclusion of perceptive, subjective and objective criteria into the system model.
- New services and associated business models.
- Methods to increase surety and resilience in complex systems.
- Defining value and not quantity.
- Integration of 'slow' and 'fast' data models.
- Standards, guidelines and codes of practice for data integration.

The review identified other areas that would benefit from further analysis, as follows:

- Methods to trigger behavioural change.
- Development of methods to present complex information and manage choice for the digitally emerging or excluded members of society.

- Risk, liability and commercial impact for asset information availability, accuracy, integrity, completeness and timing.
- Awareness, training and development in an accessible and consumable form throughout the supply chain and society.
- Measurement, control and nudging of demand at different levels of abstraction.
- Understanding the 'give and get' at an individual and consolidated level.

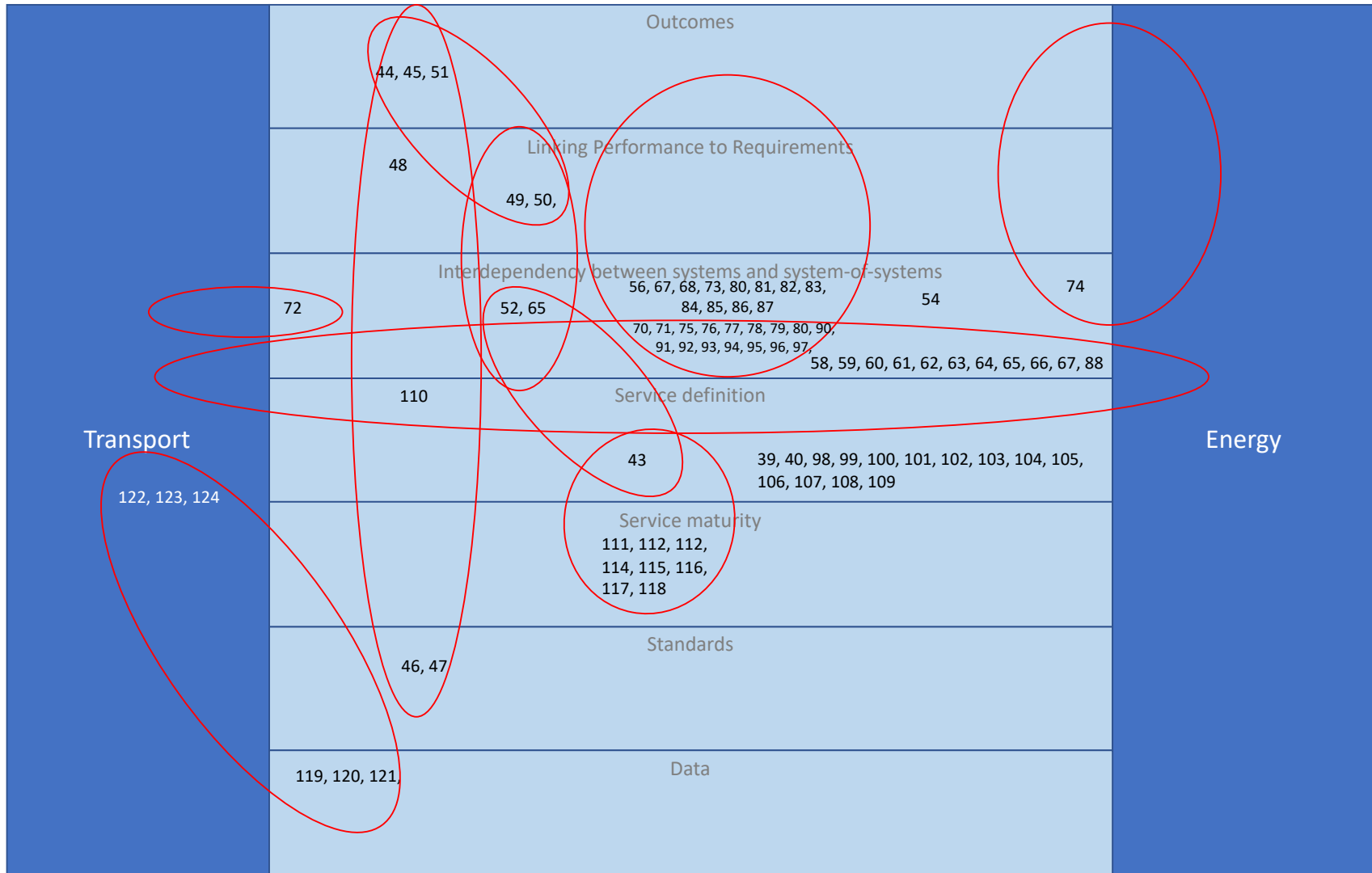


Figure 15 – Services research landscape

Table 12 - Comparison of research gaps to CDBB required capability and industry drivers

CDBB Required Capability	Literature Review – research gaps	Road Transport						Energy						
		Air pollution	Decarbonisation	Changes in demand	Mobility-as-a-Service	Autonomous vehicles	Digitisation	Closer coupling	Changes in demand	Decarbonisation	Decentralisation	Digitisation	Customer experience	Electric vehicles
Integrated system modelling at varying levels of geographical focus and with focus on service outcomes.	■	●	●	●	●			●	●	●	●		●	●
Impact on transport and energy network of electrical demand.		●	●											●
Socioeconomic evaluation of infrastructure impact and capability.	■	●	●	●	●								●	●
Methods to trigger behavioural change.	□	●	●	●	●				●	●				
Define service outcomes, capability and capacity, linked to the elements of the infrastructure and service required.	■				●	●							●	●
Inclusion of perceptive, subjective and objective criteria into system model.	■				●			●			●			
Exploration of new service offering, associated business models, supply chain formation and contractual structures.	■ (5)				●								●	
Methods to increase surety and resilience in complex systems.	■				●		●				●		●	
Development of methods to present complex information and manage choice for the digitally emerging or excluded members of society.	□				●		●				●		●	
Determination of ongoing asset condition for the suitability of CAV operation.						●								
Use of asset information to optimise CAV operation within existing infrastructure.						●								
Use of assets information to mitigate and respond to incidents on the network, and integrate with CAV vehicle control.						●								
Risk, liability and commercial impact for asset information availability, accuracy, integrity, completeness and timing.	□ (5)					●								
Awareness, training and development in an accessible and consumable form throughout the supply chain and society.	□ (5)						●					●		
Integration of ‘slow’ and ‘fast’ data models.	■						●					●		
Standards, guidelines and codes of practice for data integration.	■						●					●		
Data privacy and security.						●	●	●				●		
Understanding the ‘give and get’ at an individual and consolidated level.	□											●		
Measurement, control and nudging of demand at different levels of abstraction.	□										●			
Greater insight and access to demand data.											●			

3.3. Domain review

Nearly 80%¹⁴⁴ of the whole UK economy is service based, of which over 50% is reliant on the built environment for the delivery of the services. This section takes a thin slice through the actors involved in surface transportation and energy to gain insight to their current relationship with the built environment.

A series of stakeholder interviews were conducted across the surface transport and energy sectors, and at different levels within the respective supply chains. The interviews were conducted under the Chatham House Rule¹⁴⁵ for expediency and in order to get an honest opinion, avoiding approvals required from Government or other organisations. The participants included in the market engagement included:

- Regulators.
- Government: National.
- Government: Local.
- Infrastructure creators.
- Infrastructure maintainers.
- System Operators.
- Service Providers.

The interviews were semi-structured and guided, but not constrained, to understand the purpose, vision, mission and strategies of the different organisations, and to gain an insight to the following questions:

- How are services defined?
- What data is used to inform the outcome, how is that defined and how is it captured?
- How is the infrastructure considered in the development and operation of the service?
- Are there any standards, guidelines or codes of practice used?
- Are there any internal or external programmes ongoing to inform this process?
- Are there any other services or factors that have a material impact on your ability to achieve the desired outcome?
- How are externalities considered, captured, relationships with other parties etc?
- What would good look like, what actions are needed and what are the barriers preventing this?
- What are you seeing in the market or wider afield that you believe will change the manner in which the service is described or provided?

The stakeholder engagement has sought to gain insight from a cross section of the supply chain concerned with energy and surface transport. However, it is a finite sample of the market and a finite sample of individuals in the organisations. Therefore, it is likely there will be exceptions and other views and capabilities expressed. We have endeavoured to select the target organisations as representative of the market and interviewees within the

¹⁴⁴ <https://www.ons.gov.uk/economy/economicoutputandproductivity/output/articles/fivefactsabouttheukservicesector/2016>

¹⁴⁵ <https://www.chathamhouse.org/chatham-house-rule>

organisations who have positions that would require knowledge in this regard. We also cross-checked market knowledge during the interview to validate insight and opinions.

The interviews provided a rich insight into how services are defined and how the underlying infrastructure is considered. This section draws out the key themes from the stakeholder interviews across the sectors and throughout the value chain.

3.3.1. There is a distinctive separation between the service provision to customers and the service provided to the assets.

Within an organisation all departments contribute towards the goals of service provision to the user, but the requirements for servicing customers versus internal users and assets is not specifically linked throughout. The premise that the 'customer is king' is understood, but how their needs are met and the role of the underlying infrastructure in the fulfilment of these objectives is not broadly understood nor is it communicated within the organisation. There are groups, such as the strategic planners, who need to create these connections and balance supply and demand. This activity does centre around funding periods or investment cycles, rather than being an intrinsic element of the operational consideration.

