Supporting material for CDBB's report, 'Modelling across the built and natural environment divide: Conclusions from an interdisciplinary workshop'

Kirsten Lamb

March 2021

Contents

1 – Why built/natural environment model integration?

'Given the complexity, non-linearity, space and time dependency of the shocks which may generate in one area of the nexus and trickle down with a cascade effect on the others, eventually affecting other linked dimensions such as finance and real economy, there is a need to move away from current sector-based approaches to knowledge development and solution creation and develop a transdisciplinary approach of analysis.' (Howarth & Monasterolo, 2016)

Digital models of the built environment (of individual buildings, bridges, tunnels, roads, factories, energy grids, water pipes, broadband cables, etc.) are frequently used to monitor the condition of assets and predict their performance in the future. This helps decision-makers know when to repair, replace or modify them to improve their longevity or the services they provide.

In the natural environment, ecosystems and processes are also monitored, and digital models enable decision-makers to understand how to predict future states, minimise risk and understand complex interdependent systems.

While there are intersections between these two modelling disciplines – for example, using flood models to predict damage to low-lying cities, or river flow models to predict scouring on bridge supports – the disciplines have remained largely separate. This division is mirrored in the funding bodies for academic research, government departments and the way we talk about the built and natural environments around us. However, these two systems are deeply intertwined.

Almost nowhere in the UK is nature untouched by human intervention, and built infrastructure both relies on nature for resources and has a range of impacts on it. The built and natural environments of the UK are complex, interdependent systems that cannot continue to be considered separately if we are to face the challenges of the climate emergency and social inequality.

The interdependencies between the built and natural environment are evident, but worth stating explicitly so that they are not taken for granted. First, buildings and infrastructure are reliant on nature for raw materials, utilities such as water and energy, and the land or water on which they are situated. They are vulnerable to changes in natural systems, including rapid climate change, resource shortages and extreme weather. People are also reliant on natural ecosystems for food, clean air and water, leisure, and other intangible benefits. In turn, the construction, operation and end-of-life of the built environment impacts natural ecosystems and processes through routes such as emissions and pollution, land use change, ground surface change and increased noise levels. These dependencies and impacts happen within complex social and economic contexts, making a web of interrelationships that is difficult even for experts to understand in detail.

Ecosystem services (ES) are the various – often conflicting – demands people have from the natural environment. The modelling discipline around ES interactions and trade-offs is calling for the 'development of general rules about the relationships among ES' that would help reduce uncertainty and model complexity (Spake et al., 2017). Balancing the trade-offs when considering ES is a challenge, as they interact in complex ways and some are clearly prioritised over others. 'For example, increasing food production has often been at the expense of other ES that act to maintain and regulate environmental quality which has tended to result in increased greenhouse gas emissions, soil degradation, water pollution and biodiversity loss.' (Brown et al., 2015)

Understanding how the built environment shapes demand for different categories of ES, then, and how to provide multiple ES from the same land in sustainable ways, is a key challenge for decision makers to address and be aware of. Without awareness of these interconnections, interventions in one part of the built or natural environment could have a knock-on impact on the ability of people and the planet to flourish.

Opoku (2019) further states the case for the built environment addressing the vulnerability of the natural environment, saying that, 'A built environment with incorporated biodiversity improves the planet's ability to adapt to climate change, improves the quality of air, flood mitigation and the overall health and wellbeing of people in society.' Biodiversity is a crucial ES to human wellbeing, and, alongside protecting resources such as air, water and soil quality, biodiversity can help with resilience of people and cities. There are ways of designing and retrofitting the built environment that would encourage biodiversity within cities and around built infrastructure. These are out of scope for this work, but a range of templates for biodiversity support in the built environment exist and more are being developed now.

Modelling complex systems

An aphorism popularly attributed to the statistician George Box (Burnham & Anderson, 2002) holds that, 'All models are wrong, but some are useful.' Just as a map of a trail glosses over individual trees, stones and blades of grass to favour landmarks that are more useful to walkers, model developers must make decisions about what is relevant to users and what is out of scope, the quality, scale and granularity of data used, and many other attributes. The greater the complexity of the system being modelled, the more complex these decisions about what to include and what to leave out become.

While some might argue that the incomplete picture provided by models is not useful for making decisions, Bankes (1993) retorts,

> *'For many problems partial information can provide partial answers. For most policy problems, some decision must be made … regardless of the level of uncertainty. … When dealing with complex systems, both what is known and what is uncertain may be best represented by computer models. Thus computers can have a role in revealing the implications of what is known or believed and the possible consequences of what is unknown or uncertain.'*

Much of the literature breaks modelling into two broad categories of purpose: predictive and exploratory. **Predictive modelling** uses past and current data to understand what a system is likely to be like in the future, attempting to arrive at a best guess. This relies on high quality, high fidelity data, and a thorough understanding of the relevant parameters. Models that attempt to predict when a bridge will need to be serviced or what the capacity of an energy grid at some future point will be are examples of predictive models.

Exploratory modelling, on the other hand, is used to explore scenarios, options and trade-offs. As a modelling discipline, it is more comfortable with uncertainty, as long as the models lead to better decisions. As Bankes says, exploratory modelling reveals a range of possible outcomes, enabling better informed decisions in which uncertainty is understood as a feature, not a flaw (*ibid.*).

The caveat to this approach, as described by Blainey & Preston (2019), is that by emphasising the uncertainty about the future, exploratory models may give planners and policy-makers the impression that they have very little power to shape outcomes. 'In fact, while a range of futures is undoubtedly possible, perhaps the biggest single determinant of which future becomes reality is the decisions taken by those in positions of power, be they world leaders or local transport planners.' This means that decision-makers today have more impact on complex systems than some of the processes being modelled. The benefit of modelling is in helping decision-makers better understand the potential impacts of interventions they choose to make on those systems.

Few systems are as complex as the deeply intertwined built and natural environments, comprised of countless processes, individuals, relationships, resources, needs and values. As Whyte et al. (2020) point out, there are three ways for modellers of complex systems to think about the relationship between the built and natural environment. The first approach frames natural processes and resources as entirely external to the built environment. This approach keeps the models from these disciplines entirely separate.

The second approach frames natural and built processes as infrastructure systems that are equivalent and parallel. Indeed, the workshop discussed in this report revealed many similarities between these two areas in terms of drivers, barriers and complexity. This approach, 'would suggest equal attention to modelling the natural and built environments, or attention to modelling the relationships between them, however typically including aspects of the natural system as pre-defined boundary conditions.'

The third approach Whyte et al. discuss is the one they advocate, which frames the natural environment as, 'all pervasive, where the built environment is inseparable from it and an adaptation of the natural environment to suit societal needs, using its materials and resources.' Operating within this framing, so-called 'grey infrastructure' of the built environment cannot be considered without also considering its wide-reaching reliance and impact on natural processes. This concept is behind the approach to planning identified in the workshop as 'environment-led design'.

Decision-making

Treating the built and natural environment as a complex, interlinked, socio-technical-ecological system-of-systems helps us understand how the decisions and actions we take impact those systems, enabling us to make better choices in the future. Using predictive modelling where uncertainty is low, and exploratory modelling to develop scenarios to think about the range of outcomes, could help to generate more workable recommendations (Harty et al., 2007). Conducting this type of model-based decision-making across the built and natural environment interfaces could be a powerful tool for operating within the limits of the environment while providing for society's needs (Doughnut Economics Action Lab, 2021).

Connecting long-term objectives with short-term targets, aligning policy with vision, fast and simple policy models (Walker et al., 2013), and the avoidance of lock-ins are discussed as essential components of decision-making based on uncertain models of complex systems. '"Monitor and adapt" is gradually becoming preferred to "predict and act"' (*ibid.*), showing the preference for exploratory modelling and scenario-based methods for decision-making.

An example of this type of decision-making can be seen in the Thames Estuary 2100 plan (Environment Agency, 2012), which sets out a strategy based on various climate models over nearly 100 years, then revisits 10 indicators periodically and updates policy plans through this monitoring programme. The programme then makes interventions or updates the strategy accordingly. It empowers multiple agencies to work toward the same strategy and iterates according to the latest modelling to protect lives and property in the face of an uncertain climate future.

It is not only policy makers who have important decisions to make. Clients, contractors and sector leaders have a role in balancing the interfaces between the built and natural environment. Their levers are around procurement, where they can create policies that dictate how their partners and supply chains do business, ensuring that the value of ecosystem services and social benefits are embedded in their business models[1].

Modelling today

Built environment modelling

Units of built infrastructure, for example a building or a bridge, also referred to as assets, may now described digitally through a process known as Building Information Modelling (BIM). BIM is a project delivery approach that captures, stores and hands over essential information about an asset throughout its lifecycle, from design to decommission (Chong & Wang, 2016). In this way, all project stakeholders have access to the data and information they need to do their jobs and ensure the asset delivers the required outcomes. It is well suited to sustainable development, as it can require that designers, contractors and operators provide information about factors such as energy efficiency, thermal performance of materials and water use. That information is captured and maintained such that others can learn from the performance of individual assets and get a better picture about the sustainability of the built environment overall. BIM as a concept is enshrined in national and international standards.

Another powerful concept emerging from built environment modelling is that of digital twins. 'Digital twins—of cities or the built environment—are better characterized as cyber-physical-social eco-systems, analogous to organisms "with a brain"…. This interpretation highlights the complexities of applying the digital twin concept to the built environment due to bi-directional coupling across the digital, physical, and social spheres.' (Nochta et al., 2020) Digital twins are developed iteratively and develops alongside its physical twin. While digital twins to-date have focused on built assets, the eventual aim of projects like the National Digital Twin programme (NDTp) is to make accessible to decision makers relevant data or models, from building information to socio-economic modelling, that would help drive better physical, social or policy interventions and better outcomes[2].

In the UK, city-scale 'urban observatories' have explored the utility of right-time sensor data and visualisation for decision support in early experimentation with connected digital twins for planning (Nochta et al., 2020). Wan et al. (2019) discuss city-scale digital twinning in this context as exploratory modelling that is used to solve complex problems and guide policy decisions by

[1] https://constructioninnovationhub.org.uk/value/

[2] https://www.cdbb.cam.ac.uk/what-we-do/national-digital-twin-programme

identifying 'system-level risks and inefficiencies of development options and to foster cross-disciplinary/professional collaboration'.

There are various barriers to connected data, models and digital twins at city, regional and national scales. Data quality, access and security are ongoing cultural and technical challenges and, while standards are being developed to address them, they remain tricky problems that are fundamental to get right (Dent, 2019). Integrating BIM with geographic information systems (GIS) and other types of data is yet another challenge. Mismatches in information between different formats, different spatial scales, different semantics and granularity, storage and access methods are all barriers to interoperability (Liu et al., 2017). Work is ongoing to overcome these issues, as the value of getting it right is widely recognised.

While some are concentrating on the culture change barrier, others are focused on creating the architectures that translate between and connect different data and model types: taxonomies, ontologies, reference data libraries, common data environments and information management frameworks (IMFs) are all being developed to help harness the power of joining up data from across the built environment (e.g. Carhart & Rosenberg, 2016; Hetherington & West, 2020).

Digitalisation, data collection and modelling are not just for ultra-modern infrastructure and buildings. Historic urban landscapes are also being defined by a growing body of standardised descriptors, digitised and modelled in order to better understand their performance and their role in the urban environment (Kokla et al., 2019).

While there is a mandate from the UK government that public projects should use BIM to manage data over project lifecycles, for the most part there is the expectation that clients should drive change toward using digital modelling, and set the principles to be delivered by the project (RICS, 2015). The Gemini Principles (Bolton et al., 2018) seeks to address this gap by recommending a set of principles for guiding the development of digital twins. Government policy priorities as dictated in documents such as National Infrastructure Commission (2017) – such as capacity, carbon and congestion – set the types of questions that will be asked of built environment modelling.

Natural environment modelling

The field of environmental modelling is widely varied, from climate and meteorological prediction, to tracking endangered species populations, to global biomass modelling. Therefore, this review will focus primarily on integrated modelling of the natural environment that is aimed at decision-making about land use: still a broad scope, but easier to summarise.

To illustrate the wide range of disciplines in this area, Harrison et al. (2018) list several categories of natural environment modelling, including:

- Biophysical models – processes and functions related to ecosystem service supply, e.g. species distribution models, hydrological models, soil erosion, ecosystem dynamics / species loss;
- ES models – supply and demand of various services, often rendered in a GIS-like software environment, ecosystem service cascade models showing a production chain 'linking ecological and biophysical structures and processes with elements of human well-being' (*ibid.*);

- Agent-based models – modelling human decision processes involved in policy or land management decision making;
- Integrated assessment models – couple sector or ecosystem models to simulate land use change/change in the delivery of ecosystem services;
- Socio-cultural models – participatory mapping to include local stakeholder knowledge, scenario models, narrative methods, preference assessment from consultation;
- Monetary models – cost effectiveness, cost-benefit analysis, market price and exchange methods, mitigation/restoration/replacement/clean-up costs, revealed preference measures, simulated exchange, benefits transfer;
- Integrative methods – Bayesian Belief Networks, with nodes based on a combination of historical data and expert knowledge exploring causal relationships between values of nodes; Multi-criteria decision analysis.

