The Sociotechnical Digital Twin: On the Gap Between Social and Technical Feasibility

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The Sociotechnical Digital Twin: On the Gap Between Social and Technical Feasibility

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***Abstract*—The last five years has seen an exponential increase in interest around the notion of a digital twin. Multiple systematic reviews have established a base set of findings which are now broadly taken as assumptions in the field. The findings have outlined frameworks, integration patterns, distinctions between product and process oriented digital twins, simulation and the leveraging of artificial intelligence to support prediction and optimisation. As the use cases of digital twins have evolved from a predominance in manufacturing and into the sociotechnical domain to support the social world, a gap emerges between the social requirements and the technical machinery of digital twins. This gap is significant and worthy of exploration as it presents important challenges for digital twin research including use of sociotechnical design methods, problems arising from a so-called abstraction gap and various epistemological concerns. This paper proposes an analytical route to ameliorating the sociotechnical gap which is discussed within a future notion of an Environment Digital Twin.**

***Index Terms*—Digital Twin, Computational Model, Socio-technical, Abstraction**

I. Introduction

Digital twins are examples of the more general phenomena broadly covered by computational modelling. Simply put, a digital twin is a virtual representation of a real-world system capable of facilitating a bi-directional communication between the system and its digital representation. A real-world system could include entities such as physical components, systems, processes and even organisational units. Applications of Digital Twin (DT) range from manufacturing, health, oil refinery management, supply chain and physical infrastructure including city planning. Digital Twin and its position at the convergence of economics (the need for competitive advantage) and maturity of relevant technology places DT at the peak of the Gartner Hype Cycle (https://simutechgroup.com/digital-twin-technology/). This position also recognises the importance of DT to the general trend towards digitalisation [28]. The upper end of the scale of opportunity presented by DTs is illustrated through the EU Destination Earth (DestinE) project whose aim is to to develop a very high precision digital model of the Earth to monitor and simulate natural and human activity, and to develop and test scenarios that would enable more sustainable development and support European environmental policies (https://ec.europa.eu/digital-single-market/en/destination-earth-destine).

Numerous systematic literature reviews (discussed in section 2) demonstrate consistency of emerging themes around key features such as seamless connection between a real entity and the virtual twin, continuous exchange of multi-dimensional data, comprehensive descriptions of constructs, and a safe simulation environment for testing and prediction. Effectively, these characteristics and the multiple domains of use have become the underlying assumptions of this research field. As DTs have increased in usage, the domains of interest have expanded to other domains that utilise different types of underlying models. The engineering community has largely been driven by the use of underlying physics-based modelling. In contrast, the sociotechnical domain, for example in smart-city planning and more recently as a response planning tool for devising non-pharmaceutical interventions for managing the COVID-19 pandemic, DTs have moved to (generated) data driven modelling approaches that are much more susceptible to bias [35]. The shift away from physics based models has has also seen a recognition that agent based models, reflecting the increased uncertainty and emergent behaviour of sociotechnical DTs, are a more appropriate alternative to traditional physics based models. Applications of DT in the sociotechnical domain expose concerns that could be termed a sociotechnical gap [1]. It is this gap that opens up the research question of what is the form of this gap and what are the routes that can be taken to address this gap. This paper explores these research questions.

The rest of the paper proceeds in four parts. First, the paper provides an overview of the principal findings from DT research. The findings outlined are based on outcomes reported from several systematic review papers and therefore represent a consolidation of existing research. These multiple systematic reviews have established a base set of findings which are now broadly taken as assumptions in the field. Section two examines the gap arising from the move from physics based modelling to one that requires uncertainty and emergence. The gap exists between the social requirements and the technological machinary required for DT. The third section discusses potential avenues for ameliorating the emergent sociotechnical gap. Section four presents an illustrative example and discussion of the gaps focusing on the requirements of an ”Environment Digital Twin”. The paper concludes with some final remarks.

II. CURRENT FINDINGS ON DIGITAL TWIN RESEARCH

Since 2016, there has been a significant increase in research in DT, and numerous systematic review papers have consequently reported the state of the art of DT research. The review papers have identified directions of future research for the construction domain [13] as well as characterisations of DT in manufacturing [24], [29], logistics [33], cyberphysical systems [26], [38] and more generally on definitions, applications and design implications [11]. Analysis of these reviews reveals themes around key features that are summarised here.

The origins of DT are well described in any number of review papers, for example [11]. Definitions of DT vary, but DTs convey an essence of both a physical and virtual (computer based model) connected entity where the virtual model evolves and follows the lifecycle of its physical twin.

The current literature, especially systematic review papers have proposed various syntheses of predominant characteristics. These can be synthesised into four principal characteristics or features such as: seamless connection between a real entity and the virtual twin; continuous exchange of multi-dimensional data; comprehensive descriptions of constructs; a safe simulation environment for testing and exploration; and finally extensive use of AI/ML to support adaptation and prediction.