The benefit of linking the information at these different levels is not clear or not established to those it should assist in the organisations. At a macro level, in energy, the demand and capacity data are closely coupled, as the lights go out if there is a deficit. In surface transport congestion occurs, which is an accepted norm. Whereas the nuanced optimisation of demand and supply based on individual needs is not considered as the information required to achieve this and the controls needed to intervene are not available.

The concept of a real-time digital twin was suggested by many, perhaps without an understanding of exactly what it meant, whilst acknowledging it would be expensive to produce and then maintain, and the value not proven.

The day-to-day operation and maintenance of assets is conducted at a localised level and the information needed for operatives to carry out their work seldom use a comprehensive set of data. The activities are governed by maintenance schedules and actions as a consequence of network events such as accidents or cable damage.

The challenges to a digitally enabled end-to-end description of the service are many. These are not identified by all stakeholders, but represent their combined view:

- The relationship between the asset characteristics and the service provided is not uniformly understood.
- The relationship between the service provided and the socioeconomic impact is defined at a macro level but not at a level 'where it matters to me', and not always used in KPI measures.
- The investment case to create the models and maintain with 'real time data' is not proven.
- There are a number of unknowns regarding security and safety.
- Internal skills as data users are still developing.

- The shift in culture towards acceptance of these tools is not yet established.
- A number of interviewees made note of the concept of digital twin and their desire to better understand what this could afford them, both at strategic and tactical operational levels.

The greatest focus when asked about adding value to the service, focused on understanding users better and identifying latent demand as well as potential modal or vector shifts.

The concept of capability is intellectually understood by some, strategic planners and operational directors in particular, but the manner in which the service provided is very tactical and the factors that impact this capability is not considered.

3.3.2. Customer centricity and demand insight

‘The service design and delivery has always been very tech driven rather than needs driven, but the real challenge is in being able to understand and then model these needs in a reliable way.’

Transport and energy operators are reliant on demand data to determine supply profiles. This is real-time demand regulation and load balancing by an energy provider or speed regulation on a smart motorway, along with the macro level demand and supply required for long term strategic planning.

The public service providers have a duty to the taxpayer, and an expectation to cater for citizens’ basic needs. However, even the private organisations, whose responsibility is to shareholders, understand and believe that greater shareholder value will only be achieved through an improvement in customer understanding and quality of service provision.

The capacity and availability of service does not follow the micro level of demand. Instead it caters for the greatest peaks and troughs to ensure a reliable and trusted service. Small efficiencies in running one less train at the weekends, for example, is not economically viable and it is not worth the loss of reputation as a result of disappointing customers who expect this service, even if it would create efficiency gains.

The potential for on-demand services becomes real when the demand volume is not very large or event driven. For example, trains cater for millions of customers every day and therefore the train service has to run reliably and consistently whereas road surface services, such as demand driven minibuses, can more easily add value by on demand-driven operation.

Describing capabilities should be a holistic process that starts from a deep understanding of current and future demand needs, addressing the asset levers required and looking at the interdependency of the levers at a system scale. Once the ‘ask’ is understood and described, the requirements of a service provided, the activities to deliver it and the infrastructure needed to do so can be described and optimised. Importantly, information and data allow a more accurate and faster assessment of trade-offs to balance the quality of the service with its economic and financial case.

3.3.3.Data Users

The value of data is increasingly understood and demonstrated within organisations, if not fully integrated and embedded. There are competing priorities between different data users in the supply chain and in some cases, within the same organisation. For example, consider the users at either end of the planning cycle: strategic planning and operations.

User preference and demand trends is key for:

- Policy making.
- Service planning.
- Demand latency identification.

Asset performance and operational data is key for:

- Ensuring capacity and availability of service.
- Understanding asset performance and asset availability.
- Operational resource management.

There is a large overlap in the underlying data and information needed to serve each data user. It is the view of the data that differs both in terms of the time slice and the fidelity required. The interviews demonstrated that these different uses do not integrate by default resulting in data being procured or captured multiple times, data not being managed as an asset and the value inherent within it being lost.

As the use and value of data is emerging, challenges are naturally encountered. The common themes reported are:

- Data is not considered as an asset that has a lifecycle and needs maintaining.
- The required data is not well understood.
- Data requirements are not well defined.
- The lack of data literacy results in errors in the procurement of data, the management of data and the use of data.
- There is a distrust of data quality which drives individuals to re-procure or recapture.

It was reported that the key data sets used in the planning of infrastructure and services in transport and energy are broadly similar:

- Economic, environmental and social indicators.
- Projected population growth and demographics.
- Demand data, quantity and timing.
- User behaviour and patterns.
- Current infrastructure.
- Future planned infrastructure.
- Large scheme city developments.
- Performance and operational data is also fed back to the planning team to inform the models used.

These are complemented by more detailed data specific to each data user, especially at the operational and service end of the business. Even though there was an

understandable reluctance to share specifics of the data used, dialogue disclosed the core data sets are very similar. It is the time horizon and fidelity that differs.

We found the widest description of data sets being used or requested by local authorities. This is due to the overall agenda of the LA, rather than just linking to transport and energy they also include environmental services, health and education. However, it has been noted that the local authorities recognise they are early in their data maturity and skills development. Broadly speaking, there is significant work needed to promote and embed an information driven culture, increasing information literacy and what this can bring to the local authority. This is not the case everywhere. There are a number of cities in the UK that are leading the way globally in regard to smart city solutions. Cambridge, Oxford, Bristol and Milton Keynes, amongst others, are making considerable progress across most fronts of data literacy, culture and advocacy, technical readiness, funding models and procurement practices.

There is an acknowledgement of the importance of standards, but the detailed understanding of what is available, where it applies, and the benefit was quite limited. There was a concern that standards could be a time and cost burden, especially when accreditation was necessary.

It is also worth reflecting on where the industry is on the journey to be asset managers and the value seen within organisations of this approach. PAS55, the precursor to ISO55000 was released in 2004 with the ISO following some ten years later. Considering the longevity of many assets, this shift to valuing and managing assets is in its early stages. The interviews suggested that the use of information to inform this and service management will need a similar ten to twenty year push for its inclusion within the fabric of normal business.

3.3.4. Financial viability and business case

The interviews have highlighted there are often gaps and overlaps between the overall strategic (master) planning process and the individual business cases developed for discrete investment. This is more pronounced when the benefits and interventions are across traditional boundaries with organisations (Government or private sector) and across traditional views of market segmentation. This was reported to cause a challenge to develop funding propositions and to allocate risk/reward to the appropriate parties.

Introducing new solutions with new cost and revenue structures requires various supply chain actors to adapt or modify the way they operate. The interviews concurred with the research that new models tested through the supply chain are needed. From a highly cost driven public organisational perspective, investing or procuring 'different' services are considered to be of higher risk, largely created by uncertainty from limited, unknown or poorly documented exemplar. It was reported that as the financial pressure on Government and business continues to grow, the lower risk solution is often given disproportional merit as some benefit is better than potential negative press. There was a clearly articulated need to understand what has worked where in detail and how to manage the transition.

Value is recognised to have a financial and non-financial component. Determination and measurement of service value was a common theme expressed. Business cases are

developed on a regular basis where the value calculation is not as robust as desired, and the methods deployed to appraise benefit are wanting. Whilst the concept of the value relationship between asset and service is recognised, the detail that underpins the relationship was not well understood or modelled. Where it was in place, the establishment of causality is of varying degrees of quality. When there are interdependent relationships between the service provided or the assets used, the complexity of the challenge was considered almost insurmountable for many and the efforts involved questioned. Local Authorities in particular noted an interest in case studies where these relationships and benefits have been established, as this would help with the creation of future business cases.

Within the infrastructure asset management industry, collecting and analysing data from the built environment has become a core capability. However, the wider feedback is that often *'we don't know how to quantify this value'*, whether this is from within an organisation or in a combination of actors across the supply chain.

When value is created by sharing and integrating data with other actors within the supply chain this causes other issues in terms of ownership and rights to use. This is borne from a combination of the decades of outsourcing many activities without the creation of a strong and intelligent client, and a lack of consideration of the value of information. Both result in data and information as an afterthought which causes downstream commercial tensions when requested. It should also be noted that often the anticipated monetary value of the information is overstated, preventing transaction and use case development. This hinders the use cases being proven, thus testing the latent value, which establishes benchmarks and promotes market activity.

This highlighted the challenge of understanding the whole value chain and establishing the relationship between the creator, user and beneficiary, and how new models to enable these new relationships can be created.

3.3.5. Mobilising problem owners

There is an increasing realisation of the value of data throughout the client and supply chain. In order to unlock this value, the need to co-operate is also recognised. The move by forward-thinking organisations to regain ownership of their data, particularly Government agencies, companies or local authorities, is helping to provide some structure to the market and, with the right leadership, enabling mobilisation around specific issues and challenges.