Models of complex environmental systems are used to make decisions about the management of ecosystems and landscapes, and various methods have been developed to do so. Harrison et al. (2018) propose a flexible decision support system using decision trees and other guidance tools in order to use the same models for varying researcher and practitioner needs. The CLIMSAVE (Climate Change Integrated assessment Methodology for cross-Sectoral Adaptation and Vulnerability in Europe) was developed as a user-friendly web tool for stakeholders to assess climate change impacts in a range of land use sectors from a quantitative basis. Its creators note that, 'The linking of models for the different sectors enables stakeholders to see how their interactions could affect changes to the rural and urban landscape of Europe.' (Harrison et al., 2015). Modelling changes of land use and their impact on ES helps understand the trade-offs between services such as food production and biodiversity, aiming for consistency system-wide, while changing land uses at a local level to best meet the idiosyncrasies of a particular area.

Willcock et al. (2020) report on the benefits of federated models of Ecosystem Services (ES) to robustness and accuracy for decision-making. Federated models, like that proposed by the NDTp, use a wider library of interoperable data to gather greater insights than any of those datasets individually. The Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) framework is a tool that provides a unifying structure for bridging interventions and policies to address climate change, and the need for ESs for human flourishing (Holland et al., 2016).

Rieb et al. (2017) point to various ES modelling tools, and various critical frontiers of understanding the relationships between land use changes and human well-being, but point to questions that remain around integrating ES models with other perspectives, 'that would more accurately include other forms of capital or social factures such as infrastructure (e.g. pipes for irrigation) or management institutions (e.g. collective use rights around irrigation water) that can be critical to the delivery or accessibility of ES and their benefits'. They go on to state that the, 'failure to explicitly include human made infrastructures and capital in ES models and tools means it is impossible to assess their relative importance to service provision'.

This mirrors the perspective of Whyte et al. (2020) that people in cities can often feel detached from the ecosystem services on which they rely because they are mediated through the built environment, i.e. water from a tap, or food from a restaurant. Modelling has the power to make these services and resources more visible to decision-makers to better demonstrate the reliance of societies, services and the built environment on ecosystems.

Modelling built and natural environments

Built and natural environment modelling are integrated in some areas, particularly through flood and other hydrological modelling. The Environment Agency and Centre for Ecology and Hydrology (as well as their partners and other organisations) use models to explore where, when and how big floods might be, how much damage they are likely to do to property, and how many people are at risk, enabling decision makers to mitigate risk to life and property[3].

Sub-surface modelling is used to understand groundwater flow dynamics, geothermal energy, shifting geology, underground assets and how they interact with one another. There are tremendous risks to buried infrastructure, aboveground structures and water quality if we make the wrong decisions, so modelling in these areas is already a vital tool (Bricker et al., 2017).

However, the dependencies of these systems on each other are not fully understood, and there are dynamic factors in play, most notably climate change. Experts who model the effects of climate on bridge support scour point to the fact that climate change causes major uncertainty in infrastructure performance modelling; we do not know exactly how bad extreme weather will be in the future. This undermines the conventional thinking that solid, dependable infrastructure such as bridges are inured to uncertainty (Dikanski et al., 2018). (Deierlein et al., 2020) discuss computational modelling of the risks to the built environment of climate disasters, organised around a framework of shared data and models for a more robust analysis. Once again, federated modelling gives a broader – and potentially more accurate – picture of potential scenarios.

Aware of all of these interactions, the developers of the National Infrastructure Systems Model (NISMOD)[4] and its related analysis tool, Data & Analytics Facility for National Infrastructure (DAFNI)[5], brings together climate scenarios with infrastructure system-of-systems models to produce a range of possible futures for UK infrastructure using exploratory modelling (Blainey & Preston, 2019). This tool can be used by academics to share their models of infrastructure and related systems, creating a large, interoperable, potentially integrated library of models to address questions about interdependence, trade-offs and opportunities between the built environment and related systems.

From the broad scope of infrastructure systems to specific cities or sites, modelling can help understand the interactions and interfaces between the things we build and those that occur naturally. Moravej et al. (2021) write about their tool, Site-scale Urban Water Mass Balance Assessment (SUWMBA), which brings together information about the way water will flow over surfaces and materials, through sub-surface geology and assets, and across whole urban systems in a 'joint consideration of architectural design, water servicing technologies and environmental context'. This tool advances conventional planning tools, which only consider water systems after the built assets already exist. 'This overlooks the interactions between urban design and urban water systems and the potential that can be unlocked by better integrating the two.'

Similarly, Aktas et al. (2017) describe a tool for understanding local climate variations based on how climate and temperature behave in response to the properties of specific materials covering areas of land, not just on what category of land use they fall under. This gives a high-resolution model of

---

[3] https://www.ceh.ac.uk/services/flood-modelling

[4] https://www.nismod.ac.uk/home/
[5] https://dafni.ac.uk/about-2/

temperature at the local scale. **Both are positive early demonstrators of the type of integration that was explored in the workshop discussed in the report.**

-

The benefit of modelling complex systems, especially crossing traditional silos to do so, is in better decisions and better outcomes for people and the planet. As Bateman et al. (2016) put it, 'No single discipline is sufficient to tackle the challenge of integrated environmental-economic decision making.' The complexity of our world defies simplistic modelling. We can use the innovations of cyber-physical systems and digital twins to better unravel that complexity, and make the right interventions in the built and natural environment. However, it will take a shift in decision making tools, practices and mindsets.

Webb & Bailey (2017) point to the need for innovation in how information is shared within the planning system. Currently, information in this system is not machine readable or easily retrievable, and so methods like BIM could be transformative in ensure that planners see the right data at the right time. Among options such as common data environments and planning portals, Webb (2017) describes a 'Land Information Platform' for planners, echoing the emphasis in this workshop on the need for a shared platform for model creators and decision-makers in the built and natural environments.

Meanwhile, Dudley & Banister, (2018) point not to a technological need but a cultural one, saying that within the planning and political arenas, 'expertise must break out of its specialist niches, and paint a coherent picture that captures public and political attention and imagination.' This echoes a point from the workshop that communicating the value of modelling outside of ones' own discipline is an important enabler, as is active collaboration with other disciplines.

According to Dittrich et al. (2016):

> *'Where planned adaptation to climate change is necessary, decision makers need to move away from striving for solutions that assume that an investment today will necessarily match the actual state in the future. Uncertainties surrounding climate change projections and impacts, as well as changes in emissions in the future, mean that these assumptions will be invalid. Taking these uncertainties on board, decision-makers should consider more robust decision-making methods instead of standard cost–benefit analysis, cost–effectiveness analysis or multi-criteria analysis.'*

This points to the need identified in the workshop that, beyond making data interoperable, new decision processes and culture change among decision-makers is needed.

-

This brief review of the literature makes it clear that there is work being done to integrate built and natural environment models for different purposes[6]. However, this work has not necessarily been

[6] It should be noted that an exhaustive literature review on the topics discussed in this report was not attempted as there were many potential threads to follow and huge bodies of work in both areas, and therefore there may be relevant work that has been missed out. The aim of the review that was done was to provide context for the workshop and underpin the recommendations made by the report rather than to form an exhaustive survey of the literature.

visible to those working in BIM and digital twins of the built environment. For example, literature from the National Digital Twin programme (NDTp) mentions the context of the built environment within nature, but has not explored the interactions between these areas, nor has it delved into the challenges that would arise from integration of natural environment models into an NDT[7]. Nor has it necessarily been a major part of the thinking among those studying modelling for land use decision making.

Therefore, the contribution of the report is to frame the discussion of built and natural environment model integration in the context of federated models for planning decisions in the UK. The intention is that the report will provide useful evidence for future collaborative research projects, and inform the perspectives of those working on an Information Management Framework (IMF) for federated digital twins of national infrastructure. It also makes recommendations for the early stages of a programme of interdisciplinary work that would produce case studies and a toolkit for local projects that seek to use built and environmental models to create better outcomes through 'optioneering'; for example providing a range of options that involve built, nature-based and hybrid interventions in the system.

[7] https://www.cdbb.cam.ac.uk/what-we-do/national-digital-twin-programme

2 - Workshop background

'Interdisciplinary work is a particular priority in the realm of sustainability, where the global reach and complex nature of the work to be done can realistically only be approached across our traditional academic and geopolitical silos' (Cornell & Parker, 2014)

The workshop described in the report consisted of two three-hour long sessions in January 2021, spaced around a week apart, with around 10 participants who remained mostly consistent across both sessions[8]. It also involved reflective work between the two sessions to give participants the opportunity to present more considered ideas in the second session.

The participants were experts from either natural environment (NE) modelling or built environment (BE) modelling backgrounds, and from both academia and industry, with a few early career participants amid the more established experts. It was hosted virtually on Teams and an online whiteboard tool called Miro.

Origins

The origins of the workshop began prior to the COVID-19 pandemic when the report's author encountered the Natural Environment Research Council (NERC) Landscape Decisions research programme online. Its stated research questions,

- 'How can land be managed, to realise benefits for the benefit of society, individual well-being and the environment, both now and in the future?', and
- 'How can research and innovation provide solutions to support effective (real world) land-use decisions that deliver improvements to the environment, health, well-being and the economy?'[9],

mirror the mission of the National Digital Twin programme, which seeks to leverage information management and federated digital twins to provide 'better outcomes for all stakeholders per whole-life pound spent in the built environment'[10]. While they utilise different methodologies, their visions are similar: using evidence to make better decisions that lead to better outcomes for people and the planet.

Underlying each of these programmes are policy priorities such as housing provision, energy infrastructure performance and carbon neutrality, as well as societal demands such as preventing flooding, providing accessible green spaces and addressing inequality. Both programmes share this diverse set of stakeholders, and have different strengths to share with each other.

For that reason, this workshop was devised to bring these two groups together to explore commonalities and opportunities for collaboration. The original concept was to use design thinking

[8] One participant was unable to make the first session and another was unable to make the second.
[9] Source: https://nerc.ukri.org/research/funded/programmes/landscape/
[10] https://www.cdbb.cam.ac.uk/what-we-do/national-digital-twin-programme

to envision a future National Digital Twin (NDT) that effectively manages the interfaces and trade-offs between the BE and NE. Participants would consider who would be using the tool and what types of questions it would answer in the interest of better balance between the built and natural environment, and better outcomes.

Planning

Planning took place during the Autumn of 2020 with every expectation that it would be impossible to meet in person. It was therefore designed from the beginning as a virtual workshop, developed to use the digital tools available.

The initial concept for the workshop was to bring together a wide range of 30-40 early career and established researchers from across built and natural environment modelling for a virtual conversation (taking place over 2-3 half day sessions) about opportunities for integrating models across these sectors. The original intended outcomes were:

- Initial ideas for a **glossary** highlighting areas where each discipline might benefit from some translation work and key concepts in each discipline (co-developing a **common vocabulary**);
- Rich **commentary** on what data/information an NDT would need to manage, what insights it would need to provide and any issues future researchers/practitioners should be aware of (co-developing **specifications**); and
- Co-developed **personas** outlining users of an NDT, how they would interact with it and how they use the insights they get from it (co-developing **personas**).

The logic behind this approach was based on literature about interdisciplinary collaboration that emphasised the need for translation between the disciplines at the outset (e.g. Bruce et al., 2004; Cornell & Parker, 2014). While this would still be of benefit in the future, however, the purpose of this workshop was not to bring together an interdisciplinary community for long-term collaboration, but rather to explore in a tentative way the feasibility and opportunities for doing so in future. Therefore, these original outcomes were not considered as useful.

The external supplier chosen to facilitate was Good Beyond, who proposed to focus on opportunities, and to reduce the participant number to around 10 so that each participant has more of an opportunity to express ideas. The facilitators have experience using Miro whiteboards as a tool for structuring conversations, capturing insights and voting on them, so this was the platform selected for collaboration. The meeting was hosted on Microsoft Teams, and the duration was changed to two half-day sessions.

Throughout the planning process, the focus of the workshop shifted from the outcomes stated above to the following:

- Prompt an **interdisciplinary discussion**, focused on the UK context, between groups modelling built and natural environment assets, systems and processes;
- Identify **new opportunities** for model integration across the built/natural environment; and
- Provide **seeds for future research projects** and insights for the development of the Information Management Framework (IMF).

The most important outcome was simply convening the conversation and reporting on the results rather than producing a glossary and a list of specifications for a future NDT. That work could come later, but in the meantime, it was deemed more important to identify opportunities and initial steps from the small but diverse cohort.

Concept map

In order to help the participants situate themselves in the world of integrated modelling that was the topic of the workshop, the facilitators decided to use a concept map that encompassed both NE and BE modelling, as well as the drivers and producers of that modelling. Morse (2014) advocates the co-design of disciplinary concept maps by interdisciplinary collaborators, but such an exercise would require at least one workshop, and similar activities have already been undertaken separately in the Landscape Decisions and the digital built Britain programmes.

Therefore, the facilitators provided a very high-level map at the first session of the workshop to act as a tool for the participants who work at different scales and in different disciplines, and to point to commonalities. This map was checked with a selection of participants before the workshop, shared in the first workshop and was presented again in Session 2 with annotations based on the discussions (Figure 1).