A. *Seamless connection*

A computational model, in the sense of a computer program that acts to represent and 'animate' processes of concern, is not a strictly a digital twin but is part of an evolution towards a DT. Similarly, Computer Aided Design/Computer Aided Engineering (CAD/CAE) models and simulations [27] are also not what might be described as complete digital twins. In essence then, a digital twin notion exists at various levels to allow for cases where a physical system need not exist, or where there is not direct correspondence of internal states of the physical and virtual representation. Figure 1. indicates a characterisation of DT based on seamless (possibly real-time) connection. Note that the mechanisms for *how* connection is maintained has been omitted. These types of DT bear analogy with those reported in [27] and [41]. A Real World Asset (RWA) is connected to a Digital Representation (DR) through either an automated connection/update process or a manual intervention.

Digital Blueprint: A simulation is used to construct the design of a complex system and is subsequently used as the design blueprint (forward engineering). The twin can be used to explore the space of design options. The twin is not linked in any way to the real system and is discarded once the real system is produced. We can see this as a "traditional" computational model. The synchronisations are mostly manual and there may be the application of model driven engineering principles. Design data can be synthetic.

Digital Model: A simulation is constructed from the real system in order to understand how it works, to perform maintenance, and to improve performance (reverse engineering). The

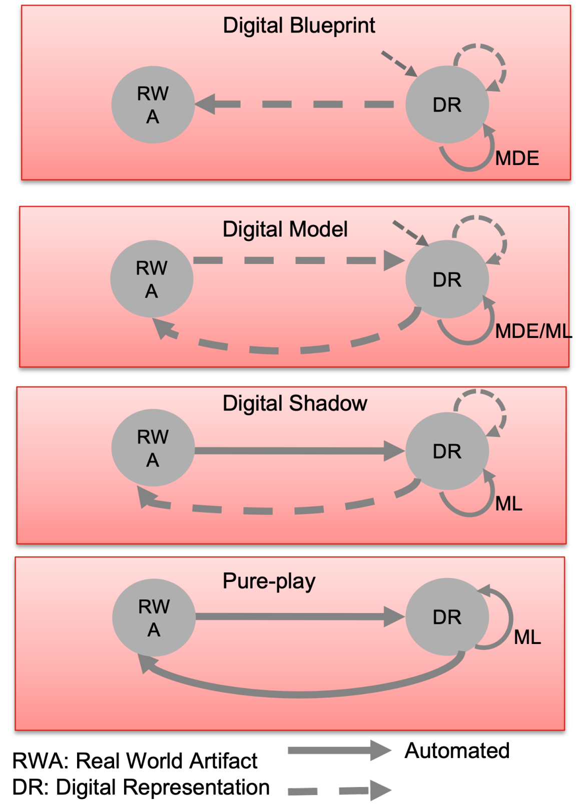

Fig. 1. Types of Digital Twin based on the level of seamless connection. Solid arrows indicate automatic update, dashed arrows indicate manual update.

twin is run against historical data produced by the real system. The insights are reflected back into the system by hand after which the digital twin is discarded. Again this could be seen as a "traditional" computational model. The synchronisations are mostly manual and there may be the application of model driven engineering principles. More advanced forms may include machine learnng to inform the development of the DR particularly with regards to self-regulation and self-adaptation. The RWA is updated manually.

Digital Shadow: A twin is created in order to run alongside the real system using data produced by the real system. The twin is used to gain insights into the behaviour of the real system and to perform what-if scenarios. The outputs from the twin are consumed by humans in order to be reflected into the real system by hand. The twin is long-lived. This type is recognisably a DT as popularized. There is periodic but regular automated synchronization to the DR and there is use of both manual methods and ML to inform the development of DR with regards to self-regulation and self-adaptation, self diagnosis and other aspects. Critically, the RWA is updated manually.

Pure-Play: a twin is created in order to shadow the real system and to control it. The twin represents the idealised behaviour for the system which it monitors in order to determine controls that are automatically injected back into the real system in order to maintain a collection of business goals. The Pure-Play DT operates as a controller of the RWA. Synchronization is regular, frequent and often in real-time and there is extensive use of ML.

As outlined above, the types of digital twin are dependent upon the types of integration between the physical asset and digitalized version. Digital twin models also depend upon a range of information models (the data requirements), the processing performed upon the data including machine learning and other types of analytical processing and the communication infrastructure (increasingly based upon IoT platforms).

B. Safe simulation environment

A feature of computational models more generally, and digital twin models specifically, is the notion of a safe environment for testing the impact of change intentions and exploratory what if scenario modelling [11]. Simulation environments integrate data collected from the existing system (real world artifact) with expert knowledge, informed judgements and even best guesses. Essentially, the simulation component provides a mechanism for theory construction and validation.