The city stakeholders all cited the convening function they had conducted to build an ecosystem would have enduring impact, rather than *'just another smart city pilot that withers as soon as the European funding is stopped'*. These ecosystems generally pivoted around the council, university and a range of innovative businesses. Under NDAs, examples were given that illustrate sustainable financial viability has been proven, each one being focussed on real-world challenges that would make a demonstrable impact on the local citizen. This focus on real-world challenges, avoiding the smart city hype and building alliances of practitioners, was one of the most impactful reasons given for success.

Infrastructure providers noted an effective decoupling of the outcomes of a scheme by the time works are instructed. There was an overriding cost and time focus when

considering the capital works rather than a broader perspective. This dissociation throughout the client organisation and throughout the supply chain was cited as often leading to poor decision making that will impact the whole life cost and the value created through effective outcomes.

3.3.6. Supply chain

There are a broad range of supply chain and commercial models deployed with varying degrees of coupling between the asset and the service with the interviewed stakeholders. The stakeholders all cited the need to have a 'controlling mind', or sponsor, who understood how the value in the service would be created, how the different actors in the service would be rewarded or penalised, and the information about the service required to demonstrate performance and enrich the asset attributes. When pressed to give examples of this working in practice, unfortunately there was an absence of examples where the end-to-end value chain was informed by data. There were impressive examples within the value chain, but not the end-to-end.

The manner in which contracts were let was cited as a key reason for the broken information value chains. This was due to a combination of traditional contract boundaries being used due to perceived risk mitigation and the absence of substantive or meaningful information requirements. When pressed, the feedback received indicated a capability gap to procure information and link aspects of a value chain through effective contracting.

The themes about the supply chain that surfaced through the engagement, include:

- Central controlling mind: a client organisation with clear vision and strategic overview of all services.
- Clearly identified and described capabilities: both the existing asset and service capability, as well as the future ones. Understanding the current capacity and availability of assets is needed to plan future infrastructure and balance the increasing demand.
- Co-operation and collaboration with supply chain operators: looking into the future, information exchange and data insight is a key value-adding element. The ownership, access, usage and maintenance must be defined within the contractual structures and a culture of information-led planning promoted.
- Early involvement of operators at planning stage: a perspective shared by those in the operation delivery roles. Bearing in mind that the day to day expertise, and also knowledge, of the challenges and obstacles to delivery lies with these stakeholders, encouraging earlier involvement could lead to a higher predisposition to sharing risk and therefore allow for greater investment in new innovative solutions.
- Understanding the data users throughout the lifecycle of the service: a key aspect of better planning, capital delivery and service provision is to think about not only the stakeholders involved in the operation of a service and assets but specifically identify the data created and needed at each stage of the cycle.
- Contractual forms: creation and use of contracts that are aligned to shared vision and outcomes, informed by information.

3.3.7.Asset security

There was a reassuringly good general appreciation of the security implication of asset and services. The closer the stakeholder was to the asset, the higher the appreciation of the security implications and mindedness needed. The stakeholders focussed on service provision generally had an appreciation but were more concerned about personal safety.

The implications of an increased reliance on data and information was not well understood by those in more tactical roles. Those in strategic or senior management roles had a good understanding of the risks but did not uniformly demonstrate translation into security plans. As information is being used to inform more services, the breadth and depth of security mindedness will need to be increased.

The increase in individuals with access to key information will also need careful consideration. It was noted that there needs to be methods established to ensure the appropriate individuals had access to information, that there was automation to reduce the need for access, and that there was resilience to provide continuity of service in the event of an incident.

3.3.8.Research and development

All stakeholders viewed their collaborations with academia as the key to moving forward. The symbiotic nature of the relationship was suggested but probably not fully appreciated. Applied and industrial research, where early proof of concepts, pilot or demonstrators are delivered, is key to the successful implementation of new solutions in the future. This allows testing of the technology in place, understanding the user reaction to the new service and the overall viability of the solution. A large number of stakeholders discussed demonstrator fatigue and expressed concern that a proof-of-principle or concept is often not enough to mobilise the market and instigate lasting change. It was suggested that structure method of support is needed to 'hand hold' organisations and local authorities as they enter uncertain waters to ensure the benefits are realised.

The highly competitive commercial nature of services contacts continues to be a barrier to collaboration. The assets constructed, and the services provided, yield low percentage profit (whilst providing modest absolute values), leaving little headroom for experimentation. It was suggested a review of what is commercially sensitive and what could be shared would be useful to advance the different sectors in a safe collaborative industry forum.

3.3.9.Digital maturity

Despite the advances made with data and information literacy, and the adoption of BIM for Government projects starting to percolate through to the private sector, there is still an overall deficit in information capability across many organisations. This manifests in many ways: from understanding how to procure data as a strategic asset, to analysis of the available datasets, to digitally enabled service design to streamline customer experience.

For local authorities this challenge is amplified when those most in need of assistance or at risk of exclusion are considered. It is recognised that as digitisation of many services increase the need to invest in outreach and inclusion programmes, it is essential to avoid marginalisation or increase individual risk. A number of interviewees cited this aspect is

often ignored or is an afterthought, whereas it should be a precursor to any new digital service implementation.

3.3.10. Summary

The key messages emerging from the stakeholder engagement are:

- Establishment and demonstration of causal relationship between an asset and a service is at a level below macro-strategic.
- There is a distinctive separation between the service provision to customers and the service provided to the assets.
- There is not a mature understanding of how to describe the outcome or capability of a service.
- The business case for new methods of working needs to be established.
- Value is an overused but seldom understood term.
- Technology for technologies sake often realised in proof-of-principle has created a scepticism that needs rebalancing.
- The benefit of digital as a concept is understood, the translation to realising the benefit throughout the value chain requires support.
- Despite the advances made with data and information literacy, and the adoption of BIM for Government projects which is starting to percolate through to the private sector, there is still an overall deficit in information capability across organisations.
- The need to ensure digital inclusion should be properly considered within the overall digital strategy for any implementation.

The key messages have been interpreted and overlaid to the CDBB required capability matrix in Table 13. This shows a picture building where there are national requirements, and where there are gaps in research and domain capability. This is explored further in the next section.

Table 13 - Domain capability gaps

CDBB Required Capability	Domain Review - Gaps	Literature Review – research gaps	Road Transport							Energy					
			Air pollution	Decarbonisation	Changes in demand	Mobility-as-a-Service	Autonomous vehicles	Digitisation	Closer coupling	Changes in demand	Decarbonisation	Decentralisation	Digitisation	Customer experience	Electric vehicles
Integrated system modelling at varying levels of geographical focus and with focus on service outcomes.	◆	■	●	●	●	●			●	●	●	●		●	●
Impact on transport and energy network of electrical demand.			●	●											●
Socioeconomic evaluation of infrastructure impact and capability.	◆	■	●	●	●	●								●	●
Methods to trigger behavioural change.	◆	□	●	●	●	●				●	●				
Define service outcomes, capability and capacity, linked to the elements of the infrastructure and service required.	◆	■				●	●							●	●
Inclusion of perceptive, subjective and objective criteria into system model.		■				●		●			●				
Exploration of new service offering, associated business models, supply chain formation and contractual structures.	◆	■ (5)				●								●	
Methods to increase surety and resilience in complex systems.		■				●		●			●			●	
Development of methods to present complex information and manage choice for the digitally emerging or excluded members of society.	◆	□				●		●				●	●		
Determination of ongoing asset condition for the suitability of CAV operation.							●								
Use of asset information to optimise CAV operation within existing infrastructure.							●								
Use of assets information to mitigate and respond to incidents on the network, and integrate with CAV vehicle control.							●								
Risk, liability and commercial impact for asset information availability, accuracy, integrity, completeness and timing.	◆	□ (5)					●								
Awareness, training and development in an accessible and consumable form throughout the supply chain and society.	◆	□ (5)						●				●			
Integration of 'slow' and 'fast' data models.		■						●				●			
Standards, guidelines and codes of practice for data integration.		■						●				●			
Data privacy and security.							●	●	●				●		
Understanding the 'give and get' at an individual and consolidated level.	◆	□										●			
Measurement, control and nudging of demand at different levels of abstraction.	◆	□										●			
Greater insight and access to demand data.												●			

4. Gap analysis and capability development

This section will analyse the different perspectives on the research landscape to derive the needs for future research and capability development by the Centre for Digital Built Britain. This considers the required capability needs of UK Plc, the state-of-the-art research and stakeholder interviews.

This report has developed the findings throughout by the completion of Table 11, Table 12 and Table 13 and summarised further in Table 14.

Table 14 - Summary of required capability, national themes, available research and domain requirements.