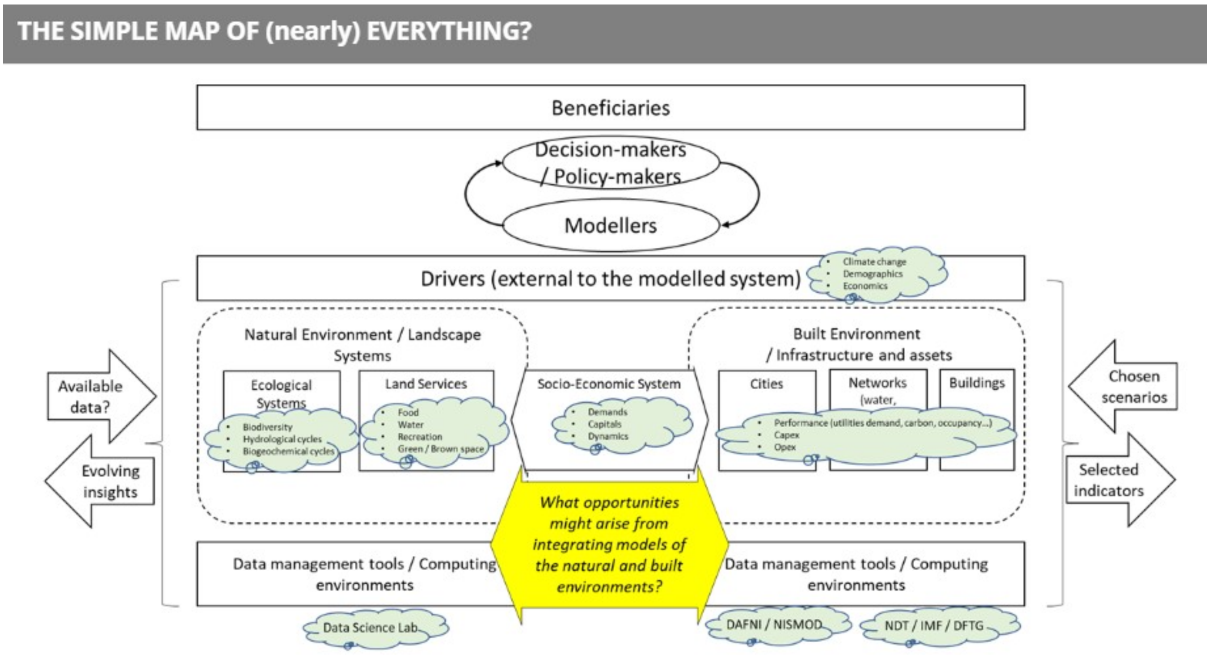

Figure 1 - The 'Simple Map of (Nearly) Everything' as presented in Session 2, with annotations about where various topics and platforms fit.

This concept map shows at a simplistic level the different types of stakeholders, inputs, outputs and relationships between models and sectors. One of the things it fails to capture is the way in which modelling contexts are nested within one another. For example, the built environment is nested within society, which in turn is encompassed by the natural environment. These relationships may be important to the ways in which models are integrated or described using ontologies. However, this discussion was out of scope for the workshop.

Interdisciplinarity and terminology

The literature of interdisciplinary collaborations commonly states that difficulties may arise due to 'mismatches in space and time scales, in forms of knowledge (e.g., qualitative versus quantitative), and in levels of precision and accuracy.' (Benda et al., 2002) This was a potential issue that the facilitators were aware of and sensitive to throughout the planning process. However, starting with a key question that is relevant to both disciplines is a useful way of smoothing over these differences. There can be discomfort among experienced researchers in particular at being placed in a position of not knowing (Cornell & Parker, 2014), and the facilitators were aware of this potential issue. The workshop was therefore designed to enable people to share their own ideas while learning from each other's areas of expertise. It was framed as exploring a gap in knowledge and practice, and therefore 'not knowing' was normalised.

There was also an attempt to focus on opportunities centred around model integration without completely abandoning all understanding of the ethical and human-centred components of this work. Therefore, as suggested by Cornell (2010), the facilitators tried to strike a balance between staying on topic and allowing participants the time to express and explore the ways they view the world. They were already aware of the possibility of language for which it might be difficult to agree on a comprehensive meaning during the workshop – words such as 'scale', 'uncertainty', 'asset' and even 'natural'. As noted by Cornell and Parker (2014), however, academics tend to want to avoid '"those pointless semantic discussions"' about terminology and the facilitators opted to follow that instinct and focus on the core purpose of the workshop rather than getting stuck on language. While this increased 'the risk of talking at cross purposes', it was seen as the lesser risk of derailing the workshop from its objectives.

Participant recruitment and induction

Participants were recruited through a process of discussions with known experts from the NDTp and LD programmes. Initial expressions of interest were gathered by emailing the Landscape Decisions community. Further participants were identified through a process of stakeholder mapping and conversations with experts. Ultimately, 17 people expressed interest in attending, and the decision was made to recruit from among these people on an invitation basis to ensure a balance of representation from different disciplines and organisations. Around half of the participants (n=5) were recruited from the Landscape Decisions cohort, and the rest (n=6) from the built environment and National Digital Twin programme areas.

All participants were briefed with basic information about built environment modelling, the National Digital Twin programme, DAFNI, and natural environment modelling, in addition to the workshop agenda and a how-to guide to Miro.

Workshop agenda

The facilitators designed the flow of the sessions, with input and sense-checking from selected participants. The following is the agenda for the workshop:

Session 1: Seamless integration between natural & built environment modelling - What could this deliver?

- ***Exercise 1: What could integration enable?***
  Explore & discuss the wider opportunities the integration of models enables.
  Develop ideas for what integration means for your area.
- ***Exercise 2: What benefits could this bring to people and society?***

Individuals invited to describe their most compelling opportunity idea & why it is important. Discuss the wider benefits that could be realised from these opportunities.

'Homework' between sessions

- *Using the 'opportunity sheet' for expanding & capturing further thinking.*

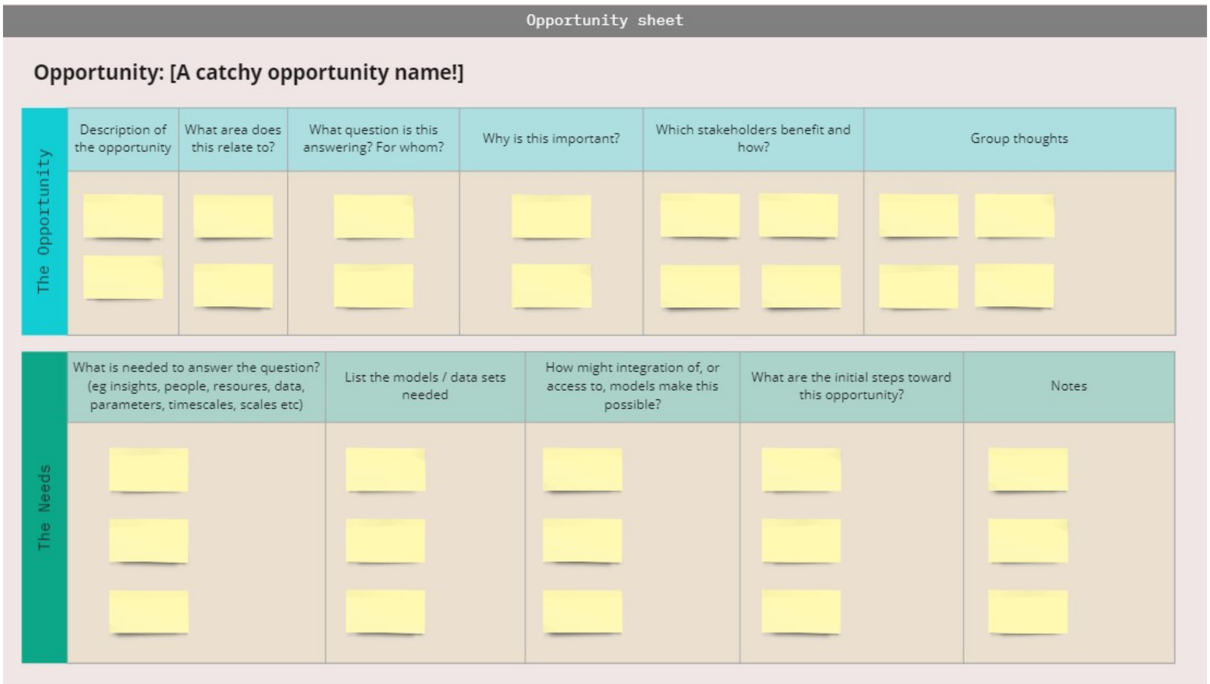

Figure 2 - Blank opportunity sheet for the 'homework' between sessions

Session 2: Seamless integration between natural & built environment modelling - How to realize this opportunity?

- ***Explore compelling opportunities***
  Individuals present their opportunity sheets, with their further thinking on a chosen opportunity and what is needed to achieve it.
- ***Exercise 1: What is needed to unlock these opportunities?***
  Explore what is required in different areas to be successful.
- ***Exercise 2: How to make it happen?***
  Explore where to focus initial attention and what will ultimately lead to the greatest impact.

Each session started with an introduction by the facilitators and was followed by a summary wrap-up.

Reflection on suitability of the method

The vital groundwork for this workshop were the initial emails and conversations to communicate the aims and vision, gain the trust of potential participants, and bring them onboard. All participants received briefing materials and multiple other communications during the development of the workshop, and some had discussions with the author prior to the event. This meant that participants arrived with a good understanding of the purpose and importance of the conversations that would take place over the two sessions. This resulted in conversations that were collaborative, amiable and driven by curiosity and a common purpose.

The virtual tools used for this workshop, Teams and Miro, have some advantages over working in person on post-it notes and flipcharts. First, ideation can happen much more quickly once participants are used to the application. No time is spent getting up to place post its, sorting them is much easier, and splitting into groups happens more or less seamlessly. Participants who want to speak can virtually raise their hands to avoid cross-talk. Less vocal participants may feel much less singled out if they are contributing chiefly on post-its, and everyone had the option of contributing to the Teams chat as well, since the facilitators were capturing ideas from the chat on the Miro board. These various routes to contribution make for a more inclusive experience in some ways than an in-person event.

What is lost with a virtual meeting are the informal conversations between participants that spark ideas, and the moments between exercises during which participants get up and walk around, giving them time to think and a shift in perspective. Issues of connection speed and familiarity with the tools meant there was a potential for accessibility issues to the workshop. Similarly, if any participants had audio or visual accessibility issues, the activities would need to be adapted to be inclusive. The facilitators did their best to support participants who were unfamiliar with the tool, had family commitments or connectivity problems.

Given the limitations of the pandemic, however, the methods used covered a range of contribution styles and encouraged participation by everyone attending the workshop. With a mixture of exercises, allowing views to diverge through individual thought, then converge through group discussion was an effective way of both exploring a wide range of ideas and identifying top priorities.

3 – Workshop description

'First you integrate the people, then you integrate the data.' – Workshop participant

Session 1

The first session of the workshop began with an overview of the background, purpose and agenda; introductions by the facilitators and participants; and a brief activity to practice using Miro. This was followed by short presentations from an NE modelling expert and a BE modelling expert respectively, introducing the interdisciplinary cohort to the basics of model integration in each discipline and what current challenges exist. While each discipline has its own unique features, there was remarkable accord between the accounts of challenges and barriers to model integration between the two presentations. Then, one of the facilitators presented the concept map (Figure 1).

The exercises that followed took participants through some initial scoping of wider vision, stakeholders and opportunities that would be revisited in Session 2, so the input from participants here is not as developed as the thinking in the section for Session 2, and these questions were addressed again later in different forms. The conversations from Session 1 are presented here for the information of readers about the foundation of the later conversation.

Part A - What could integration of built and natural environment models enable?

The first question participants addressed was:

What are the big challenges or unanswered questions that model integration might enable?

Participants used post-it notes on the Miro board to place as many ideas as they had for several minutes, while the facilitators asked follow-up questions. The challenges and issues identified in this exercise into common categories:

- **Systemic challenges and opportunities**: (n=13) including managing trade-offs, impacts, interdependencies and conflicting policies in complex systems; developing pathways to multiple goals (e.g. Net Zero carbon emissions, biodiversity); and envisioning sustainable land use for the UK, coupled with environment-led planning, design and optimisation of the built environment.
- **Better interventions or implementation**: (n=6) including reassessment of the value and categorisation of land, making land use decisions based on the needs of the built environment; better implementation of existing biodiversity or environmental investments; and better optioneering/taking a broader view when planning major projects.
    - Within that, specifically **green energy / decarbonisation challenges and opportunities**: (n=4) including increasing use of renewable energy in ways that enhance environmental synergies; finding alternatives to 'hard' infrastructure to prevent carbon emissions from construction; and understanding the pathways to integrated approaches to carbon emissions reduction.
- **Technical and structural challenges:** (n=6) including secure integration of heterogenous data across sectoral, ownership, geographic and other boundaries; managing who has control

over and the ability to interpret model outputs; CAD-GIS model interoperability; linking data into decision-making process; and enabling machine-to-machine communication to automate aspects of built/natural environment management in trusted and transparent ways.

- **Socio-ecological challenges:** (n=3) including how societal behaviour influences both natural and built environments; and modelling dynamic land use change and built environment impacts on resources as well as processes and phenomena such as flooding (as well as understanding how ‘soft’ infrastructure may be used to manage flooding).

This differed from what the facilitators had expected. Some of the participants seemed to see the word ‘challenges’ in the question and interpret that as barriers to model integration, rather than questions that model integration could answer. The facilitators did not re-run the exercise, however, as its purpose was to encourage participants to think about a broad vision of what could be possible with model integration, only to revisit that later.

The ‘Socio-environmental’ and ‘Better outcomes’ categories contain contributions that were more aligned with what the facilitators had anticipated. Similarly, the contribution ‘Setting pathways to multiple policy goals’ indicates that model integration could help identify opportunities for cascading benefits, or interventions that would deliver against multiple strategic aims.