C. Constructs and Fidelity

Digital twin models require mechanisms for describing physical and functional descriptions of a component, product or system and maintaining the state of the digital twin in synchronisation with the physical model. More often than not, these mechanisms are domain specific such as that for inventories of parts of an aircraft [40]. Constructs can exist at both a specification and implementation level. In the National Digital Twin work underway in the UK, the Information Management Framework for Digital Twins developed by the Centre for Digital Built Britain refers to the collection of these constructs as the Foundational Data Model [23]. Constructs are also critical to the notion of fidelity. Fidelity describes the parameters, their accuracy and level of abstraction that is transferred between the physical and virtual environment. Fidelity of the virtual model is described as a highly accurate replication of the physical entity [24].

D. Use of AI and ML: Adaptive and Intelligent Digital Twins

Applications that have limited variables and complexity and where linear relationships between inputs and outputs are easily discoverable do not need to employ machine learning (ML). Significant advances in usefulness are possible where applications require multiple data streams and analytics to make sense of data. ML applied to data streams can be used to automate complex analytical tasks, evaluate real-time data, adapt behaviour, support decision making based on actionable insights. ML uses include: reinforcement learning in uncertain and partially observable contexts.

This analysis based on the characteristics discussed above leads to a preferred definition for Pure-Play digital twin as follows:

Definition: A pure-play Digital Twin is a self-adapting, self-regulating, self-monitoring, and self-diagnosing system-of-systems which is characterized by a symbiotic relationship between a physical asset and its virtual representation, whose fidelity, rate of synchronization, and choice of enabling technologies are tailored to its envisioned use cases, and which supports services that add operational and business value to the physical asset.

III. THE SOCIAL GAP

Digital twins of phenomena that model elements of human interaction with cyber-physical system (CPS) components are a sociotechnical system (STS) in that socio and technical elements are brought together towards some goal directed behaviour. Further, requirements of a STS span hardware, software, personal, and community aspects. System performance is dependent on joint optimisation of the technical and social subsystems and excludes focus on just one aspect [42]. The *design* of such a digital twin demands that the most important contribution of Sociotechnical Design, its value system, in particular, the rights and needs of workers and that of democracy are met [31]. Such rights and needs of the worker can manifest themselves by incorporating universal values such as privacy, security, transparency, and trust into the design process. Notions of democracy can be integrated by participatory design activities where all stakeholders are engaged in the design of system. By making sure all voices are heard, democratic design can be instigated. The principles of value sensitive design (VSD) [19] are particularly helpful here. A challenge here is that participatory, and therefore democratic engagement, in the design and use of sociotechnical digital twins remains relatively invisible. Currently there is little or no research specific to exploring value sensitive design issues in digital twin research.

Critically, sociotechnical systems acquire additional design complexity through the involvement of multiple disciplines. For example, efforts at constructing digital twins of cities to monitor pandemic behaviour [7] have included social geographers, computer scientists, economists, medical practitioners as well as computer scientists.

Further concerns arise from the complexities from the problem domain that is representative of sociotechnical requirements. Typical characteristics of a complex, real-world situation (aka system) are:

1) The inter-connectedness between systems and subsystems and where the connections lead to interdependencies.
2) The emergent behaviour of human agents that stems from basic rules which govern the interaction between the elements of a system.
3) A requirement for adaptive human agent behaviour that reacts to the environment, is self-organising, goal directed and has internal state and decision-making capability.
4) Heterogeneity - the need to recognise that there are multiple types of human agents.
5) Equifinality - the recognition that there may be multiple means of achieving system goals.

These properties are also those that are characterised by agent based systems and make such systems ideal for representation of sociotechnical DTs despite computational cost [22].

Other sociotechnical concerns including abstraction traps, epistemological concerns (validation and verification) and processes for domain understanding are the main focus of this paper.

In terms of the typology presented earlier, a sociotechnical digital twin is closest to the Digital Model type and can be defined as follows.

Definition: A Sociotechnical Digital Twin is a system-of-systems that can include a learning component which is characterized by a relationship between a real world system and its *partial* virtual representation, whose fidelity, rate of *manual synchronization*, and choice of enabling technologies are tailored to *theory exploration and explanation* and will include a mix of modeling approaches including *agent based simulation*.

A key feature of this definition is the focus on partial representation, theory exploration and the dominance of the use of the agent based simulation. The latter is important, because agent based simulation is ideally suited to understanding the human behaviour component of a socio-technical environment. Systems of systems creates a large scope of study that necessitate the specification of boundaries. Partial representation is therefore an important decomposition tool. The data generative approach underpinning simulation allows the design and testing of theories to support exploration [21].

Limitations of the class of systems that can be addressed by this definition is perhaps most helpfully addressed through experimentation and then a process of induction to determine what problems can be addressed. Prior experiments reported by the author and colleagues have explored computational models, that would fall into this definition, in a range of areas including: demonetisation in India [5] and a software services company [6]. These experiments provide some basis for the challenges described here. The Demonetisation case study for example used agent based modelling to derive emergent behaviours, and the simulations offered scope for theory based exploration.