CDBB required capabilities	Domain Review - Gaps	Literature Review – research gaps	Number of themes	
			Road Transport	Energy
Integrated system modelling at varying levels of geographical focus and with focus on service outcomes.	◆	■	5	5
Impact on transport and energy network of electrical demand.			2	1
Socioeconomic evaluation of infrastructure impact and capability.	◆	■	4	2
Methods to trigger behavioural change.	◆	□	4	2
Define service outcomes, capability and capacity, linked to the elements of the infrastructure and service required.	◆	■	2	2
Inclusion of perceptive, subjective and objective criteria into system model.		■	2	1
Exploration of new service offering, associated business models, supply chain formation and contractual structures.	◆	■ (5)	1	1
Methods to increase surety and resilience in complex systems.		■	2	2
Development of methods to present complex information and manage choice for the digitally emerging or excluded members of society.	◆	□	1	
Determination of ongoing asset condition for the suitability of CAV operation.			1	
Use of asset information to optimise CAV operation within existing infrastructure.			1	
Use of assets information to mitigate and respond to incidents on the network, and integrate with CAV vehicle control.			1	
Risk, liability and commercial impact for asset information availability, accuracy, integrity, completeness and timing.	◆	□ (5)	1	1
Awareness, training and development in an accessible and consumable form throughout the supply chain and society.	◆	□ (5)	1	1
Integration of 'slow' and 'fast' data models.		■	1	1
Standards, guidelines and codes of practice for data integration.		■	1	1
Data privacy and security.			3	1
Understanding the 'give and get' at an individual and consolidated level.	◆	□		1
Measurement, control and nudging of demand at different levels of abstraction.	◆	□		1
Greater insight and access to demand data.				1

1 = Number of common themes between CDBB required capability & sectoral challenge
 ■ = Research gaps
 □ = Areas not explicitly analysed, but of suggested interest
 (-) = Other potential workstreams of interest
 ◆ = Domain gaps

Table 14 illustrates of the 20 initial capabilities there are ten dominant capability areas common across both surface transport and energy, which have limited published or accessible research and require market improvement. These are as follows:

- Integrated system modelling at varying levels of geographical focus and with focus on service outcomes.
- Socioeconomic evaluation of infrastructure impact and capability.
- Methods to trigger behavioural change.
- Define service outcomes, capability and capacity, linked to the elements of the infrastructure and service required.
- Exploration of new service offering, associated business models, supply chain formation and contractual structures.
- Development of methods to present complex information and manage choice for the digitally emerging or excluded members of society.
- Risk, liability and commercial impact for asset information availability, accuracy, integrity, completeness and timing.
- Awareness, training and development in an accessible and consumable form throughout the supply chain and society.
- Understanding the 'give and get' at an individual and consolidated level.
- Measurement, control and nudging of demand at different levels of abstraction.

As the research has continued the capabilities identified have been informed by each stage undertaken. This next section will group and refine the capabilities further as the various dominant themes are consolidated and refined into four required principal capability statements.

These are set out below and detailed in the following pages:

- The value of the technical, social, economic and environmental causal relationships between service outcomes and the underlying infrastructure are defined.
- Service outcomes and underlying infrastructure can be measured and controlled with incentives to modify individual patterns of behaviour and preferences that result in improved personal and socioeconomic outcomes.
- Value creation through new commercial relationships and business models for asset intensive services are established.
- Organisations are able to provide digitally enabled services in an accessible form to enable all individuals to benefit from new services. All individuals have access, are able and are digital equipped to benefit from the new services.

The value of the technical, social, economic and environmental causal relationships between service outcomes and the underlying infrastructure is defined.

This combines the following:

- Integrated system modelling at varying levels of geographical focus and with focus on service outcomes.
- Socioeconomic and environmental evaluation of infrastructure impact and capability.
- Define service outcomes, capability and capacity, linked to the elements of the infrastructure and service required.

This capability is the core to all other capabilities developed. If the relationship and impact of the services and infrastructure are not established at a demonstrable and irrefutable casual level, it will not be possible to develop any of the other capabilities. Having established these relationships, it will be possible unlock a multitude of opportunities for new services, and gain greater insight into strategic planning and improved outcomes. It will also highlight risks and vulnerabilities in the system(s) that will need addressing before the relationships are shared and measures that need to be implemented to afford appropriate national protection.

It is expected this capability will need careful attention to define and test the causality of the relationship. This is expected to be a particular challenge when the complex non-linear multi-variable interrelationship between different assets, systems or services are considered. Nevertheless, the statistical analysis of the source material is expected to yield levels of confidence that can be used as a basis for trial to build experience and consolidate knowledge.

The definition of asset and service capability is another key element of this CDBB capability, as this will crystallise what the asset or service should be able to provide. Having established this, it can be tested and refined as the understanding and experience develops.

Many of the infrastructure models are focussed at a national level and serve a vital role. For this capability to have impact, it will be necessary to have different geographical perspectives and abstraction nationally, linked with localised level of modelling, including the service provided.

The key elements within the capability description are:

- There is a causal link established between the service and infrastructure at varying degrees of geographical abstraction.
- The service and infrastructure cannot be viewed in isolation, it needs to be considered as part of a broader system of systems at degree of fidelity that is 'significant'.
- The concept of capability is introduced, describing what the asset or service seeks to achieve, and this is married to capacity that describes how much capability is available.
- How value is defined, assigned and considered by different actors.
- The technical relationship refers to the mechanics of converging the different elements of the solution.
- The social, economic and environment relationship refers to the triple bottom line¹⁴⁶ impact and benefit.
- The security implications of establishing relationships and creating dependencies.

¹⁴⁶ <https://www.economist.com/news/2009/11/17/triple-bottom-line>

Service outcomes and underlying infrastructure can be measured and controlled with incentives to modify individual patterns of behaviour and preferences that result in improved personal and socioeconomic outcomes

This combines the following:

- Methods to trigger behavioural change.
- Measurement, control and nudging of demand at different levels of abstraction.

Having established the relationship between the outcomes, services and assets, the next capability to be developed is the inclusion of the relationship between the individual, their behaviour and preference within the ecosystem. An understanding of this and the measures necessary to shift behaviour will enable the aspired personal and socioeconomic improvements to be realised.

The ability to encourage individuals to modify their choices and create habitual preferences linked to positive personal and societal outcomes will be key. This is a challenging area to address as it subjective, dependant on a myriad of different factors that affect personal choice and surfaces ethical considerations.

The ethics of choice within complex interrelated systems require understanding. Areas include: who has the right to decide that a particular outcome has a higher value than another? Is a societal outcome more valuable than an economic outcome? Who in society benefits from a behavioural change? Is it ethical and fair to be consciously making a commercial decision that will knowingly impact vulnerable members of society?

To address the complexity around this subject it is expected that a layered model of agreed principles will need to be developed. This would need to begin with a series of core values, most likely linked to the UN sustainable goals, Government strategy and societal principles, or similar. These may include safety, environmental considerations, care for the vulnerable and value for money. These could form the cornerstones from which a consensus could be established. From this core further layers of principles could be developed and devolved from a national to local level. This would also provide a prompt for higher civic engagement.

Having established a methodology for selection and decision making, the service and infrastructure systems will need to be monitored and modulated to ensure supply matches the preferred demand. This will require a degree of system sensing that exceeds the level currently deployed. This may range from measuring the road surface quality and duty cycles to determine the right time to make an intervention, to decoupling the personal control of home heating schedules to provide a level of comfort based on daily patterns of behaviour and activity.

The key elements within the capability description are:

- Understanding the relationship between an individual's behaviour, the service delivered and the infrastructure utilised.
- On what basis can personal choice be influenced.
- The ethical consideration of influencing choice.
- How to value one outcome against another, particularly when it has personal impact.
- The information needed about the services and infrastructure to inform the decision-making process.
- Service supply and demand regulation.
- The level of control to be relinquished to achieve an outcome.

Value creation through new commercial relationship and business models for asset intensive services are established.

This combines the following:

- Exploration of new service offering, associated business models, supply chain formation and contractual structures.
- Understanding the 'give and get' at an individual and consolidated level.
- Risk, liability and commercial impact for asset information availability, accuracy, integrity, completeness and timing.

This capability, like others, builds on the definition of the relationship between the service outcome and the underlying infrastructure. Without this clear line-of-sight between cause and effect, it is unlikely that Government, private organisations, regulators or the general public will adopt.

A clear line-of-sight it will provide the canvas on which new business models can be developed to leverage the insight provided. These are expected to include many of the -as-a-Service propositions such as energy or mobility. Here it is essential to understand the current state and silos that exist, whilst not being constrained to create these new technical and commercial ecosystems enabling a value trade to occur at new boundaries with a corresponding risk/reward exchange. Early examples of multi-vector/mode services include the TfL Oyster card system which provides access to transport via a single payment route, with the operators of the service receiving remuneration through a service provision model.

It is expected for the full benefits of a mobility-as-a-service approach a step change in the reach will be needed. This will require the vectors to be expanded, the infrastructure to have greater prominence and be used as a control factor in the arbitrage, along with other adjacent service providers who may not necessarily be under the direct control of a single party to participate in combination of financial and non-financial transactions.

As the services and infrastructure become closer coupled and dependant, this brings forward the challenge of reliance. The responsibility and liability for information along with the actions required to ensure its integrity will need careful consideration if transformational business models are to be adopted. Otherwise there will be no trust in the supply chain which will erode the value created and cause the integrated services to breakdown. Data governance and data lifecycle management are anticipated to be an essential element of any commercial structure or business model capability.

This capability is intrinsically linked to Workpackage 5: Making the digitally enabled services and supply chain work, and the observations from this workpackage will be made available.

The key elements within the capability description are:

- The causal relationship between the infrastructure and service must be established.
- The responsibility, accountability, liability, risk, consequence and reward for the provision of the information is to be established.
- The existing commercial ecosystems will change as the manner in which value is exchanged evolves.