Next, using the same technique of post-it notes added to a shared board, participants answered the question:

Where can we have the greatest impact?

After a brief discussion, participants voted on their top three from the group using five coloured dots each, and one ‘monster’ sticker to indicate their top choice. The top three choices were:

1. **Environmental-led design of new infrastructure**. This was explained as the need for modelling and insights about environmental impacts and opportunities to be made available earlier in the planning process. In current practice, the environmental impact assessment process occurs in response to a design, and might be seen as presenting roadblocks. In this suggestion, environmental trade-offs, impacts and opportunities would be embedded in design and planning criteria so that sustainability is not a box to tick but part of the core principles leading a project or intervention.
2. **A truly joined-up approach for planning for sustainability, through targeted allocation of scarce resources**. This suggestion was explained as the need for cross-sector coordination on sustainable land use and construction, based on an understanding of how best to utilise land, water, materials and

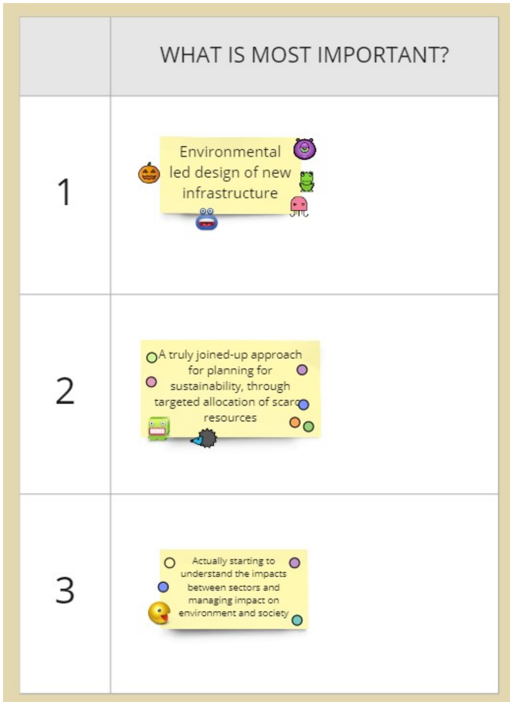

Figure 3 - Top three areas for impact

other limited resources to meet policy goals, creating a systemic approach to resource allocation and making the trade-offs between projects and resources more visible.

3. **Starting to understand the impacts between sectors and managing impact on environment and society**. This suggestion echoes the previous one by pointing to the need for better visibility and coordination across the sectoral gaps and governing bodies on environmental and societal goals. In both circumstances, better integration of models was discussed as key to enabling managing these impacts and interventions, and both are centred on managing trade-offs.

The synergy of these three priorities is captured by Whyte et al. (2020), who highlight the significance of indirect effects, interdependencies and impact pathways that are not currently well understood in the overall health of natural systems. They argue for an approach to engineering design that improves 'how we produce systems modelling and **how we share that information through forms of visualisation and decision rooms that get all relevant stakeholders to look at the same data, see their role in the system and accept their responsibility for system change**'.

Part B - Who are the stakeholders?

Using a loose framework prepared by the facilitators (Fig. 3), the participants filled in as many stakeholders as they could. The volume and variety of the stakeholders they came up with shows that model integration faces a complex landscape across different sectoral and governance silos, but also has numerous potential champions that can be leveraged for systemic change.

The stakeholders listed in the right-hand column show that the stakes themselves are high enough to be an organising principle for the activities of system users and model creators; our communities and society, and the wellbeing of our global climate and resources.

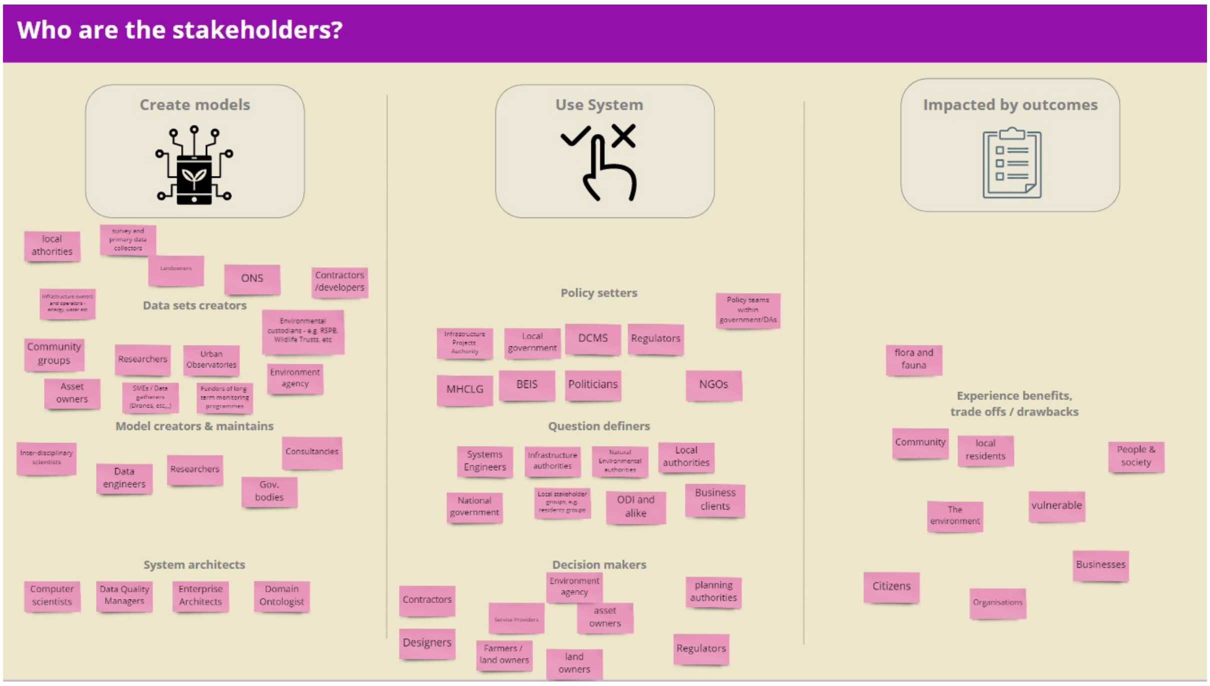

Figure 4 - Stakeholder mapping.

The responses are provided here for better visibility (similar answers have been combined):

Table 1 - Stakeholders

Create models	**Use system**	**Impacted by outcomes**
Data set creators	*Policy setters*	*Experience benefits, drawbacks*
Local authorities Survey and primary data collectors/researchers Landowners ONS Contractors/developers Community groups Asset owners and operators	Policy teams within government/devolved authorities Government departments NGOs Politicians Local governments Infrastructure Projects Authority	Citizens/local residents Vulnerable communities Society The environment Flora and fauna Businesses Organisations
Model creators and maintainers	*Question definers*	
Interdisciplinary scientists Data engineers Researchers Government bodies Consultancies	Systems engineers Infrastructure authorities National environmental authorities National and local government Local stakeholder groups Open Data Institute and similar Business clients	
System architects	*Decision makers*	
Computer scientists Data quality managers Enterprise Architects Domain ontologists	Contractors Designers Service providers Land owners/farmers Asset owners Regulators (Environment Agency etc.) Planning authorities	

The purpose of this exercise was to encourage participants to think about the range of people who can influence model integration and who experience benefits or drawbacks from the outcomes. It also contributed to the understanding of the context in which model integration happens.

Part C - What opportunities could integrated models unlock in your area?

Next, participants worked on individual Miro board areas to answer the question: *What opportunities could integrated models unlock in your area?*

For several minutes, participants filled in post-its, and then voted on their top three from their own boards. After the session, the top three opportunities from each participant were categorised into the following themes, presented here with descriptions and a representative quote from the participants' post-it notes:

Table 2 - Themes

Theme	Description	Illustrative quote
Data access and quality	Secure access to relevant, contextualised data of verifiable quality, discovered at the right time to make informed decisions.	'A lot of data is available but not always in the right formats, not discoverable and is not used in decision-making. Improving data and model delivery and integration means we can make better use of the knowledge we have.'
Interdisciplinary and cross-sector collaboration	Integration of data, models and processes across silos in and between industry and academia, recognition of the value of expertise and perspectives outside of your own area.	'Need to recognise others' disciplinary perspectives as well as our own disciplinary capabilities, biases and limitations in order to advance model integration.'
Understanding complexity	The ability to see the various trade-offs, risks opportunities, interventions and impacts at the point of decision-making.	'Balancing the need for economic growth and environmental sustainability - developing mitigating measures if necessary.'
Values-driven policy and procurement frameworks	The environment and frameworks in which decisions are made that determine – through incentives, timing, legislation, etc. - which routes are taken.	'Better influence values in policy making towards sustainability (rather than immediate economic gain).'

All of the uncategorised top three opportunities that the participants selected from their own boards are listed in full here:

Table 3 - All top 3 opportunities

	Top three opportunities	Why
P1	Integrating environmental value / impact with other value metrics in option choice and decision-making around e.g. projects (through good data & models).	If we are going to address Net Zero and the ecological emergency, decisions need to be based on best available data. Including environmental data and impacts in a 'system of systems' approach is the only way to really address this.
	Create decision-making tools that engage the full range of stakeholders in integrated decision making.	Engaging stakeholders in decision making means that they understand and agree on compromises, so decisions more likely to be accepted and acceptable.
	Address climate exposure reporting requirements - and include benefits where relevant.	Brings a compelling reason for private sector to engage.
P2	Improve access to datasets and models.	-
	Better understanding of the impact we are having on the environment.	-
	Environment led designs and interventions.	-
P3	Through interdisciplinary cooperation	-

	Better influence values in policy making towards sustainability (rather than immediate economic gain)	-
	Improve interdisciplinary understanding to come up with comprehensive evaluation of decisions	-
P4	Run planning scenarios across sectors (using different data sources).	To be able to analyse and identify the best interventions on the system-of-systems.
	Consolidate and share knowledge on data modelling.	To foster innovation on models and integration and support of new ways to do things, improving efficiency in services and delivery.
	Improve data quality.	Data quality is the biggest challenge for enabling integration. It is foundational for most opportunities raised here.
P5	Feed environmental models into Environmental Led Design.	This would identify new trade-offs at an early stage.
P6	Better identification of ground risks for construction and infrastructure linked to cost models/ business case.	Aligned to major infrastructure strategy; build back better. Better lifecycle costs. Less delay/over costs in projects.
	Identifying options for use of geological natural capital through planning and design, e.g. materials re-use; suds	We focus on risks not opportunities. Need to make sure we are identifying early on where we can design and plan better for green futures.
	Enabling better use, re-use, access to data that isn't always discoverable - derive more value from our data.	A lot of data is available but not always in the right formats, not discoverable and is not used in decision-making. Improving data and model delivery and integration means we can make better use of the knowledge we have.
P7	Closer model coupling between asset and environment.	Influence design earlier, proactively and seek more opportunity rather than just mitigating the worst effects.
	Interdependencies between disciplines.	Understand and prioritise most complex issues.
	Identify gaps in open and accessible data.	Close knowledge and data gaps.
P8	Data sharing.	Increase scope and save time.
	Better trade-off assessment.	Because there is very rarely a single best solution - an option has advantages and disadvantages.
	Consistent national coverage.	Administrative boundaries or variable survey effort can be a big problem.
9	Cross-validation and competition of models.	Competition leads to efficiency and accuracy.
	Quicker policy response in emergencies such as Covid.	Conventional approach is in strain in light of crisis
	Balancing the need for economic growth and environmental sustainability - developing mitigating measures if necessary.	Planning often see no single optimum - mitigating measures based on quantified impacts are essential.
10	Participatory design of integrated models.	Already lots of interest/demand from policy decision-makers. Transdisciplinary co-learning. Decision-makers more aware of interactions.
	Collaboration with other disciplines opens up new ideas.	Need to recognise others' disciplinary perspectives as well as our own disciplinary capabilities, biases and limitations in order to advance model integration (this needs long-term funding!)

	Improved collaborative environments to facilitate model integration.	Needed so we don't all continually reinvent the wheel! Make model coupling easier and more accessible.

A picture was beginning to emerge at this point in the first session of two disciplines with many shared challenges and priorities, both technical and systemic. There was a clear opportunity to learn from each other. The question remained, however, of what the benefits of bringing these two disciplines together through integrated models might be to wider society.

Part D - What benefits could this bring to people and society?

After a break, the 10 participants broke into two groups to discuss each of their top opportunities with a premade framework (Fig. 5).

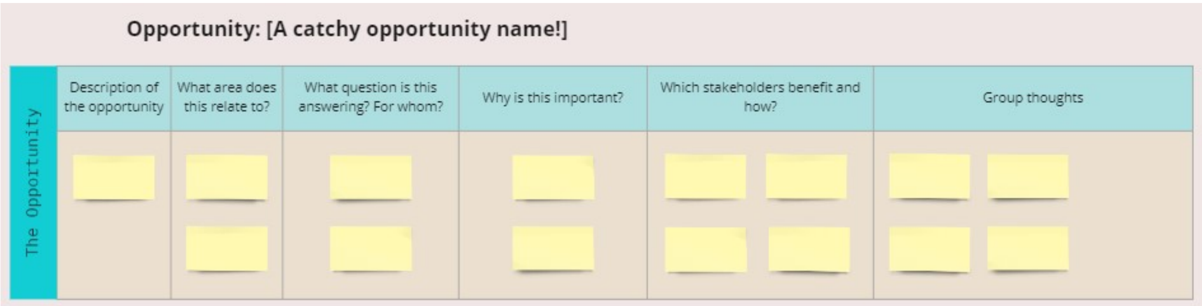

Figure 5 - Blank opportunity sheet that participants used to discuss opportunities in groups.