To help illustrate the definition, consider the following sociotechnical DT representing a University campus (See Figure 2). In this representation, the system of systems is represented by digital models of various information systems such as class room use, payments in coffee shops, library usage, and timetabling. The human interactions are represented by an agent based simulation. The interaction between the agent based simulation and the other digital models within the sociotechnical DT supports theory exploration and explanation that goes *beyond* normal social simulation experiments such as that exemplified by [25] and is what makes the context sociotechnical.

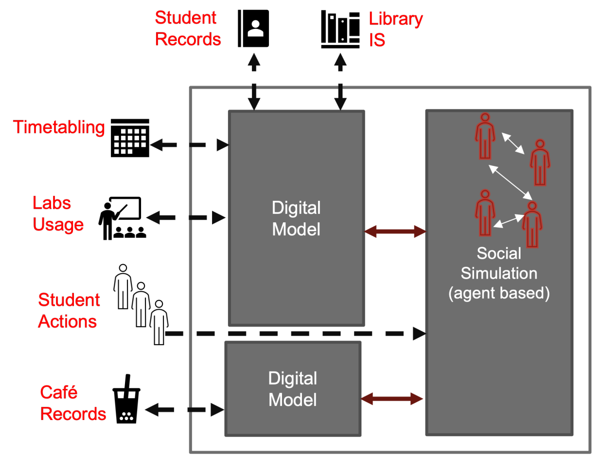

Fig. 2. Candidate Sociotechnical Digital Twin for a University Campus

A. The Abstraction Gap

Selbst et al. [37] claim that the notion of abstraction, characterised by them as a "black boxes, defined precisely by their inputs, outputs, and the relationship between them", abstracts away the social context in which (ML) systems operate and thus information necessary to create fairer outcomes is lost. This paper posits that several abstraction traps that befall ML systems are also applicable to sociotechnical DTs. A first abstraction trap is the framing trap - the failure to model the entire system over which a sociotechnical criterion, e.g. privacy, is to be enforced, can lead to unintended consequences. Conversely, the complexity of a sociotechnical system means that it might be impossible to model the entire system. Thus modelling of concepts directly impact on the constructs and fidelity of the DT w.r.t the real world artefact. Choices are made to determine the scope and detail of the real world to be modelled through a DT. This choice we can refer to this as a conceptual problem frame. For example, Barat et al. in their city digital twin of Pune, for modelling the COVID-19 pandemic, observe that existing agent based systems for pandemic modelling do not show sufficient granularity of types of people and their movements within the city raising concerns of model completeness [7]. While they increase the number of types of citizens in their model, more types could be introduced. This issue is consistent with Ashby's Law of Requisite Variety [4]. The law states: The larger the variety of actions available to a control system, the larger the variety of perturbations, it is able to compensate. There are some practical implications for this in that the potential for the variety of perturbations is unlimited but variety in the control mechanisms may not be of the same order of magnitude [10].

A second relevant abstraction trap is the solutionism trap - the failure to recognise that a DT may not be the best solution to the problem. The presence of DTs on the Gartner Hype cycle makes this particularly pertinent. Also relevant here, are the distinctions between types of digital twin. A DT solution could simply be the need for a *Digital Blueprint* for developing a computational model of a physical asset rather than a fullblown *Pure-play* DT.

B. Ethical and Epistemological concerns

Digital twins that include machine learning algorithms raise important ethical concerns. In 2016, Mittelstadt et al. [30] conducted a systematic review in an attempt to map the ethical problems prompted by algorithmic decision-making. Their conceptual map has been used to critique references to algorithms in the public media [9] and is a helpful summary. The Mittelstadt et al. research comprises a conceptual map that consolidates themes emerging from the literature to a unifying framework that can serve as an "organising structure based on how algorithms operate". Four ethical concerns are identified:

- **Inconclusive evidence**: Conclusions drawn from inference are probable and therefore an epistemic limitation.
- **Inscrutable evidence**: Connections between the input data and conclusion should be accessible and open to critique.
- **Misguided evidence**: Conclusions are dependent upon the quality of data.
- **Unfair outcomes**: Actions based on conclusions should be broadly understood as "fair" and not discriminatory even if well-founded.

Other key concerns with a "black box" approach to DT design can arise through normative transformative effects. For example, through modelling and simulation, and subsequent policy implementation, non-pharmaceutical interventions such as mask wearing becomes the norm on public transport even outside of a period of a pandemic. Determining if this is an acceptable secondary outcome of a DT is also part of the decision making process.

The definition of a sociotechnical DT specifically includes the notion of agent based simulation. Epistemic concerns that arise directly out of simulation as a form of scientific experiment are prevalent [34]. Epistemic concerns are further compounded by the acceptance that sociotechnical DT will invariably incorporate theories from the social sciences which are multi-paradigm sciences where validations generate specific issues [3] such that validation is rarely present. Social simulations may draw upon multiple theories, approximations and data sets such that when a validation if it exists, fails, the complexity makes it challenging to identify the point of failure.