Organisations are able to provide digitally enabled services in an accessible form to enable all individuals to benefit from new services. All individuals have access, are able and are digitally equipped to benefit from the new services.

This combines the following:

- Awareness, training and development in an accessible and consumable form throughout the supply chain and society.
- Development of methods to present complex information and manage choice for the digitally emerging or excluded members of society.

For digitally enabled services to be adopted there is a notable capability development to be addressed. At an organisational level, whether this is Government or private sector, the general level of digital maturity is emergent from both the perspective of service design and application. The design of digitally enabled services is a new skill that is being developed across the country and will be core to achieving adoption. Whilst central Government has invested heavily in the Government Digital Services (GDS) activity, the same level of investment has not always been possible away from Whitehall. This can result in services that are difficult to use for the most IT literate people and prove to be a stubborn barrier for others.

How people access services is changing with advancement in technology. Capability development needs to ensure inclusion not gentrification of new services is achieved with the technology and attention is given to those most in need or vulnerable. The capability needs to consider end-to-end service design, the relationship with the technology stack and the infrastructure.

The technology market will need to listen to the needs of the digitally enabled service designers and prospective users and be informed by them. This will include how to provide digitally enabled services to those who are not digitally enabled and would benefit the most.

There will be a large amount of data used and information developed with the new services. The provision of just the information needed to decide, in a contextual and consumable form, will be key to adoption and therefore impact. The determination of relevance to an individual and a context is another area for exploration. Here, preferences will need to be determined with the context of the information provided, at a point in time, at a location, on the basis of other service information and informed by previous choices. This will require simplification to provide just that which is relevant and is key to the decision-making process.

The key elements within the capability description are:

- How to build and building digital capability across society.
- How to build and building digital capability throughout the supply chain.
- Development of end-to-end full stack services.
- How to serve contextual information in a consumable form.
- Development of decision support tools.
- How to provide digitally enabled services to those who are digitally emerging or digitally devoid.

5. Demonstrators

Within the scope of the Centre for Digital Built Britain and this workpackage, this section will describe the current demonstrator capability in the UK, and draw upon international references where applicable or in the absence of UK capability. The current demonstrator capability will be cross-checked to the required capability for the Centre for Digital Built Britain to determine whether there is an alignment. Where an alignment does not exist, a judgement will be made to suggest adjacent capabilities worthy of consideration for further development. Where neither an existing nor an adjacent capability exists, this will highlight a white spot for capability development and will require further action to be taken.

Demonstrators are an invaluable method to develop capability and transition from laboratory to practice. They have been used extensively to manage the transition from research to application to show that a theory can scale, to build confidence and introduce real-world factors. The commonly used method of describing this maturity development is the Technology Readiness Level (TRL). The TRL has been developed to illustrate the purpose and scale of the different types of demonstrators in Figure 16. The demonstrators normally take the form of either projects to illustrate functionality at varying degrees of scale, or test beds with the underlying technical infrastructure.

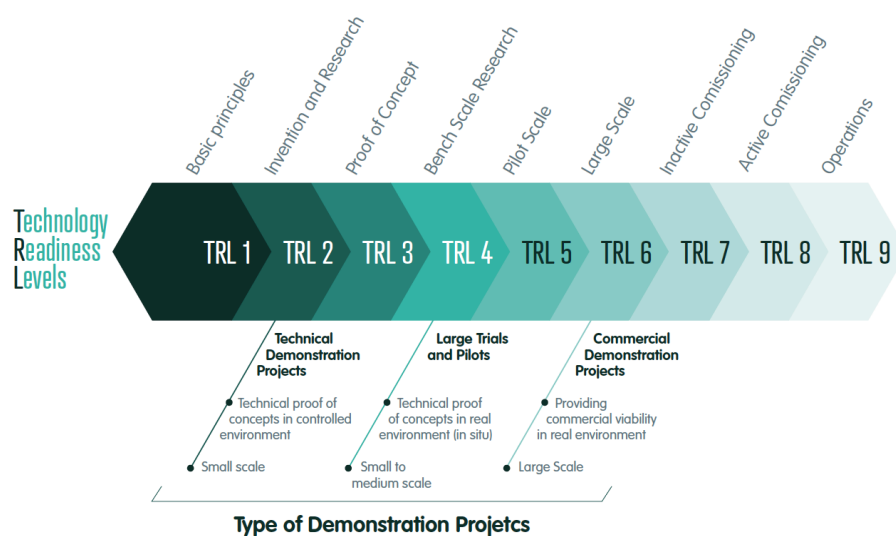


Figure 16 - Technology Readiness Levels and demonstrator types¹⁴⁷

5.1. Summary of demonstrators

The UK has invested heavily in developing its demonstrator capacity across the sectors and the scope of CDBB is no exception. An analysis of the demonstrators created in the past four to five years for new smart city, smart energy, connected and autonomous vehicles, mobility-as-a-service and systems-of-systems is shown in Table 15. This provides a summary of some of the applicable demonstrators, the location, the type of demonstrator and scope of works.

¹⁴⁷ https://futurecities.catapult.org.uk/wp-content/uploads/2018/03/Hyperconnected_smart-city-demonstrators_v3.pdf

Table 15 - Summary of demonstrators

Subject	Project Name	Location	Type	Comments
Smart City	Smart cities and open data reuse (SCORE) ¹⁴⁸	Aberdeen and Bradford	Demonstrator	Aim is to improve public service delivery (PSD) based on smart, data-driven solutions. Target to increase the efficiency and quality of PSD in cities to reduce costs by 10% (€50M savings for partner cities by 2020). Areas of focus are traffic flow and routing, mobility hubs, air quality and drainage. Funded by EU INREG.
Smart City	Future City Glasgow ¹⁴⁹	Glasgow	Demonstrator	Aim to improve public services and citizen engagement based on democratised data for the public good. Considerable component of the spend was to create the city control centre with upgraded CCTV and integration with emergency services. Various apps developed to promote active mobility and citizen engagement. Funded by Innovate UK.
Smart City	Remourban ¹⁵⁰	Nottingham	Demonstrator	Aim is to design and deliver a model to show how sustainability can be integrated into the regeneration of our towns and cities to develop 'Smart Cities'. The REMOURBAN model will take advantage of the crossover between energy, mobility and ICT to develop a new method for developing smart cities. The model aims to improve quality of life for people living in the area, improve environmental sustainability, speed up the amount of time it takes to deploy innovative solutions, develop new business and funding models for city regeneration and ensure that the solution is welcomed by the local community and fit for how people want to live their lives. Funded by EU H2020.
Smart City	Sharing Cities ¹⁵¹	Greenwich	Demonstrator	Aims is to change the way we think about the role of digital technology in our cities and to clarify how we all can benefit from and contribute to this transformation process. With an ambition to be a more agile and more collaborative smart cities market that dramatically increases the speed and scale at which we implement smart solutions across European cities. To engage society in new ways to enable them to play an active role in the transformation of their communities, delivering more vibrant, liveable, economically

¹⁴⁸ <https://northsearegion.eu/score/>

¹⁴⁹ <http://futurecity.glasgow.gov.uk>

¹⁵⁰ <http://nottingham.remourban.eu>

¹⁵¹ <http://www.sharingcities.eu>

Subject	Project Name	Location	Type	Comments
				active, and resource efficient cities. Focus on deployment of smart city solutions (lamp posts, refurb), district heating, bike scheme and increased participation. Funded by EU H2020.
Smart City	Triangulum ¹⁵²	Manchester	Demonstrator	Aim is to understand that cities function as systems, involving a complex interaction between individuals, markets, infrastructure networks and public services. Building on the investments already made, it focuses on the integration of energy, mobility and ICT systems around core infrastructure assets within the 'Oxford Road Corridor Manchester'. These assets supply heat and power to the respective estates and buildings belonging to the Corridor partners. All the new investments around renewable energy generation, supply and demand management will be connected to a new ICT infrastructure called 'Manchester-I'. This platform consists of a number of discrete layers, which creates two new knowledge environments. The first: a network of data and services that bridge the investments set out above in an integrated way to enable greater analysis and better-informed decision making at both a strategic and operational level to improve energy efficiency, reduced carbon emissions and a greater ability to meet demand in a more cost-effective way. The second is the establishment of an open access marketplace from which innovative end-user and business applications can be developed and marketed independently. Funded by EU H2020.
Smart City	City Verve ¹⁵³	Manchester	Demonstrator	It aims to build and deliver a smarter, more connected Manchester, creating a city that uses technology to meet the complex needs of its people. It covers various sectors that include transport and energy. Within transport, the project covers talkative bus stops, city concierge, transport capacity sensing and smart parking. Within energy, areas of note include building management systems and air quality monitoring. Funded by Innovate UK.
Smart City	MK Smart ¹⁵⁴	Milton Keynes	Demonstrator	Concluded in 2017, the project built on the MK data hub to provide innovation opportunities in transport and energy, amongst others. This included the development of