These opportunities fed into the work participants did between sessions and discussed at the beginning of Session 2, so the individual opportunities will not be discussed in depth here. As this was the first major opportunity for participants to share their ideas at a bit more length, however, the main ideas of the discussion are relayed here.

In the first group, the discussion of the opportunities flowed neatly into one another as if describing parts of an interdependent system. Two participants focused on data quality and accessibility, two on the processes by which decisions are made, and one on better outcomes from using data integration to better understand complexity. The participants agreed that each of these opportunities supported the others in a symbiotic system; ideally we need to do all of them well.

The second group's opportunities ranged from participatory design, interdisciplinarity and data sharing, to identifying environmental risks and integrating environmental value into BE decision making. Discussions here focused more on the complex processes and systems about which – and through which – decisions are made.

By the end of Session 1 there were multiple divergent opportunities that had been identified at varying levels of detail, each fitting within one or more of the four themes (Table 2). Participants had described context for model integration across the BE/NE divide, the breadth of relevant stakeholders and had initial ideas about the priorities for greatest impact as they headed into their independent 'homework' between the two sessions.

Session 2

The second session of the workshop took place about a week after the first, and with most of the same participants. After a reminder of the purpose of the workshop and a summary of the key insights from the previous session, participants who had completed it were invited to present their 'homework', opportunities for integrating models that they had filled in with more detail after the first session.

Part A – Exploration of opportunities

The opportunities that participants brought up were not what the facilitators had expected, but were more valuable because of that. Starting with the question from Session 1, *'What benefits could this bring to people and society?'*, the facilitators had expected the participants to suggest more specific examples of possibilities when joining up a specific type of model from the built environment (e.g. traffic patterns) with a specific type of model from the natural environment (e.g. animal movement models), and specific questions that could be answered by doing so (e.g. 'How would restricting motorway traffic in this area impact badger population health?').

Instead, participants identified a gap in knowledge about what data and models exist in other sectors, the quality and scales they are available at, and how to access them. The opportunities they discussed, therefore, focused more on general capabilities at the level of decision-makers, designers and model users. The discussion touched on the need to ask specific questions – such as the ones the facilitators had anticipated – as a prerequisite to joining models together. The consensus was that problems, questions and needs should drive integration, rather than the other way around, but that the activity of setting these questions was framed as at least one step further along in collaboration than the current workshop. It is an area of future work that would have enormous potential value and could take place in multiple contexts and multiple scales.

The opportunities as they were presented, and the ensuing discussions, are captured here in full.

Opportunity 1: Co-designing integrated built-natural environment models with stakeholders

Description: Participatory design of integrated models, involving policy decision makers in the design of the integrated model to ensure it is relevant to their decision-making context and will be used. This is about cross-sectoral, systemic decision-making, and could help with policy design and implementation.

Why is it important?: There is already lots of interest and demand from policy decision-makers. Transdisciplinary co-learning. Decision-makers more aware of system interactions. Integrated model actually used in anger to inform policy design and implementation.

Stakeholders: DEFRA, devolved authorities, farmers, land owners, citizens (through public good), species, ecosystems

What is needed?: Brainstorm specific cross built-natural environment stakeholder needs, source long-term funding, raise awareness of benefits of transdisciplinary learning to gain buy-in from stakeholders across domains (e.g. Rural Economy and Land Use programme – a multiple discipline funding programme), showcase examples where a decision-maker was brought into the team early.

Models needed: Depends on the stakeholder need. Natural environment data could be land cover, soils, protected areas, economics. Models could be agricultural farm-scale models, tree and forestry models, species/biodiversity models, water resource, quality and flooding models. (Methodological and technological developments are also needed to underpin this.)

Initial steps toward opportunity: Further specify the problem through workshops, hold follow up workshops/events to further involve relevant stakeholders, apply for funding to realise the specific opportunities for model integration.

Discussion:

- Whose KPIs move as a result?
- Catchment Based Approach (CaBA) as an example. Needs to bring in differences between city catchments and natural catchments.
- Solving common problems in cross-sectoral, environmentally-led ways, e.g. traffic congestion, air quality, wellbeing, community. Could be used to look at multiple pressures acting on cities/communities downstream.

Opportunity 2: A platform for systemic evaluation of the environmental and social costs/impacts of planning decisions

Description: A platform for making better planning decisions by systematically evaluating the environmental and social costs and impacts of planning decisions. This is relevant to infrastructure sectors such as housing, and the broader sustainability policy agenda. It can answer key questions for national and local planning authorities such as 'Will the housing crisis be solved by boosting housing supply with the government new dwelling target through the planning system? What will the environmental cost of this achievement be?' and will assess the true environmental and social costs behind 'build, build, build'. It should take into account the agricultural and natural land resources lost, soil sealed under the urbanised land for housing, transportation, and other infrastructure, urban heat island effects and climate change, biodiversity loss, buran sprawl and resulting commute times/footprints, driving lifestyle and health consequences, wellbeing reduction due to the reduced urban green and blue, etc.

Why is it important?: It would reform the planning system dramatically. COVID, like all previous economic crises, is causing more financial incentives for building, localising and deregulating the planning system, putting the environment and social outcomes at risk. Accounting for multi-dimensional environmental and social costs/benefits, and comparing that with the immediate economic benefit may influence the planning decision to build on agriculture and natural land, the value system of the planning system to prioritize economic and immediate political gain so that new sustainable alternatives are sought.

Stakeholders: National and local regulators and planners, home owners, local communities, the general public, future generations.

What is needed?: Systematic evaluation method for determining social and environmental costs, participatory and crowdsourced information platform for local and citizen knowledge, high quality and consistent land use and land cover (LULC) data covering a long time period. (Discrepancies exist in open datasets, leading to inconsistent or even wrong research conclusions, so a data assurance process would be needed for this platform.) Influence the value framework of the planning system to use economic and political gain as an incentive for new sustainable alternatives.

Models needed: GIS information layers on local, regional and national scales; planning boundaries and residents' work, commuting, home choice to identify mismatch; better integration of different scales of planning, e.g. a way of identifying the missing regional strategic planning that cannot be realised by local planning authorities.

Initial steps toward opportunity: Interdisciplinary understanding and cooperation to bridge gaps among different research realities and methodological silos; combine domain knowledge and existing methods; identify and address conflicting policies.

Discussion:

- Crowd-sourced datasets could be interesting/useful for various questions when considering the total cost of green/blue space loss.
- While 'Citizen science' data is also used a lot in the natural environment, data-to-data integration is problematic when taking account of potential bias/quality issues.
- Also a great opportunity to link into the social value frameworks and be able to use the models to start a dialogue with communities.
- Need to ask the question, 'Do we need the new-build housing?' if other ways of meeting the need at lower environmental cost are available. This goes beyond NE/BE modelling to behaviour and culture change in planning.
- Is there a common methodology for calculating the total cost of housing that policy people recognise?
- 'We recently modelled the effects of government projections for future housing needs (with other assumptions that led to increases in agricultural land as well) in the UK and this led to the loss of all unprotected natural land by 2030! (see FABLE consortium)'

Opportunity 3: Cross-validation and competition of models

Description: Sharing models may be difficult, but model outputs could and should be comparable and falsifiable, e.g. by providing the elasticity or uncertainty of key model variables and model assumptions. Among all relevant digital twin models, there should be a system using cross-validation and competition to encourage data/model quality, and ensure that we use models and datasets that are fit for purpose.

Why is it important?: Competition leads to efficiency and cost-effectiveness, e.g. coordinating data collection schemes across stakeholders and projects. It would avoid monopolies within data silos, enhance trust between modellers and users, and aid knowledge discovery, answering questions of what can be modelled and how. Model integration has to reflect how people work on the front line.

Stakeholders: Data modellers, model clients, enterprise architects, local authorities, society.

What is needed?: Legal frameworks for sharing input data across models; sharing model outputs, underlying assumptions, sensitivity test results etc.

Models needed: Users need to understand key inputs/outputs rather than the whole structure. Models should be targeted, not generalist.

Initial steps toward opportunity: More meta-analysis of sectoral models, leading to: identifying key variables for evaluating sectoral models (e.g. in transportation, the price elasticity of demand for cars), and developing high-level guidance for model development (e.g. WebTAG). A culture of sharing assumptions underlying models, and their boundaries/limitations is very important to trusting models for integration.

Discussion:

- Meta-data and ontologies are critical underlying support for model integration.
- Transparency in model documentation and assumptions is key to integration and ensuring replicability. This may look like a transparent, practical matrix to evaluate models from whatever sector is needed.
- This process should be problem-driven or policy-led to ensure model integration will be effective: 'I think a way of simplifying models (very important to avoid the "integronsters" (Voinov)) is to make them quite targeted on specific questions at the outset. That will help with figuring out key variables that need to be integrated.'
- It is also important to consider what level of integration is actually required, i.e. transfer of data, direct links, feedbacks, etc.
- Tag models, not people: 'I think there is a lot to be said for flagging common models, and/or datasets and/or projects that exist across the disciplines, rather than just people, as a resource for encouraging collaboration.'
- Open source resources came up again – as more people use Open Street Map and other API-based sources, it may become easier to integrate models as the data we're working with will be similar.
- During this discussion, the participant remembered the brief – opportunities for cross-sectoral model integration and realised that creating an interdisciplinary community was at the heart of this opportunity, stating, 'Before you can integrate the data, you have to integrate the people.'

Opportunity 4: Infrastructure BFG (Better, Faster, Greener)

Description: Model integration should enable better identification of environmental risks for construction and infrastructure linked to cost models/ business case. 'Better. Faster. Greener.' This should be extended to include environmental opportunities - aligned to the Enviro-led design opportunity proposed. This can be used in the infrastructure planning and investment sector to improve design and maintenance. For asset owners, this would address design options and lifetime management. For investors, it would present options that are financially viable and identify investment risks. For contractors and consultants it would optimise ground investigation and construction, offer better control on timelines, costs and risks. For all parties, it would enable better early-stage awareness of risk and cost, design optimisation (e.g. environmentally sensitive design), and infrastructure resilience.

Why is it important?: It is aligned with UK infrastructure strategy ('Better, faster, greener', 'Build back better' and 'Levelling up'), supporting faster, greener planning, better construction and lifecycle costs, less delay or over-costs in projects, and innovation through digital technology in the construction sector. It supports decision-making in which environmental matters are front-loaded. It would create a shared model to communicate decisions across and between discipline experts.

Stakeholders: Contractors and consultancies; wider BE community on future projects (as better models exist); planners, through more efficient processes, more confidence in decisions; asset owners through better design, better investment decisions and improved resilience of assets; the natural environment and environment sector, through better use of data and models, increased awareness of environmental interactions with infrastructure.

What is needed?: Gather intelligence from recent government reviews (Project Speed, New Construction Playbook, National Infrastructure Planning Reform). Explore where on the infrastructure life cycle data and models are needed. Explore links between the ground models (2D, 3D, 4D), environmental models and infrastructure models, identifying specific challenges with different scales and levels of detail (linear vs. spatial, site to region scale). Buy-in from people: infrastructure project owner/funder, contractor, ground engineer, environmental specialist, data or model owners. Funding mechanism and licensing policy that allows public-private-academic sectors to co-develop on equal terms. A project to trial and test methods.

Models needed: Ground models at site-regional scale (2D, 3D, 4D); environment and climate models at site-regional scale (2D, 3D, 4D); infrastructure BIM models, accounting for multi-hazard and linked hazard, risks and benefits; cost-benefit models.

Initial steps toward opportunity: Better awareness of what types of environmental models can help address questions in the different stages of infrastructure planning, construction and maintenance. Review the current use of and barriers to integration of the various models, e.g. scale, accuracy, technical, licensing, etc.

Discussion:

- Strong links with Opportunity 1, but more targeted on identifying risks and other things that might cause delays. This is less a technical problem and more a problem of how people work together to share data and identify common risks.
- Scale is key – local vs. national scales have conflicting risks, e.g. a linear asset passing through lots of local areas but providing national services. There are not many examples of this working well, especially capturing local character as a receptor in models.
- Need to target models to specific questions to deal with the complexity.

Opportunity 5: Collaborative platform for model integration

Description: Collaborative environment for datasets and models that all domains would be able to use, integrating BE and NE models. It would enable more questions to be asked, such as ‘How do we identify hidden interdependencies between systems (transport, energy, environment etc.)?’, potentially using connected digital twins across sectors.

Why is it important?: This platform would enable interdisciplinary work, facilitating the exchange of datasets and models between research groups. It is essential for developing federated digital twins.

Stakeholders: Researchers/academia, modelling communities, decision makers.

What is needed?: An online platform for data and model sharing, with: data quality guidelines, secure repository for data and models; controlled access; and the ability to integrate all relevant datasets and models.

Models needed: Not explored.

Initial steps toward opportunity: Initiatives like DAFNI are the foundation. Consistent ontologies across sectors, focus on data quality rather than quantity, academic projects should have the publication of the model as an objective/output, funding for implementing and publishing models.