DTs for explanation generate three potential positions on epistemic value of such DTs [34]. A first position argues that a sociotechnical DT cannot be validated since a final simulation output could be arrived at from different starting positions. The basis for this derives from the emergent behaviour, probabalistic events and actions for which complete event traces may not be technically or practically feasible. Hence, there is an *Inscrutable evidence* claim. If an explanation cannot be forthcoming for the final outcome, any actionable insight leading to a decision could lead to an *Unfair Outcome*.

A second position maintains that a sociotechnical DT exhibits macroscropic behaviour that emerges as a result of plausible, validated behaviour rules defined at agent level (microscopic behaviours). Thus the DT offers explanatory behaviour, and insights and potential actions arising from the insights that may still lead to an *Unfair Outcome*.

A final position proposes that a sociotechnical DT can offer both explanation and prediction. Identification of patterns of context, associated entities and activities allow predictions be generated and tested independently. Such a position can be considerably strengthened through the use of ML techniques such as Reinforcement Learning. Some simple experiments demonstrating this have been reported Clark et al. [17].

The 2018 Gemini Principles report published by Centre for Digital Built Britain (https://www.cdbb.cam.ac.uk) provides a relatively limited response to these needs by curating all the above ethical concerns into one of trustworthiness [14]. The principles set out a context for framing questions on how a national network of Digital Twins (National Digital Twin (NDT)) must be trustworthy through ensuring security, openness and assurance of quality of data. Such a National Digital Twin must be "must be 'ethical by design' and the governance and regulatory arrangements for overseeing it must be transparent, open and effective in ensuring that its operation is consistent with the Gemini Principles." [14].

Inclusivity requirements are presented in the principles through a key statement that the NDT must be used to deliver genuine public good in perpetuity and should start with end-user's end-users' needs and should help to deliver inclusive social outcomes. This straight forward requirement is however in conflict with a principle of 'value creation' that implies both public and private investment in digital twins. Given that the latter is sometimes beyond regulatory control, the inclusive social outcomes desired are not guaranteed. Hence, while the principles are laid out, the means by which this implicit gap is addressed are not prescribed and therefore the challenge remains.

IV. ADDRESSING THE GAP

For sociotechnical DT it is critical that useful DTs must prioritise the social understanding gulf for DT models that can be constructed and those that cannot. A realisable set of actions requires us to plan a route starting from palliative approaches to ameliorating the social gap, through first-order approximations and then to methodological advances. Using the terminology from [1], the palliatives can serve to meet current social conditions while first order approximations can enable exploration of the problem space and create research questions that can contribute to the understanding of DT.

A viable palliative approach is one that engages key stakeholders early in the design process. Such a participatory design approach is somewhat ideological in that it foregrounds the needs of users of intended DTs. The purpose of a DT model might vary with the domain and depending upon the domain there may be well established information availability. Thus, complexity of the problem can be counter-balanced by a fairly well understood problem. In such a case, DT modelling can be done remotely because of prior knowledge. Sociotechnical domains for DT are well suited for participatory modelling approaches because of attendant benefits such as direct engagement of decision makers (those requiring the DT), use of both available objective information but also estimates based on informed judgements or even best guesses and operating assumptions. Participatory approaches also help address the democratic principles underlying sociotechnical design.

Sociotechnical DT design gaps could also benefit from a more sophisticated education initiative. Value sensitive design and related approaches that explore more fundamentally the nature of social requirements and (unintended social impacts) of software remains an ongoing project in software engineering [8]. Insights from more expansive educational perspectives would enable knowledge that provides clarity on what can and cannot be done within a sociotechnical DT.

Engineering based disciplines, when faced with a function that is too difficult to work with directly, will instead work with a simpler function that approximates the function of interest. Although the resulting solution will be an approximation, it can still provide insight into a problem. In sociotechnical setting, an exact solution, in any case, may be impossible and an approximate solution may present the only option. In a software application context, potential first order approximations are prevalent. Electronic mail systems do not satisfy all requirements, nor do platforms that support online meetings. A modeling language such as the Unified Modeling Language (UML) includes extension elements such as stereotypes that can work effectively as approximation functions.

Earlier, validation of sociotechnical DTs was identified as an important concern. Indeed, publishing of simulations without empirical validation is a documented problem termed the YAAWN Syndrome ("Yet another Agent based model...Whatever...Nevermind." [32]. Addressing validation concerns can be partially accommodated through three considerations. First, in the initial design of the sociotechnical DT, by presenting the primary objective of the DT as a thought-experiment, empirical validation is not always required. Second, and this is related to the abstraction gap, discussed earlier, by focusing on a tightly restricted topic, it is possible to find the right level of abstraction [3]. Such an example is illustrated in the area of organisational decision-making [6]. Third, where simulations are applied in policy settings, it is the target community that determines if the outcomes are valid and it may do so by considering observations of the real world [2].