¹⁵² https://www.triangulum-project.eu/?page_id=2291

¹⁵³ <https://cityverve.org.uk>

¹⁵⁴ <http://www.mksmart.org>

Subject	Project Name	Location	Type	Comments
				an app to inform transport route loading, the deployment of EV charging points and the visualisation of energy usage within districts. Funded by HEFCE.
Smart City	SynchroniCity ¹⁵⁵	Manchester	Demonstrator	The aim of SynchroniCity is to open up a global IoT market where cities and businesses develop shared digital services to improve the lives of citizens and grow local economies. The SynchroniCity IoT Large-Scale Pilot for smart cities is built on a simplified, open and agile digital market across borders will help cities and its citizens get better services. It provides access to open data from Porto and Santander for new services to be developed to improve social outcomes. Funded by H2020.
Smart City	Connect Bristol ¹⁵⁶	Bristol	Demonstrator	Connecting Bristol is the city's digital partnership and is co-ordinated by the Bristol City Council with the aim to pilot the potential of the latest smart technologies to ensure that Bristol becomes a resilient, sustainable, prosperous, inclusive and liveable place. The work is delivered in partnership with other public sector agencies, the private sector and the community and their representatives. The work covers all sectors from healthcare to creative arts, from open data to energy. This is the umbrella organisation for Bristol Open Data project and the IES cities project. Funded by a variety of UK and EU sources consolidated by the Council.
Smart City	Future Street Incubator ¹⁵⁷	London	Demonstrator	This demonstrator project is designed to trigger innovation that will lead to long-term improvements across London, addressing congestion, overcrowding, air quality and noise pollution. This includes urban energy generation, dynamic routing, noise absorbing materials and logistic consolidation. Funded by the London Mayor.
Smart City	Cardiff Smart Parking ¹⁵⁸	Cardiff	Demonstrator	This is a collaboration between Smart Parking Limited and Cardiff Council. The council has installed 3,300 sensors in 'paid-for' and disabled parking bays. Cardiff Council is the first Council in Europe to roll out this technology across its city-wide road network. Populated with data collected through the sensors, drivers in Cardiff can download an app, called

¹⁵⁵ <https://synchronicity-iot.eu>

¹⁵⁶ <https://www.connectingbristol.org>

¹⁵⁷ <https://tfl.gov.uk/info-for/media/press-releases/2016/february/tfl-funding-for-street-improvement-trials>

¹⁵⁸ <https://www.cardiff.gov.uk/ENG/resident/Parking-roads-and-travel/parking/On-street-parking/SmartMap/Pages/default.aspx>

Subject	Project Name	Location	Type	Comments
				'Park Cardiff', to search and view a real-time map of parking availability and be directed to an empty space.
Smart City	East Birmingham Growth Corridor ¹⁵⁹	Birmingham	Demonstrator	Working with the Smart City Commission, this demonstrator is exploring how the wider deployment of smart city/future internet-based technologies and services can help drive innovation and accelerate delivery of city outcomes bringing together both needs of public services, community and private sector. The demonstrator will aim to tackle local problems in a more holistic, layered and integrated way. It will drive greater connectedness along urban clusters – connecting assets, data, talent, location, infrastructure to combine innovative design, use of community and social spaces and services with housing and infrastructure developments, and new models of commissioning and service delivery enabled through civic and social enterprise.
Energy	Smart Systems and Heat Demonstrator ¹⁶⁰	Newcastle, Bridgend and Manchester	Demonstrator	The Smart Systems and Heat (SSH) programme is a collaborative project exploring how to accelerate to market innovations that decarbonise domestic heating. It has five elements: 1. Creating a Home Energy Services Gateway, which enables a change in the customer-supplier dialogue from units of energy input to a language of service outcomes. 2. Establishing a test bed with this Gateway in real homes, opened to innovators seeking to become energy services providers that sort out integration to deliver service outcomes. 3. Enabling policy makers to work with these innovators in this test bed to explore new options for areas such as carbon policy, tackling fuel poverty, and protecting consumers. 4. Creating a platform, EnergyPath Networks, to enable a dialogue between local authorities, network operators and energy services providers to plan local infrastructure. 5. Creating a platform, EnergyPath Operations, to help the sector explore new system architectures that put understanding, shaping and delivering customer value. Funded by Innovate UK.

¹⁵⁹ <http://digitalbirmingham.co.uk/project/east-birmingham-smart-city-demonstrator/>

¹⁶⁰ <https://es.catapult.org.uk/projects/smart-systems-and-heat-ssh/>

Subject	Project Name	Location	Type	Comments
Energy	Flexible Urban Networks Low Voltage ¹⁶¹	London and Brighton	Demonstrator	The aim of this project, concluded in 2016, was to monitor candidate LV networks and identify network issues, assess how these networks would conventionally have been reinforced to resolve these issues, identify where power electronics solutions can be used to resolve these issues, and deploy and evaluate power electronics applications on LV networks, compared to conventional reinforcement. Funded by the Ofgem LCNF and UKPN.
Energy	Customer-Led Network Revolution ¹⁶²	North East	Demonstrator	The project was designed to predict future loading patterns as the country moves towards a low carbon future and to research novel network and commercial arrangements and techniques to establish how they can be integrated to accommodate the growth of low carbon technologies in the most efficient manner. The project trialled new network monitoring techniques to measure power flow, voltage and harmonics, trialling alternative smarter solutions that employ active network management and customer engagement to increase network capacity and/or modify load patterns. Finally, it also developed new planning and design decision support tools for engineers. Funded by Ofgem LCNF.
Energy	Keele Smart Energy Network Demonstrator SEND ¹⁶³	Keele	Test Bed	SEND will be the first facility in Europe for at-scale living laboratory research, development and demonstration of new smart energy technologies and services in partnership with business and industry. It has the digitalisation of 24 substations, the installation over 1,500 smart meters, 500 home controllers and a 5 MW renewable integration package. Funded by ERDF, ESIF and BEIS.
Energy	Centrica ¹⁶⁴	Cornwall	Demonstrator	Centrica's Distributed Energy and Power business is building a pioneering local energy market in Cornwall, which over 3 years will test the role of flexible demand, generation and storage via a new virtual marketplace. This will be supported by the installation of new generation and storage technology into over 150 homes and businesses. Funded by ERDF.

¹⁶¹ <http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Flexible-Urban-Networks-Low-Voltage/>

¹⁶² <http://www.networkrevolution.co.uk>

¹⁶³ <https://www.keele.ac.uk/business/newkeeledeal/priorities/smartenergynetworkdemonstratorsend/>

¹⁶⁴ <https://www.centrica.com/innovation/cornwall-local-energy-market>

Subject	Project Name	Location	Type	Comments
Energy	Power Networks Demonstration Centre ¹⁶⁵	Glasgow	Test Bed	Based at the University of Strathclyde, this test bed are real 11kV and LV distribution networks, which are flexible with the ability to vary voltage, frequency and perform disturbance testing in a controlled environment.
Energy	Community Energy Demonstrator at Trent Basin ¹⁶⁶	Nottingham	Demonstrator	Involving solar photo-voltaic panels, this is Europe's largest community energy battery, local thermal energy production, distribution and storage and research expertise, with the aim to generate renewable energy, support local communities, address key research and policy gaps and deliver low carbon grid services to the National Grid. Funded by Innovate UK.
Energy	Science Central Smart Grid Land and Energy Storage Test Bed	Newcastle	Test Bed	Based at the University of Newcastle, this looks at how grid scale storage of energy can be incorporated into city scale energy systems. The test bed is of particular interest in investigating the response time of storage being introduced to the wider network.
Energy	BRE Innovation parks ¹⁶⁷	Watford and Ravenscraig	Test Bed	The innovation parks are being used to demonstrate and test how innovation at scale are performing under simulated and real-use condition.
CCAV	Midlands Future Mobility ¹⁶⁸	Birmingham and Coventry	Test Bed	This recently announced test bed is a network of over 50 miles of roads in Coventry, Warwickshire and Birmingham, and will be optimised to ensure we can gather useful data, measure public interaction, while constantly monitoring the technology in action. Funded by Innovate UK and partners including University of Warwick, TfGM, Amey, AVL, Costain and Mira.
CCAV	CAPRI	London and South Gloucestershire	Demonstrator	This project is for the development of the next generation of PODs, as well as the systems and technologies that will allow the vehicles to navigate safely and seamlessly in both pedestrian and road environments. The project includes four trials, with the first on private land at Filton Airfield near Bristol. The aim of this trial will be to test and validate the performance of the new generation PODs. The second trial will test a public service in a shopping centre car park to assess performance in busy pedestrian areas. The final two