Discussion:

- DataLabs are a similar collaborative environment being developed and tested with NE cases. They are a configurable coupling framework within a virtual lab environment to make it easier to run models in the cloud, couple models, access statistical and visualisation tools.
- 'Agree that it is the models and not just the data that need to be shared. Not sure that DAFNI has cracked that.'
- Open access is key to sharing of knowledge, data, code and functions that facilitate model integration.
- Also needs different functions to make model coupling easier and more automated.

Opportunity 6: Environment-Led Design

Description: Environmental assessment of design is often reactive. Work done in the early stages (e.g. Strategic Environmental Assessment) often fails to be capitalised at design stage. A left shift of environmental assessment to identify constraints and opportunities that inform scheme outcomes prior to design could significantly improve the environmental outcomes, reduce the design cycle churn of design mitigation of unforeseen issues and speed up planning consent and programme. In the infrastructure and urban planning sectors, this can answer questions such as 'How can we reach net zero through environmental led design?'

Why is it important?: By identifying new trade-offs at an early stage and pre-empting decision-making, environment-led design would create an opportunity for better outcomes from infrastructure investment, identify and close gaps in data openness and access, and help decision makers balance conflicting needs for service growth and environmental preservation. It would help environmental data and modelling influence design proactively for sustainability, and provide opportunities for greener infrastructure rather than just mitigating the worst environmental impacts. Furthermore, there are benefits to long-term resilience and maintenance with this approach as well.

Stakeholders: Local communities, especially in ecologically sensitive areas, asset owners, regulators, designers, non-human receptors of impact (e.g. flora and fauna), planning authorities, construction contractors.

What is needed?: Key stakeholders – asset owners, planners, regulators, EIA consultancies etc. – need to buy in to this approach. Furthermore, we need to better understand gaps in open available data, and improve the integration and interoperability between CAD and GIS models, as well as value models. For example, while property value and flood modelling are currently used interoperably, this process needs to be improved and extended.

Models needed: Health of environmental assets/receptors and their processes (environmental asset data model); design data models; broad range of other environmental models, e.g. flood risk, air quality, soil quality, ecosystem health, contamination etc.; models of demand for ecosystem services. Integration of these models would enable better exchange of data from infrastructure and environmental assets in the decision process of exploring development and land use options.

Initial steps toward opportunity: Development of a schema for environmental assets; break down of blockers to CAD/GIS interoperability; identification and exploration of the opportunity to influence an asset cycle to better understand when intervention is required.

Discussion:

- The key issue is that this is not currently considered up front, either in the processes or culturally. This makes it a big shift from current culture and practice.
- Better design up front allows planning for maintenance, which also needs to be embedded in the cost model of projects. Reflection from environment community: 'Are we good enough at presenting information to the built sector so they embed it in cost models?' How do we communicate the value of the natural environment to built environment professionals? How do they value it in their business case?
- Could environmental destruction be avoided if impacts were considered earlier in major infrastructure projects such as HS2?
- Data needs to be available to planners earlier. However, 'One thing we are learning on the NDTp is that the availability of data does not fix the processes associated with decision making.'

Opportunity 7: Environmental monitoring of scheme performance

Description: Monitoring of environmental performance after a scheme is built is poorly done due to the lack of data and will. Digital twins offer the opportunity to cheaply and effectively monitor environmental promises made at planning and optimise operation to maintain or enhance environmental performance. When projects get to the operation and monitoring stage, this would be an opportunity to ensure adherence to regulations and quality of performance. Leading on from environment-led design, it would address the question, 'Have the environmental promises and conditions made at the planning stage been executed during construction and operation?'

Why is it important?: Currently, the environmental monitoring of scheme construction and operation is not effective at ensuring meaningful compliance to regulations and standards of sustainability over the whole life.

Stakeholders: Regulators; model developers; asset owners; construction contractors.

What is needed?: Right-time, low-cost sensors could be utilised to help monitor asset performance through digital twins. Environmental asset models of receptors could be used to verify actual impacts and tie into a right-time digital twin of environmental performance. Integration of these models to link scheme performance directly to environmental performance (looking for cause/effect relationships and predicting lifetime environmental impacts).

Models needed: Various. Some good initial examples could focus on air or water quality in the area local to a built asset.

Initial steps toward opportunity: There is a need to understand what is being done in this space already, e.g. a state-of-the-art review. A lot of BE digital twin work is in this area - operations - but does not touch on environmental impact in a meaningful way yet. There is the aim of reducing energy/water use, increase efficiency and elongate life, which is implicitly better for the NE, but other impacts are not measured in an operational digital twin yet.

Discussion: This opportunity was not discussed with the group for the sake of time, and because the contributor had already shared an opportunity.

Part B – What is needed to unlock these opportunities?

After hearing from each participant and discussing their opportunities, the group used post-its on four boards to explore the question above from four different angles, each with different prompting material, listed below:

- *What is important for realising opportunities of model integration?* (e.g. user interfaces, model governance, connections, reporting, evolving questions, flexibility, data availability)
- *What technical modelling and data aspects need to be considered?* (e.g. quality, common standards, terminology, scale matching, security)
- *Which different stakeholder groups need to be engaged and on board?* (e.g. funding, access rights, champions, promotion, teams, influencers, organisations, ownership)
- *What else is important to make this happen?* (e.g. stakeholder enrolment, visible champions, platforms)

Over a break, the facilitators grouped these answers into thematic categories for easier voting.

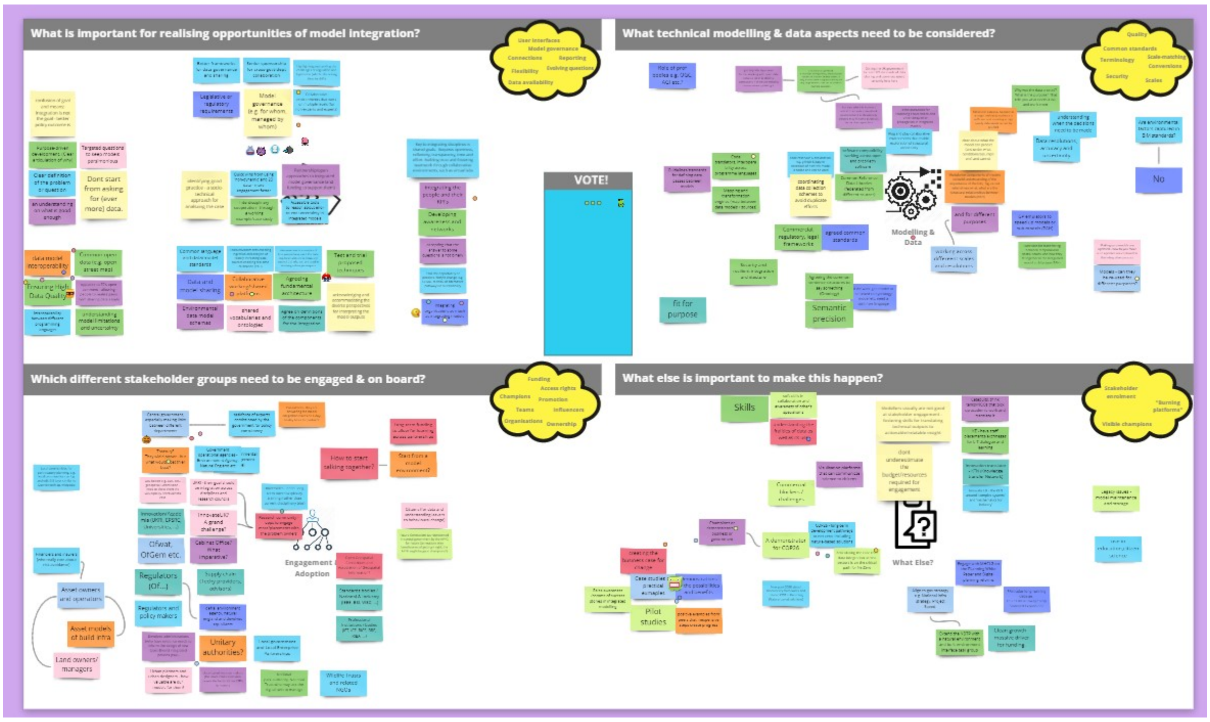

Figure 6 - Long term priorities boards with votes

Important opportunities for model integration

Many of the same themes came up here as in the earlier discussions. For example, several people pointed to the need for targeted, clearly defined questions as the initial basis for model integration, as well as for governance and funding incentives to support the work of integration. Finally, an interdisciplinary community and shared examples of good practice rounded out the general, non-technical enabling factors.

Many of the answers also centred around data quality, data-model interoperability, uncertainty and transparency. Others focused on systems, ontologies and other architectures for sharing data, models and discipline vocabularies.

What technical modelling and data aspects need to be considered?

These technical requirements were explored in more detail in this second frame. The comments are presented here as a list of system requirements with brief discussion where it is beneficial:

1. Fitness for purpose – this links to the notion of starting from a clearly defined question
2. Understanding when the important decisions need to be made – this links to the idea of environment-led design
3. An ecosystem of open, transparent, quality assured data as standard at various scales and resolutions
4. Coordination of data collection schemes to avoid duplicate efforts – the idea of not reinventing the wheel came up frequently, and there was the sense that good work and valuable models were not visible or accessible enough
5. Collaboration with organisations collecting business-critical data that is useful in answering key questions through commercial and regulatory frameworks
6. Mapping and transformation engines – ontologies with semantic precision/common languages and vocabularies, and common Reference Data Libraries (federated from different sources)
7. Ability to work across different scales and resolutions, and apply data to different purposes
8. Secure, resilient architecture/data/models
9. Techniques and tools for reasoning about end-to-end uncertainty and error propagation in interested models – ensuring clarity about what models can and cannot predict, and under what conditions/assumptions
10. Guidelines, standards and definitions for data passing between models
11. Ensuring updates to models are captured in the integration process
12. Transparency around the use of models for purposes other than those for which they were created
13. Software compatibility – working across open and proprietary software across disciplines
14. Plug-and-play collaborative environments that enable exploration of structural uncertainty – a shared platform or other collaborative environment would be an essential enabling factor
15. Modularise components of models to build understanding of the importance of the components, figure out causal and structural relationships between models/phenomena
16. Capture environmental impacts in BIM frameworks.

This list reflects commonly cited technical enablers, including shared platforms for model integration, which are characterised in CEEDS (2020) as follows: 'Various building blocks for facilitating the coupling of models could be offered within such environments: shared vocabularies and ontologies, interoperability across programme languages, functions for transferring between temporal and spatial scales, Bayesian backbones for reasoning about uncertainty, and services for creating model emulators, supporting data assimilation, or enabling plug and play of models within coupled model frameworks to analyse structural uncertainty.'

Which different stakeholder groups need to be engaged and on board?

For this frame, participants came up with a large and varied cluster of central, devolved and local government bodies and regulators, NGOs and central research funders. Participants pointed to the idea of grand challenges and appealing to funders' priorities, as well as the need for the research community to engage more and have placements with the 'owners of problems', i.e. the regulatory bodies who have responsibility for issues such as flooding, housing, biodiversity, food provision, energy and so on.

One participant noted here that the models created need to be valuable to decision-makers at all levels: to planners and designers, asset owners and operators, and landowners and managers at various scales, from the National Trust to small holdings. It was also noted that a useful change at the level of central Government would be to enhance links between different departments, perhaps through a taskforce of experts commissioned for policy consultancy and given access to integrated modelling to answer key policy questions. Professional bodies and standards development bodies are another arm of governance stakeholders, this time representing and codifying the collective expertise of practitioners.

Just outside of the governance cluster of answers were the local communities effected by interventions should be involved in participatory planning. The example was given that, 'Local communities can log and edit GIS layer[s] similar to Open Street Map, Wikipedia'. Citizens, including future generations, were noted as key stakeholders in the outcomes of this work, and so should be represented in decision processes.

Also linked to the policy stakeholders through funding are higher education and research institutions, which need to embed interdisciplinary training in programmes so that experts learn to supplement their own knowledge and methods with a more diverse range of collaborators.

A participant asked in this frame, 'How to start talking together?', and was answered with the repeated suggestion of a data and model sharing environment, and 'long-term funding to allow for learning across partnerships'.

What else is important to make this happen?

The final frame in this activity was to catch any other ideas that had not already come up from the previous prompts. The volume of material generated here was smaller, but the voting showed that some important ideas came up in this final prompt, most of which related to communication, alignment, engagement and demonstrating value to a wider audience.

The key grouping here was in awareness-raising and creating the case for change. Participants listed ideas such as success stories, pilot studies, positive peer examples showing low-cost, champions, high-impact changes, demonstrators of benefits, and business cases. Connected to these industry-focused examples, participants also suggested champions in government and demonstrators targeted at important policy milestones like COP26. These would address the commercial and policy blockers to model integration. One participant characterised this category of enablers as, 'Articulating the case that data integration across sectors is on the critical path for NetZero,' reiterating the idea that aligning with one or more policy goals is vital to secure long-term funding.

Another category of contributions focused on skills, including soft skills around collaboration and awareness of the expertise of others. Understanding the strengths and weaknesses in one's own data, metrics and assumptions was seen as another essential skill. Communication as a skill was seen as something that modellers often lack, and it was suggested that 'fostering skills for translating technical outputs to actionable/relatable insight' would be essential for enabling model integration. This quote also highlights the need to communicate the value of integrating environmental models to decision-makers in the built environment.