Methodological advances present considerable opportunity for addressing some of the concerns outlined above. Critically, though, methodology research is not identified as an important research gap in DT systematic reviews. This seems to be an important omission for future research. Sociotechnical DT design is essentially syncretic in outlook, drawing upon a range of methodological techniques from across the computing discipline. Earlier, simulation was identified as a key characteristic. The methodology for simulation developed by Sargent [36] and its derivatives is widely used and have been adapted for use in a digital twin context for example, in [6]. Such simulation methods can be enhanced by research contributions from sociotechnical design, in particular its value system [31], that manifest themselves by incorporating universal values such as privacy, security, transparency, and trust into the design process. Further possibilities for methodology improvements could also draw upon methodologies widely used in public policy environments based on the ideas around "Theory of Change". A theory of change is a rigorous, yet participatory process incorporating goals, conditions and interventions that bring some desired change arranged in a causal framework [20]. Use of domain specific constructs within such an integrated approach could also help address the abstraction gap. Methodologies could also be developed that codify expert knowledge for interpreting uncertainty, probability of events and impacts so that decision making is done in context. Work is planned on exploring how argumentation techniques (e.g. Toulmin [39]) could be used to present positions on decisions based on risk assessments of the decision and its impact.

V. Illustrative Example and Discussion

An example of a sociotechnical DT is offered as a way of outlining the complexity and scale of problems generated and where opportunities to address the sociotechnical gap exist.

Following the 2018 UK Government Office for Science publication of the Blackett Review of UK Computational Modelling capability (https://www.gov.uk/government/publications/computational-modelling-blackett-review), the UK has embarked on a national strategy to develop an ecosystem of connected digital twins to foster better outcomes from the built environment. Connectivity of digital assets (data, information, services) that can advance analytical exploration to support decision making is critical to this strategy and a framework for describing that connectivity has been labelled as an Information Management Framework (IMF) [23].

While the current scope of the IMF is for the built environment, there is now consensus that there is a similar need for the Environment domain. This is most clearly foregrounded by the focus on the impact of climate change on the Earth's natural environment forming world-wide government policy (https://ukcop26.org).

The Environment domain is already substantial user of computational modelling and models have been developed for human activity leading to emission of pollutants; dynamics of eco-systems giving rise to fluxes of nutrients and/or emissions; models for calculating pollution emission rates, meteorological models; waste-water management and others. An integrated model would seek to capture the complexity inherent in the interrelationships between: human behaviour, the water cycle, climate variability and change, human contributions and responses and change in use/land cover for example.

Therefore, an "Environment Digital Twin" (EDT) would be able to support a complex query such as:

> What are the factors that pose an aggregate set of risks to everyone living in a particular geographic area?.

Given that there is not currently an Environment Digital Twin (EDT), a candidate high-level (informal) conceptual architecture capable of answering the above query is envisioned and is shown in figure 3. Currently, such a conceptual architecture is futures experiment, but the underlying challenges are not that dissimilar to those experienced historically in the design and development of integrated project support environments [16].

Figure 3 can be interpreted in layers. Each layer generates sociotechnical gaps and possibilities to ameliorate concerns.

A. Systems, Data and Knowledge

Real-world systems and systems of systems are sources of both data and knowledge. Communication protocol services such as that for security and anonymisation support data integration into a unified Data Model. In parallel, tacit domain knowledge and codified knowledge are subject to knowledge representation services using a range of knowledge representation languages such as Unified Modelling Language (https://www.omg.org/spec/UML/2.5.1/About-UML/), ESL [18], and Business Process Modelling Language (https://www.bpmn.org) to produce a foundational Knowledge Base/Domain Model for EDT. Data Scientists, Information Systems Designers and Information Specialists will be the key users constructing the foundational Data Model.

In this layer, the production of the Knowledge Base/Domain model hinges on elicitation and abstraction. The scope of the domain model for the environment is necessarily vast and choices to determine the scope and detail can result in multiple conceptual problem frames. Choices are also made to manage problem complexity, it may be appropriate to simplify and abstract away some of the social contexts in which tacit knowledge, for example, is codified into a usable form in the Knowledge base. For example, waterways may be described in the domain model from multiple perspectives such as uses (e.g. leisure, haulage and drainage). Immediate requirements determined by some ongoing project may choose to omit fishing rights and thereby reducing the scope. These challenges are there those that are related the Abstraction Gap. Constructing the right level of abstraction, using appropriate domain specific languages will all help ameliorate this concern.

B. Digital Twin Specification

Both the Data Model and the Knowledge Base are used as the basis for developing multiple conceptual Digital Twins by collaboration between expert modellers and domain experts. Tools/Services that are needed for composing such DTs require the existence of component libraries [15] for publishing, navigating, searching DT components. Assemblies of conceptual DTs will require configuration management and variability modelling services.