¹⁶⁵ <https://www.pndc.co.uk>

¹⁶⁶ <https://www.trentbasin.co.uk/community-energy/>

¹⁶⁷ <https://bregroup.com/ipark/>

¹⁶⁸ <https://midlandsfuturemobility.co.uk>

Subject	Project Name	Location	Type	Comments
				trials will be at the Queen Elizabeth Olympic Park, a large and diverse estate. The first of these trials will test a public on-demand mobility service in pedestrian areas, with the PODs identifying and navigating the best routes. The final public trial will test the PODs on a network of roads around the park, with the service interacting with traffic control systems. Funded by Innovate UK and CCAV.
CCAV	UK Autodrive ¹⁶⁹	Coventry and Milton Keynes	Demonstrator	Completed in October 2018, this project ran for three years and demonstrated the first CAV trial at the HORIBA MIRA Proving Ground in October 2016. The final, in October 2018, on the streets of Milton Keynes and Coventry, featured the world's first multi-CAV, end-to-end journey–connected car, to driverless car, to autonomous pod.
CCAV	A2M2	London	Test Bed	This is part of the CCAV where the project aims to create a 'Wi-Fi road' connecting vehicles and infrastructure wirelessly to give drivers advanced access to road closures or congestion warnings.
CCAV	DRIVEN ¹⁷⁰	Oxford	Demonstrator	This project will see a fleet of fully autonomous vehicles being deployed in urban areas and on motorways, culminating in an end-to-end journey from London to Oxford. These vehicles will be operating at Level 4 autonomy, meaning they have the capability of performing all safety-critical driving functions and monitoring roadway conditions for an entire trip, with zero-passenger occupancy. Key challenges the consortium will address include: communication and data sharing between connected vehicles, Connected and Autonomous Vehicles insurance modelling, risk profiling, and the new cybersecurity challenges that this amount of data sharing will bring. Funded by Innovate UK.
CCAV	FLOURISH ¹⁷¹	Bristol	Demonstrator	This project seeks to develop products and services that maximise the benefits of Connected and Autonomous vehicles for users and transport authorities. As a user-centred approach, FLOURISH will achieve a better understanding of consumer demands and expectations, including the implications and challenges of an ageing society. FLOURISH will address vulnerabilities in the technology powering CAVs, with a focus on

¹⁶⁹ <http://www.ukautodrive.com>

¹⁷⁰ <http://drivenby.ai>

¹⁷¹ <http://www.flourishmobility.com>

Subject	Project Name	Location	Type	Comments
				the critical areas of cyber security and wireless communications. Funded by Innovate UK and CCAV.
CCAV	Greenwich Automated Transport Environment	Greenwich	Demonstrator	This project, completed in 2017, saw a fleet of driverless pods providing a shuttle service around the Greenwich Peninsula to understand public acceptance of, and attitudes towards, driverless vehicles. It was the first time members of the public were invited to take part in the research trial through riding in or engaging with the pods and sharing their opinions and experiences. Funded by Innovate UK and CCAV.
CCAV	Human Drive ¹⁷²	Cranfield	Demonstrator	This project aims to develop natural human style driving styles using machine learning. This project will develop testing, validation and safety methodologies and better understanding of the implications of CAV within context of the infrastructure.
MaaS	Whim ¹⁷³	Helsinki, West Midlands, Amsterdam, Antwerp	Operation	Through its subscription-based integrated mobility app, Whim, MaaS Global offers users access to a variety of transportation options, from taxis to rental cars, public transport, and bikeshare. The app learns users' preferences and syncs with their calendars to intelligently suggest ways to get to an event.
MaaS	UbiGo ¹⁷⁴	Gothenburg	Demonstrator	Trial in Gothenburg for 200 users. This fully integrated mobility service combines public transportation, carsharing, rental car service, taxi service, and a bicycle system all in one app, all on one invoice, with 24/7 support and bonuses for sustainable choices.
MaaS	Qixxit ¹⁷⁵	Germany	Operation	The Qixxit app plans routes according to user needs. It offers carsharing, ridesharing, and bike sharing options; identifies ideal train connections; and shows all travel possibilities for users to compare and choose from.

¹⁷² <https://humandrive.co.uk>

¹⁷³ <https://whimapp.com>

¹⁷⁴ <http://ubigo.se>

¹⁷⁵ <https://www.qixxit.com/en/>

Subject	Project Name	Location	Type	Comments
MaaS	Moovel ¹⁷⁶	Germany; Boston, Helsinki	Demonstrator	Enables users to search, book, and pay for rides with a single app with book and pay for car2go, mytaxi, and Deutsche Bahn in a single interface. Public transportation mobile payments are available in Stuttgart and Hamburg.
System Model	Rapid Engineering Model ¹⁷⁷	Highways England	Operation	Developed by Highways England, this is a rules based model based on the Highways standard, DRMB, and uses geospatial information to produces the outline design for smart motorways.
System Model	London Resilience Project ¹⁷⁸	London	Operation	The partnership aim is to enable London to be a resilient city. This is achieved by assessing risks to London's resilience, enhance London's resilience through prevention and adaptation, prepare, respond, recover and learn from exercises and emergencies and helping Londoners to be prepared.
System Model	ITRC: NISMOD ¹⁷⁹	Universities of Cambridge, Oxford, Newcastle, Southampton, Leeds, Cardiff and Sussex	In development	NISMOD (National Infrastructure Systems MODel) is the UK's first national infrastructure system-of-systems modelling platform and database. By 2020, the ITRC national infrastructure portal will be open to academia and industry as well as policymakers, providing access to infrastructure datasets, simulation and modelling results. The platform consists of long term performance of interdependent infrastructure systems, risks and vulnerability in national infrastructure systems, regional development and how it adapts to infrastructure provision, Infrastructure networks, demand and performance. Part of ITRC, funded by Innovate UK and EPSRC.
System Model	ITRC: DAFNI ¹⁸⁰	Oxford	In design	DAFNI is the new national research facility for infrastructure systems analysis, modelling, simulation, visualisation and decision support. Part of ITRC, funded by Innovate UK and EPSRC.

¹⁷⁶ <https://www.moovel-group.com/en>

¹⁷⁷ www.highways-uk.com/content/huk/docs/17.1-dynniq-costain.pptx

¹⁷⁷ https://www.london.gov.uk/sites/default/files/london_resilience_partnership_strategy_2016.pdf

¹⁷⁸ <https://www.itrc.org.uk/nismod/>

¹⁷⁹ <https://www.itrc.org.uk/dafni-data-and-analytics-facility-for-national-infrastructure/>

Subject	Project Name	Location	Type	Comments
System Model	CUSP ¹⁸¹	Cardiff University	Demonstrator	This platform is architected using a systems engineering approach with a combination of BIM data, semantic information and interdependency models. These are integrated with simulations of behaviours and scenarios to create a digital twin of the use case under consideration. The platform has been used for analysing single and multi-vector district services, with the most developed areas being energy and water.

¹⁸¹ <https://www.cardiff.ac.uk/bre-trust-centre-sustainable-engineering/research>

5.2. Observations

It can be seen that there is a considerable number of demonstrators within or adjacent to the scope of CDBB and many of them are already associated with the University of Cambridge.

Looking to the smart city demonstrators there is a common thread between most examples: digital, data, improved services and increased citizen participation. There is a recurrence of theme without an increase level of adoption which is an indicator of the absence or realisation of benefit. This supported by the need for funding from the EU or UK Government. The demonstrators which did look to link the infrastructure, service and citizen are listed, as follows:

- Triangulum.
- City Verve.

These did include a significant investment in capital equipment and ICT as a basis from which the new services were developed. The services created and the degree of coupling with the infrastructure will need further detailed analysis.

The energy demonstrators highlighted a number of examples where again major infrastructure investment was required to create the environment from which to develop. The majority of demonstrators looked to tackle very technical challenges specific to the domain with a reduced number focused on the service component and how that impacts the user and infrastructure as follows:

- Smart Systems and Heat Demonstrator.
- Smart Energy Network Demonstrator.
- Community Energy Demonstrator at Trent Basin.

Connected and Autonomous Vehicles is an area attracting considerable interest and investment, whilst having many fundamental questions to answer. The Government's funding of the Centre for Connected and Autonomous Vehicles is a focus of the activity and directing the funding well to address the various challenges, not least the basic control and detection. The demonstrators with focus on the road user and infrastructure are listed. These all address the relationship between the individual, the vehicle and the enabling infrastructure:

- Midlands Future Mobility.
- A2M2.
- Human Drive.

Mobility-as-a-Service was surprisingly well developed and operational. There are a number of organisations who have developed platforms that concentrate the individual transport mode operator's information to provide information, guide choice and sell tickets. There was, however, an absence of demonstrators looking to integrate the transport modes and seek to provide a seamless transition with no evidence of any demonstrators looking to integrate the infrastructure and service elements.

There is a rapidly developing capability for system modelling in the UK which is being supported with the investment needed. This capability will enable the systems and systems-of-systems to be modelled and if integrated, the line-of-sight to be established from national scale to local and the rules that underpin them. These include:

- Rapid Engineering Model.
- CUSP.
- NISMOD/Mistral/DAFNI.

5.3. Capability development

The research has identified four key capabilities for the development by CDBB, and these are mapped against the demonstrator capability in Table 16. This illustrates where the required capability could be developed in partnership with existing organisations, programmes or facilities, and where there are white spots which will require the capability to be developed.

The first required capability that identifies the value of the technical, social, economic and environmental causal relationships between service outcomes and the underlying infrastructure is an emergent theme across all of the sectoral demonstrators. The energy demonstrators are more developed with projects such as the Smart Systems and Heat Demonstrator seeking to establish and demonstrate this capability. With some guidance to establish clear scope and build a competent team, with care taken to avoid the tendency for generalised low impact activities, the city demonstrators have potential. The transport demonstrators for MaaS do not exist at the level required and the CAV demonstrators are within the correct area whilst still addressing some of the key challenges. Future development of these demonstrators would benefit from input from CDBB. The system modelling capability like CAV is expanding rapidly. It is recommended that CDBB leverage this capability with focus on the causal relationship between the service, infrastructure and citizen.