The shared platform came up again in this section, this time with a science communications focus. Visualising models in ways that can help citizens understand the evidence behind decisions would be an important part of getting community stakeholders on board. Another participant warned, 'Don't underestimate the budget/resources required for engagement.'

Participants noted that the interface between built and natural environments is relevant to multiple long-running debates on infrastructure projects. Interdisciplinary modelling including citizen and environment stakeholders could help resolve some of these disputes. Aligning communication about interdisciplinary modelling with goals such as clean growth and digital planning reforms could help generate the long-term funding needed in this area.

Organisations that specialise in translating academic work for policy and industry audiences would be vital for this communication work, for example the Catapults, NGOs and think tanks that work in relevant areas. Innovate UK's Knowledge Transfer Networks were another avenue identified. Formal programmes of knowledge exchange via placements and exchanges would help with the longevity of cross-sector collaboration.

Finally, there was a note about legacy issues, such as model maintenance and storage, that had not come up previously. Who owns and manages models, who ensures they are up to date, who is responsible for models at all stages of the data lifecycle and the asset lifecycle, remain pertinent and unresolved questions.

Part C – What should we focus on now to get started in the short term?

After participants reviewed the responses, they took a vote on priorities for short-term focus for making integrated built and natural environment modelling a reality. In the short term, the following were determined to be the top three short-term actions:

1. Formulate clear but flexible questions
2. Raise awareness and recruit champions
3. Work collaboratively, supported by a shared platform and integrated tools.

Formulate clear but flexible questions

Rather than beginning with integrating models simply because the data is available and they can be joined up, the participants agreed that it is better to begin with clearly articulated questions. This serves the purpose of helping define who the stakeholders are and dictating the course of implementation, as well as creating a compelling hook for decision-makers and other stakeholders. To achieve this, decision-makers and modellers together need to articulate their problem statements. However, the questions should be flexible enough to continue to be relevant as insights improve.

Raise awareness and recruit champions

Successful case studies and examples will help articulate the art of the possible, demonstrate the benefits and accelerate change. Business case templates, implementation roadmaps, use cases and other tools, publicised and spread by champions, help make integration feel more accessible. These champions should be people with the skill to build trusted relationships, foster respect among colleagues from different disciplines, and communicate benefits clearly to get a broad range of stakeholders on board with a common vision.

Work collaboratively, supported by a shared platform and integrated tools

There was the sense among the participants that there was a great deal of reinventing the wheel across different sectors, and that better collaboration, enabled but not led by digital tools, would give better visibility to relevant work happening elsewhere. Existing platforms for data sharing could be reviewed and considered. Practitioners, decision makers and other stakeholders should be involved from the earliest stages of projects to help frame the questions and test the models. Finally, community-driven guidelines, such as plain and respectful language as standard, should enshrine values and a vision for collaboration.

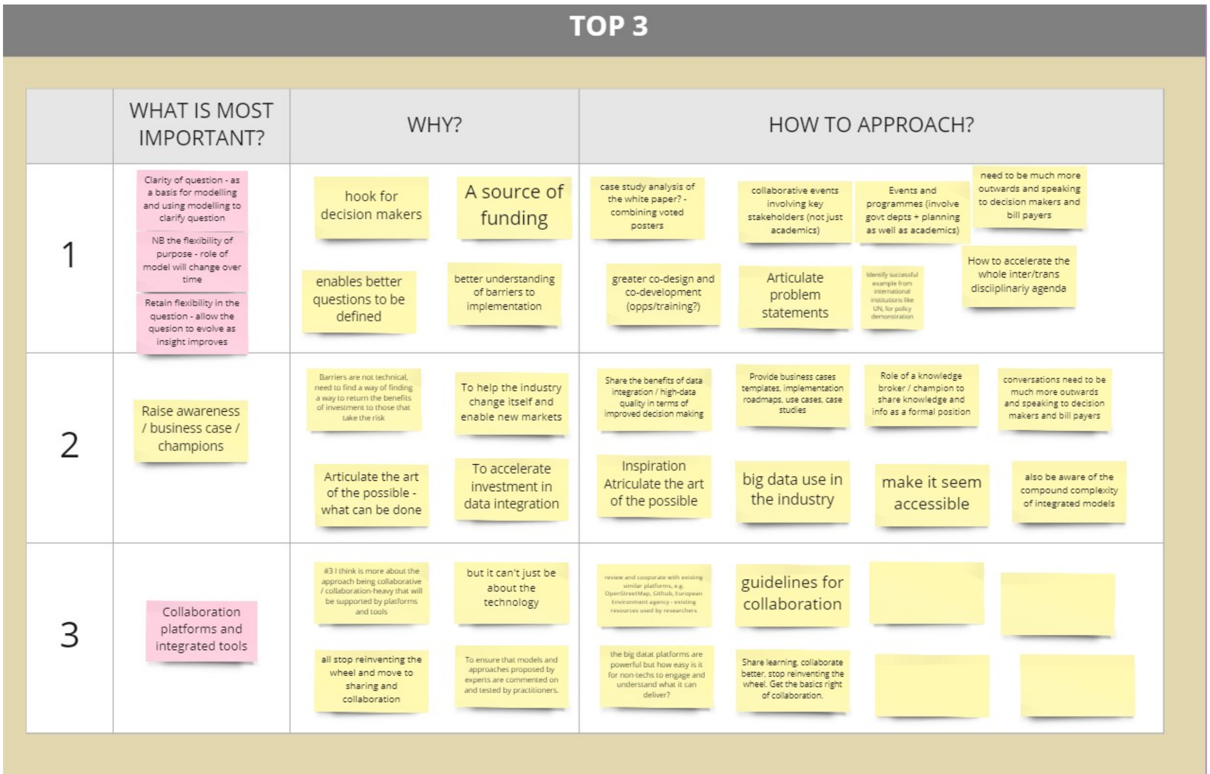

Figure 7 - Top three short term priorities board with all participant comments

Part D – What will ultimately lead to the greatest impact and success in the long term?

For the second vote, there was very little difference between the third and fourth most popular choices, so both were included to make a top four list. Longer term, the most important factors for positive changed were identified by the participants as:

1. Integrate governance, sponsorship, partnerships and consortia into a cross-functional collaboration
2. Raise awareness through visible demonstrators and business cases
3. Develop common standards for data interoperability and quality across sectors
4. Usher in culture change and effective processes and tools for collaboration

These need to start happening early in the integration and collaboration process, and to be iterated and scaled up over the long term.

Integrate governance, sponsorship, partnerships and consortia into a cross-functional collaboration

Participants agreed that platforms and processes that facilitate collaboration were essential long-term enablers for model integration. They described a collaborative environment that frames good questions; makes data and models visible, usable and adequately contextualised (with information about the limitations, assumptions and uncertainty embedded with the models); funds collaborative work; enables a cross-disciplinary community that builds mutual understanding and respect while developing shared architecture and vocabularies for model integration; and incentivises community participation and diverse inputs into decision-making processes.

Raise awareness through visible demonstrators and business cases

The cultural and structural changes required to bring this collaborative environment into being require cross-sectoral buy-in. This means that business cases, pilot studies and other ways of raising awareness and demonstrating value are vital. This is a long-term requirement, with different demonstrators being required at different stages of iteration.

Develop common standards for data interoperability and quality across sectors

Another long-term priority is to create common standards for processes and shared data environments across sectors. Participants pointed to the idea that better data quality resulting from common standards leads to better information, better decisions, better interventions, and therefore better outcomes. Open standards would help remove barriers to good data, and provide demonstrators that help usher in the necessary culture change.

Therefore, data quality standards are fundamental to model integration. While standardisation is already well underway within sectoral siloes, for example in the BE and business information world in which the NDTp operates, there is a short-term need to start working with collaborators outside those silos to develop cross-sectoral data standards, vocabularies, ontologies and other information architectures that enable interoperability and integration. The participants discussed how the quest to get common standards 'right' will likely never be finished, and that standards development is currently a slow process.

To hasten this process, participants pointed to options to adopt open standards from the USA, and leverage standards from existing communities. There is also the need to advocate and support a culture shift towards data quality and sharing where it is appropriate. According to one participant, this looks like an articulation of, 'what it takes for organisations to originate, manage and share high quality data'.

The discussion turned to existing open data platforms like Open Street Map, whose data was considered of insufficient quality for some needs. The response was that it was therefore even more important for UK datasets to be fully open and maintained as a key government priority.

Usher in culture change and effective processes and tools for collaboration

Finally, the last long-term priority points to the systems and cultures needed to enable collaboration. Interdisciplinary work across built and natural modellers happens currently, as discussed in Section 1, but the processes and tools for collaboration are not optimised. This priority encompasses what the participants termed environment-led design: there is a need to change the culture, processes and tools available to decision-makers so that they have the right information at the right time to identify critical trade-offs and opportunities to balance the management of the BE and NE.

The barriers to collaboration are well known across multiple sectors, but throughout the workshop the participants offered examples of how they might be overcome. Communicating and articulating the case for doing model integration and collaborative decision-making well, to different audiences, over and over again will help to change the existing cultures to be more collaborative. In the interim, putting together other enablers – such as a shared platform, local demonstrator projects, and bringing to together a diverse group of stakeholders to develop compelling questions – could help to accelerate the integration of models across disciplines.

Workshop wrap up

The final part of the workshop was to recap the ideas generated, discuss next steps and gather some feedback. The feedback is presented here to share the impressions of the participants about the interdisciplinarity and format of the workshop, as well as the actions they personally were excited to take.

Figure 8 - Participants were asked 'What was the most surprising thing these workshops raised from your perspective?'

The first wrap up exercise asked participants to name something that surprised them. A common thread was identifying shared issues and challenges across disciplines, and across the academic/industry divide. There was reflection on the long-term nature of goals such as governance and funding, as well as the technical challenges to integration. Finally, one participant noted the importance of framing questions in model integration as their key take away from the session.

Figure 9 - Participants answered the question, 'What is one action you want to take?'

The second question was about actions participants wanted to take as a result of the workshop. The answers here point to the energy and excitement to move forward with the interdisciplinary work discussed in the workshop. They show the interest of the participants in building a community, learning from colleagues in other sectors, and seeking funding for work that will progress the question of model integration for built and natural environment decision making. Multiple participants discussed looking for opportunities to work together, looking for case studies, reaching out and applying for funding in this area.

In answer to both questions, there was an indication from some participants that the BE modelling sector is more advanced or more sophisticated than NE modelling and that NE modellers could learn from this. However, NE modellers are more advanced than those working in the BIM and NDT areas as far as using socio-economic modelling to explore impact goes. Therefore, there is a mutual exchange of expertise that could be made through interdisciplinary collaboration, to the benefit of all.

4 – Preliminary discussion

The participant group focused on different types of opportunities, from technical to process- and people-oriented opportunities, and the resulting discussions showed strong agreement on the fact that both were important for enabling the other.

The group agreed on the importance of a **shared platform** that makes data and models from different sectors visible, accessible, and contextualised, as well as creating a gently competitive environment that cross-validates models to encourage quality. At the same time, there was agreement that bringing the **relevant stakeholders** on board early – and expanding the understanding of relevant stakeholders to be more inclusive of impacted communities – was vital to making better decisions. Finally, there was broad support for the idea that model integration should be led by **clear questions** that set the scope and context for model integration. These compelling questions may come from the usual drivers of modelling – funding agencies, governing bodies, etc. – or from other stakeholders.

All three of these opportunities – stakeholder input, access to relevant environmental models at the design stage and clear, flexible framing questions – feed into a key idea from this workshop, that of **environment-led design**. Using these three opportunities to bring environmental and social criteria into the earliest stages of planning projects, along with clear, accessible, integrated models, would help identify a broader range of options for managing the trade-offs between the BE and NE in meeting society's needs.

It is clear from these discussions that the participants saw the value in integrating data and models from across the BE/NE divide. However, they were not yet prepared to start identifying key stakeholders or framing questions that would drive interdisciplinary model integration projects. Instead, the discussion in the workshop focused on the structures, processes and investment that would enable model integration.

Therefore, the next steps identified by participants included conducting more interdisciplinary workshops and projects targeted on identifying these framing questions, developing ontologies and tools that help with model integration, and raise awareness through case studies and champions. There is a technical component to this work, but it is driven by communities of people coming together with a shared vision to gain better insights and make better decisions.

In addition to the top opportunities, other enablers were identified, such as investment in interdisciplinary projects, beginning with local-scale planning projects, broad awareness of case studies, and development of standards for data interoperability that function across sectors. The same enablers are valuable in the long-term, as each iteration, each increase in scope or geographic scale, will involve new challenges, revised standards and a broadening of stakeholders.

The open-minded, collaborative way in which the participants approached this workshop is needed throughout the integration of these modelling communities. As one participant observed, 'Before you integrate the data, you need to integrate the people'. This echoes sentiments from other authors: 'Coupling of disciplines is a prerequisite to model coupling. There is a need to really take time to communicate and understand someone's disciplinary perspective/philosophy through an open and reflexive process that builds trust around common goals.' (CEEDS, 2020)

The key insights and conclusions from this workshop are discussed in the main report.