C. Purposive Digital Twins

Purposive Digital Twins are implemented for a specific reason. Such DTs will have cross-cutting concerns. The simple query suggested earlier in the paper, for calculating risks to those resident in some specific geography will draw in risks due to atmospheric pollution, wastewater pollution, flooding, age of buildings, traffic congestion and other conceptual DTs.

In both the Digital Twin Specification and Purposive Digital Twin layers, models are constructed through engagement of stakeholders and expert modellers. Sociotechnical gaps can therefore be explored through the use of novel methodologies for DT design that also include elements of value sensitive design. It is in the construction of such conceptual DTs or Purposive DTs that attention can be paid to issues of inclusion, diversity and equality.

D. Experimentation and Interrogation

This layer utilises advances in methodological developments in simulation techniques for exploring scenarios, sense making and ultimately decision making. Primary users are domain based decision makers. Advances in query formulation to support 'what-if' and 'if-what' analysis, visualisation utilising ML techniques will be necessary to provide feedback back into real-world systems through either automated actions (pure-play digital twin) or human interventions.

Further, the given that the environment digital twin is one that incorporates technology, human behviour and multiple models of both, simulation and ML bring to the fore the ethical and epistemological concerns around transparency, unfair outcomes and inscrutability of data.

Here multiple concerns are at stake. As noted earlier, methodological challenges exist and "Theory of Change" approaches are potentially an important tool to support query building and exploration. Such methodological advances can also integrate argumentation modelling approaches that include value sensitive concerns [12]. Methodological advances are also needed to address ML algorithm concerns of problems with evidence, and unfair outcomes.

The entire architecture raises classical technical concerns such as data mapping, data integration, method integration and other architectural issues for which there is rich body of knowledge from which to produce the approximation functions. See for example the now historical work in integrated project support environments [16].

Figure 4 provides an outline of how the various sociotechnical gaps work their way across the key characteristics of DTs in the case of a putative Environment Digital Twin. The principal focal point from which gaps emanate is the production of the various data models and knowledge bases required to describe the inherent system of systems complexity of an EDT. These domain specific models, for example, water management, require the development of constructs at an appropriate level of fidelity. Scoping the problem space, building the right abstraction drives other aspects such as the simulation environment. The adaptive component of the EDT, implemented through AI/ML will also depend upon these abstractions. Epistemological gaps will manifest themselves across all four characteristics. It is plausible that such gaps decrease as the seamless communication characteristic moves