The second required capability is not well established. This is for service outcomes and underlying infrastructure that can be measured and controlled with incentives to modify individual patterns of behaviour and preferences that result in improved personal and socioeconomic outcomes. The energy demonstrators of Smart Systems and Heat along with SEND, when completed, are providing the insight at scale. There is some capability within transport but it is not covering the service and infrastructure relationship. Outside of the examples given here, there is further work nudging behaviours within transport but nothing of note for the required relationships. The system models are generally not intended to develop this capability. The only exception is CUSP where a perceptive model is under consideration.

The third capability is value creation through new commercial relationships and business models for asset intensive services. The analysis has shown this is not a well understood area. There is some capability developed at an emergent level within city and energy, but nothing identified within transport. It is expected the system models could be extended or linked to socioeconomic models if the case was made. This capability will need significant capability development if the new services are to be adopted, as without the understanding of where and how value is created and traded, it is unlikely that beyond a funded demonstrator market adoption would occur.

The fourth capability required is that organisations are able to provide digitally enabled services in an accessible form to enable all individuals to benefit from new services and that all individuals have access, are able and are digital equipped to benefit from the new services. Across all demonstrators there was some capability illustrated, but it was generally not the primary element of the work and the examples' availability were supportive of this assertion.

In summary, the capabilities required by the Centre for Digital Built Britain can be developed from existing capability in part, but require the fundamental relationships to be established between the infrastructure, service and outcomes as a priority. Once this is in place, the other capabilities for CDBB can be developed and leveraged by the other demonstrators.

Table 16 - Required capability mapped to demonstrator capability

CDBB Required Capability + = Capability emerging in part ++ = Capability emerging +++ = Capability developing in part ++++ = Capability developing +++++ = Capability established	City		Energy			Transport			Systems modelling		
	Triangulum	City Verve	Smart Systems and Heat Demonstrator	Smart Energy Network Demonstrator	Community Energy at Trent Basin	Midlands Future Mobility	A2M2	Human Drive	Rapid Engineering Model	CUSP	NISM0D/ Mistral/ DAFNI
The value of the technical, social, economic and environmental causal relationships between service outcomes and the underlying infrastructure are defined.	++	+	+++	++	++	+	+	+	+	++	++
Service outcomes and underlying infrastructure can be measured and controlled with incentives to modify individual patterns of behaviour and preferences that result in improved personal and socioeconomic outcomes.	+		++	+	+					+	
Value creation through new commercial relationships and business models for asset intensive services are established.	+	+	+	+	+						
Organisations are able to provide digitally enabled services in an accessible form to enable all individuals to benefit from new services. All individuals have access, are able and are digital equipped to benefit from the new services.	+	+	+	+	+	+	+	+			

6. Conclusions

The world is undergoing a period of dramatic challenge and incredible opportunity. The planet is under stress from global warming, society is unbalanced where the few control the most whilst others starve, and we live in an economy where growth is seen as the primary goal. This is at a time where our ability to understand our natural and built environment is greater than ever, the computing power we have at our disposal is larger than anyone could have imagined, and the pace of technological change is ferocious.

With this backdrop of challenge and opportunity, our country generates 80% of the GDP from the service sector, of which about half is dependent on the built environment. To respond to the challenges we now face, these services and the underlying infrastructure must use the opportunity presented to them.

This investigation has concluded that for surface transport, the future themes to be addressed are:

- Reduction in air pollution.
- Decarbonisation.
- Changes in demand.
- Mobility-as-a-Service.
- Connected and Autonomous vehicles.
- Digitisation.

These themes are not dissimilar for energy, as follows:

- Changes in demand.
- Decarbonisation.
- Decentralisation.
- Digitisation.
- Customer experience.
- Electrification of transport

A review of current capabilities was completed. This reviewed the literature for these thematic areas and illustrated a large body of knowledge in existence grouped around the following topics: outcomes, linking performance with requirements, interdependencies between systems and systems-of-systems, service definition and maturity, and standards and data. When the state-of-the-art knowledge is compared with the future requirements it highlights areas requiring further research, as follows:

- Derivation and description of the outcome of a service.
- The relationship between service(s) and the underlying infrastructure.
- Describing the interdependency and behaviours between different services at a discreet level of abstraction such as a borough, small city, town or campus.
- Inclusion of perceptive, subjective and objective criteria into system model.
- New services and associated business models.
- Methods to increase surety and resilience in complex systems.
- Defining value and not quantity.
- Integration of 'slow' and 'fast' data models.
- Standards, guidelines and codes of practice for data integration.

A series of stakeholder interviews were conducted across the surface transport and energy sectors, and at different levels within the respective value chain. The interviews were conducted under the Chatham House Rule for expediency and in order to get an honest opinion, avoiding approvals required from Government or other organisations. The participants included in the market engagement included regulators, Government, infrastructure creators, system operators and service providers. The principal observations of this engagement were:

- The need to establish and demonstrate the causal relationship between an asset and a service at a level below macro-strategic.
- There is a distinctive separation between the service provision to customers and the service provided to the assets.
- There is not a mature understanding of how to describe the outcome or capability of a service.
- The business case for new methods of working needs to be established.
- Value is an overused but seldom understood term.
- Technology for technology's sake often realised in proof-of-principle has created a scepticism that needs rebalancing.
- The benefit of digital as a concept is understood, the translation to realising the benefit throughout the value chain requires support.
- Despite the advances made with data and information literacy, and the adoption of BIM for Government projects starting to percolate through to the private sector, there is still an overall deficit in information capability across organisations.
- The need to ensure digital inclusion should be properly considered within the overall digital strategy for any implementation.

When the future needs of the UK are considered, alongside the state-of-the-art knowledge in these areas and reflect the current capability of the market, 20 capabilities were identified. These capabilities have been consolidated into four principal capabilities that need development for the UK to respond to the requirements in the time period 2040-2050, as follows:

- The value of the technical, social, economic and environmental causal relationships between service outcomes and the underlying infrastructure are defined.
- Service outcomes and underlying infrastructure can be measured and controlled with incentives to modify individual patterns of behaviour and preferences resulting in improved personal and socioeconomic outcomes.
- Value creation through new commercial relationships and business models for asset intensive services are established.
- Organisations are able to provide digitally enabled services in an accessible form to enable all individuals to benefit from new services. All individuals have access, are able and are digital equipped to benefit from the new services.

These requirements were considered when assessing the current demonstrator capability in the UK. Those demonstrators with a capability that could be leveraged by CDBB include:

- Triangulum.
- City Verve.
- Smart Systems and Heat Demonstrator.
- Smart Energy Network Demonstrator.
- Community Energy Demonstrator at Trent Basin.

- Midlands Future Mobility.
- A2M2.
- Human Drive.
- Rapid Engineering Model.
- CUSP.
- NISMOD/Mistral/DAFNI.

It should be noted that while the requirements of CDBB could be leveraged, the four principal capabilities proposed for CDBB will all need a substantial increase in the available demonstrator capability.

In summary, the research landscape and future capabilities to specify, procure, design, deliver and manage services based on, and embedded in, the built environment in order to optimise effectiveness, efficiency and productivity for their stakeholders, whilst making best use of data and information through-life and across assets and infrastructure, have been demonstrated. Whilst there is some knowledge in existence, this is a new and potentially transformational area of development that will need focus and funding if the future capabilities needed for the UK are to be realised.

7. Recommendations

In order to develop the national capability needed for 2040-2050, it is recommended the Centre for Digital Built Britain takes the following actions:

Create and hold the vision. This is a significant cross-sector cross-disciplinary challenge. It is not expected the answer will appear from within a traditional department or organisation, but at the edge and in combination with each other. As such it will be essential:

- For someone to create and hold the vision that can link and leverage the work of others.
- To create new ecosystems to investigate, understand and implement these transformational changes.

Research. There is an established body of knowledge that can be built upon, with fundamental areas requiring further research to unlock the potential values, as follows:

- Establish the value of the technical, social, economic and environmental causal relationships between service outcomes and the underlying infrastructure.
- Determine how service outcomes and underlying infrastructure can be measured and controlled with incentives to modify individual patterns of behaviour and preferences, resulting in improved personal and socioeconomic outcomes.
- Demonstrate value creation through new commercial relationships and business models for asset intensive services.

Collaborate. This is such a diverse subject area and will need existing organisations to work together in new ways and for new groups and ecosystems to be formed to provide the focussed outcomes, including:

- The creation of an ecosystem to provide input, be a critical friend, share knowledge and create market advocates.
- Working with other centres of capability within academia and the private sector to address these challenges and develop knowledge.
- The support of organisations who are or wish to work in this area to find funding and gain access to knowledge, people, funding and organisations.

Demonstrate. One of the strong messages resonating from the stakeholder engagement and the analysis of demonstrable capability is the need to show, prove and test a principle or concept at scale. This is market enabling and an essential element of knowledge development. The required activities include the need to:

- Demonstrate the causal links between service outcomes and the underlying infrastructure.
- Develop the business cases to demonstrate the possibilities.
- Select or identify one (or many) local authorities with the ambition and sufficient scale to: demonstrate impact; have the autonomy to implement change; have a supply chain with the willingness to change; and with access to academia to create a living lab or demonstrator to test our assumptions, gather evidence and prove a relationship.

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