References

Ahlborg, H., Ruiz-Mercado, I., Molander, S., & Masera, O. (2019). Bringing Technology into Social-Ecological Systems Research—Motivations for a Socio-Technical-Ecological Systems Approach. *Sustainability*, *11*(7), 2009. https://doi.org/10.3390/su11072009

Aktas, Y. D., Stocker, J., Carruthers, D., & Hunt, J. (2017). A Sensitivity Study Relating to Neighbourhood-scale Fast Local Urban Climate Modelling within the Built Environment. *Procedia Engineering*, *198*, 589–599. https://doi.org/10.1016/j.proeng.2017.07.113

Bankes, S. (1993). Exploratory Modeling for Policy Analysis. *Operations Research*, *41*(3), 435–449. https://doi.org/10.1287/opre.41.3.435

Bateman, I., Agarwala, M., Binner, A., Coombes, E., Day, B., Ferrini, S., Fezzi, C., Hutchins, M., Lovett, A., & Posen, P. (2016). Spatially explicit integrated modeling and economic valuation of climate driven land use change and its indirect effects. *Journal of Environmental Management*, *181*, 172–184. https://doi.org/10.1016/j.jenvman.2016.06.020

Benda, L. E., Poff, N. L., Tague, C., Palmer, M. A., Pizzuto, J., Cooper, S., Stanley, E., & Moglen, G. (2002). How to Avoid Train Wrecks When Using Science in Environmental Problem Solving. *BioScience*, *52*(12), 1127. https://doi.org/10.1641/0006-3568(2002)052[1127:HTATWW]2.0.CO;2

Blainey, S. P., & Preston, J. M. (2019). Predict or prophesy? Issues and trade-offs in modelling long-term transport infrastructure demand and capacity. *Transport Policy*, *74*, 165–173. https://doi.org/10.1016/j.tranpol.2018.12.001

Bolton, A., Enzer, M., Schooling, J., & others. (2018). *The Gemini Principles: Guiding values for the national digital twin and information management framework*. CDBB and DFTG. https://doi.org/10.17863/CAM.32260

Bricker, S. H., Banks, V. J., Galik, G., Tapete, D., & Jones, R. (2017). Accounting for groundwater in future city visions. *Land Use Policy*, *69*, 618–630. https://doi.org/10.1016/j.landusepol.2017.09.018

Brown, I., Berry, P., Everard, M., Firbank, L., Harrison, P., Lundy, L., Quine, C., Rowan, J., Wade, R., & Watts, K. (2015). Identifying robust response options to manage environmental change using an Ecosystem Approach: A stress-testing case study for the UK. *Environmental Science & Policy*, *52*, 74–88. https://doi.org/10.1016/j.envsci.2015.05.005

Bruce, A., Lyall, C., Tait, J., & Williams, R. (2004). Interdisciplinary integration in Europe: The case of the Fifth Framework programme. *Futures*, *36*(4), 457–470. https://doi.org/10.1016/j.futures.2003.10.003

Burnham, K. P., & Anderson, D. R. (2002). *Model Selection and Multimodel Interference: A Practical Information-Theoretic Approach* (2nd ed.). Springer-Verlag.

Carhart, N. J., & Rosenberg, G. (2016). A Framework for Characterising Infrastructure Interdependencies. *International Journal of Complexity in Applied Science and Technology*, *1*(1), 35–60. https://doi.org/10.1504/IJCAST.2016.10002359

Centre of Excellence in Environmental Data Science (CEEDS). (2020). *Report of the Online CEEDS workshop on Model Coupling*. UK Centre for Ecology and Hydrology. https://ceeds.ac.uk/sites/default/files/2020-11/Report_CEEDS_workshop_Model_Coupling_18Sep2020.pdf

Chong, H.-Y., & Wang, X. (2016). The outlook of building information modeling for sustainable development. *Clean Technologies and Environmental Policy*, *18*(6), 1877–1887. Scopus. https://doi.org/10.1007/s10098-016-1170-7

Cornell, S. (2010). Valuing ecosystem benefits in a dynamic world. *Climate Research*, *45*(1), 261–272. Scopus. https://doi.org/10.3354/cr00843

Cornell, S. E., & Parker, J. (2014). Rising to the Synthesis Challenge in Large-Program Interdisciplinary Science: The QUEST Experience. In M. O'Rourke, S. Crowley, S. Eigenbrode, & J. Wulfhorst, *Enhancing Communication & Collaboration in Interdisciplinary Research* (pp. 121–147). SAGE Publications, Inc. https://doi.org/10.4135/9781483352947.n7

Deierlein, G. G., McKenna, F., Zsarnóczay, A., Kijewski-Correa, T., Kareem, A., Elhaddad, W., Lowes, L., Schoettler, M. J., & Govindjee, S. (2020). A Cloud-Enabled Application Framework for Simulating Regional-Scale Impacts of Natural Hazards on the Built Environment. *Frontiers in Built Environment*, *6*. https://doi.org/10.3389/fbuil.2020.558706

Dent, C. (2019). *Centre for Digital Built Britain (CDBB) research network on Planning Complex Infrastructure under Uncertainty: Final Report*. Centre for Digital Built Britain. https://www.cdbb.cam.ac.uk/news/publication-final-report-complex-systems-network

Dikanski, H., Imam, B., & Hagen-Zanker, A. (2018). Effects of uncertain asset stock data on the assessment of climate change risks: A case study of bridge scour in the UK. *Structural Safety*, *71*, 1–12. https://doi.org/10.1016/j.strusafe.2017.10.008

Dittrich, R., Wreford, A., & Moran, D. (2016). A survey of decision-making approaches for climate change adaptation: Are robust methods the way forward? *Ecological Economics*, *122*, 79–89. https://doi.org/10.1016/j.ecolecon.2015.12.006

Doughnut Economics Action Lab. (2021). *About Doughnut Economics*. Doughnut Economics Action Lab. https://doughnuteconomics.org/about-doughnut-economics

Dudley, G., & Banister, D. (2018). Expertise in decision-making for large infrastructure projects: From UK trunk roads to High Speed Rail 2. *Transportation Planning and Technology*, *41*(5), 481–496. https://doi.org/10.1080/03081060.2018.1468969

Finch, T., Day, B. H., Massimino, D., Redhead, J. W., Field, R. H., Balmford, A., Green, R. E., & Peach, W. J. (2020). Evaluating spatially explicit sharing-sparing scenarios for multiple environmental outcomes. *Journal of Applied Ecology*, *n/a*(n/a). https://doi.org/10.1111/1365-2664.13785

Harrison, P. A., Dunford, R., Barton, D. N., Kelemen, E., Martín-López, B., Norton, L., Termansen, M., Saarikoski, H., Hendriks, K., Gómez-Baggethun, E., Czúcz, B., García-Llorente, M., Howard, D., Jacobs, S., Karlsen, M., Kopperoinen, L., Madsen, A., Rusch, G., van Eupen, M., … Zulian, G. (2018). Selecting methods for ecosystem service assessment: A decision tree approach. *Ecosystem Services*, *29*, 481–498. https://doi.org/10.1016/j.ecoser.2017.09.016

Harrison, P., Holman, I. P., & Berry, P. M. (2015). Assessing cross-sectoral climate change impacts, vulnerability and adaptation: An introduction to the CLIMSAVE project. *Climatic Change*, *128*, 153–167. https://doi-org.ezp.lib.cam.ac.uk/10.1007/s10584-015-1324-3

Harty, C., Goodier, C. I., Soetanto, R., Austin, S., Dainty, A. R. J., & Price, A. D. F. (2007). The futures of construction: A critical review of construction future studies. *Construction Management and Economics*, *25*(5), 477–493. https://doi.org/10.1080/01446190600879117

Heemskerk, M., Wilson, K., & Pavao-Zuckerman, M. (2003). Conceptual Models as Tools for Communication Across Disciplines. *Conservation Ecology*, *7*(3). https://doi.org/10.5751/ES-00554-070308

Hetherington, J., & West, M. (2020). *The pathway toward an Information Management Framework: A “commons” for digital built Britain*. Centre for Digital Built Britain. https://www.cdbb.cam.ac.uk/files/the_pathway_towards_an_imf.pdf

Holland, R. A., Scott, K., Hinton, E. D., Austen, M. C., Barrett, J., Beaumont, N., Blaber-Wegg, T., Brown, G., Carter-Silk, E., Cazenave, P., Eigenbrod, F., Hiscock, K., Hooper, T., Lovett, A., Papathanasopoulou, E., Smith, P., Thomas, A., Tickner, R., Torres, R., & Taylor, G. (2016). Bridging the gap between energy and the environment. *Energy Policy*, *92*, 181–189. https://doi.org/10.1016/j.enpol.2016.01.037

Howarth, C., & Monasterolo, I. (2016). Understanding barriers to decision making in the UK energy-food-water nexus: The added value of interdisciplinary approaches. *Environmental Science & Policy*, *61*, 53–60. https://doi.org/10.1016/j.envsci.2016.03.014

Kokla, M., Mostafavi, M. A., Noardo, F., & Spanò, A. (2019). TOWARDS BUILDING A SEMANTIC FORMALIZATION OF (SMALL) HISTORICAL CENTRES. *ISPRS - International Archives of the*

Photogrammetry, Remote Sensing and Spatial Information Sciences, *XLII-2-W11*, 675–683. https://doi.org/10.5194/isprs-archives-XLII-2-W11-675-2019

Liu, X., Wang, X., Wright, G., Cheng, J. C. P., Li, X., & Liu, R. (2017). A State-of-the-Art Review on the Integration of Building Information Modeling (BIM) and Geographic Information System (GIS). *ISPRS International Journal of Geo-Information*, *6*(2), 53. https://doi.org/10.3390/ijgi6020053

Moravej, M., Renouf, M. A., Lam, K. L., Kenway, S. J., & Urich, C. (2021). Site-scale Urban Water Mass Balance Assessment (SUWMBA) to quantify water performance of urban design-technology-environment configurations. *Water Research*, *188*, 116477. https://doi.org/10.1016/j.watres.2020.116477

Morse, W. C. (2014). Integration of Frameworks and Theories Across Disciplines for Effective Cross-Disciplinary Communication. In M. O'Rourke, S. Crowley, S. Eigenbrode, & J. Wulfhorst, *Enhancing Communication & Collaboration in Interdisciplinary Research* (pp. 244–269). SAGE Publications, Inc. https://doi.org/10.4135/9781483352947.n12

Nochta, T., Wan, L., Schooling, J. M., & Parlikad, A. K. (2020). A Socio-Technical Perspective on Urban Analytics: The Case of City-Scale Digital Twins. *Journal of Urban Technology*, *0*(0), 1–25. https://doi.org/10.1080/10630732.2020.1798177

RICS. (2015). *The Informed Infrastructure Client*. https://www.rics.org/globalassets/rics-website/media/upholding-professional-standards/sector-standards/construction/the-informed-infrastructure-client-1st-edition-rics.pdf

Rieb, J. T., Chaplin-Kramer, R., Daily, G. C., Armsworth, P. R., Böhning-Gaese, K., Bonn, A., Cumming, G. S., Eigenbrod, F., Grimm, V., Jackson, B. M., Marques, A., Pattanayak, S. K., Pereira, H. M., Peterson, G. D., Ricketts, T. H., Robinson, B. E., Schröter, M., Schulte, L. A., Seppelt, R., … Bennett, E. M. (2017). When, Where, and How Nature Matters for Ecosystem Services: Challenges for the Next Generation of Ecosystem Service Models. *BioScience*, *67*(9), 820–833. Scopus. https://doi.org/10.1093/biosci/bix075

Spake, R., Lasseur, R., Crouzat, E., Bullock, J. M., Lavorel, S., Parks, K. E., Schaafsma, M., Bennett, E. M., Maes, J., Mulligan, M., Mouchet, M., Peterson, G. D., Schulp, C. J. E., Thuiller, W., Turner, M. G., Verburg, P. H., & Eigenbrod, F. (2017). Unpacking ecosystem service bundles: Towards predictive mapping of synergies and trade-offs between ecosystem services. *Global Environmental Change*, *47*, 37–50. https://doi.org/10.1016/j.gloenvcha.2017.08.004

Walker, W. E., Haasnoot, M., & Kwakkel, J. H. (2013). Adapt or Perish: A Review of Planning Approaches for Adaptation under Deep Uncertainty. *Sustainability*, *5*(3), 955–979. https://doi.org/10.3390/su5030955

Wan, L., Nochta, T., & Schooling, J. (2019). *Developing A City-level Digital Twin—Propositions and A Case Study*. International Conference on Smart Infrastructure and Construction, Cambridge, UK. https://doi.org/10.17863/CAM.38703

Webb, S. (2017). Land Information Platform: Levelling the playing field. *Future Cities Catapult*. http://futurecities.catapult.org.uk/2017/10/19/blog-land-information-platform-levelling-playing-field/

Webb, S., & Bailey, J. (2017). Why planning is ripe for innovation. *Future Cities Catapult*. http://futurecities.catapult.org.uk/2017/11/07/blog-planning-ripe-innovation/

Whyte, J., Mijic, A., Myers, R. J., Angeloudis, P., Cardin, M.-A., Stettler, M. E. J., & Ochieng, W. (2020). A research agenda on systems approaches to infrastructure. *Civil Engineering and Environmental Systems*, *37*(4), 214–233. https://doi.org/10.1080/10286608.2020.1827396

Willcock, S., Hooftman, D. A. P., Blanchard, R., Dawson, T. P., Hickler, T., Lindeskog, M., Martinez-Lopez, J., Reyers, B., Watts, S. M., Eigenbrod, F., & Bullock, J. M. (2020). Ensembles of ecosystem service models can improve accuracy and indicate uncertainty. *Science of The Total Environment*, *747*, 141006. https://doi.org/10.1016/j.scitotenv.2020.141006