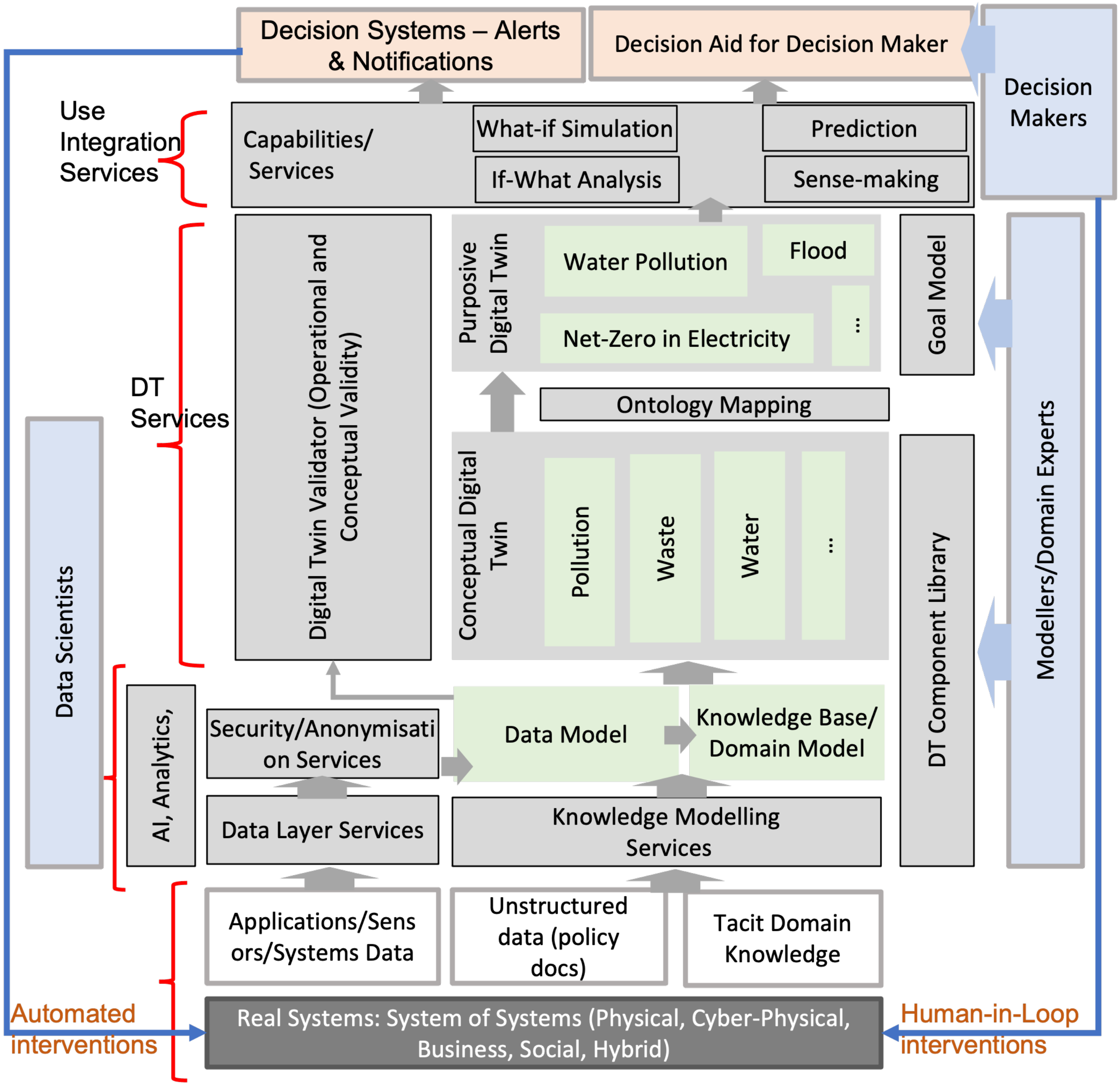

Fig. 3. An Initial Information Management Framework for Environment Digital Twin

from Digital Blueprint through to Digital Shadow. Ethical concerns primarily manifest themselves through the exploratory component of the simulation environment used in the EDT and where automated decision making takes place through the use of adaptive elements that utilise AI/ML. In all cases it is proposed that methodological developments can reduce these concerns.

VI. CONCLUSION

The idea of a sociotechnical DT represents the current directions in DT research and application. The gap between what is possible and what is desirable in an implementation of a sociotechnical DT is a critical mismatch that is based on nuanced human behaviour and context that is lost when mechanistic approaches are applied. It is argued that further advances in DT design, particularly in methodology, are required to fully develop the technical mechanisms that can support and represent human behaviour realistically without adverse effects, unintended consequences and with acceptable validation. The importance of sociotechnical DTs has been illustrated through an illustrative example of the conceptual requirements of a sociotechnical digital twin for the Environment. This is an example of an emerging concern, brought to focus through international activity on climate change. Here, the need to

	Environment Digital Twin	Seamless Communication	Safe Simulation Environment	Constructs and Fidelity	Adaptive through AI/ML
Sociotechnical Gap	Abstraction Gap		The constructs and choices made inform the simulation conceptual models.	Challenges primarily located in the data / knowledge base models, and the DT Component Library	Models informing adaptive elements reinforce abstraction gaps
	Epistemological Gap	Challenges decrease as the seamless connection between RWA and DR move towards pure-play mode.	Simulation models dependent upon the underlying constructs in the knowledge base and the various conceptual DTs required.	Validity of model used for decision making. Verification	Models informing Adaptive elements reinforce validity and verification concerns.
	Ethical Gap		Simulation modelling requires checks on balances on integrating moral values		Transparency of decision making. Fairness and bias.

Fig. 4. Example Sociotechnical Gaps for Environment Digital Twin

ensure equality and inclusion is a particular requirement. It has been argued that to truly derive value from such DTs, further research and solutions are sought to address the social gaps outlined in this article.

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REFERENCES

[1] Mark S Ackerman. The intellectual challenge of CSCW: The gap between social requirements and technical feasibility. *Human–Computer Interaction*, 15(2-3):179–203, 2000.

[2] Petra Ahrweiler and Nigel Gilbert. The quality of social simulation: An example from research policy modelling. In *Policy practice and digital science*, pages 35–55. Springer, 2015

[3] Eckhart Arnold. Validation of computer simulations from a Kuhnian perspective. In *Computer simulation validation*, pages 203–224. Springer, 2019.

[4] W Ross Ashby. Requisite variety and its implications for the control of complex systems. In *Facets of systems science*, pages 405–417. Springer, 1991.

[5] Souvik Barat, Vinay Kulkarni, Tony Clark, and Balbir Barn. An actor-model based bottom-up simulation—An experiment on Indian demonetisation initiative In *2017 Winter Simulation Conference, WSC 2017, National Harbor, MD, USA*, pages 860–871. IEEE, 2017.

[6] Souvik Barat, Vinay Kulkarni, Tony Clark, and Balbir Barn. An actor based simulation driven digital twin for analyzing complex business systems. In *2019 Winter Simulation Conference, WSC 2019, National Harbor, MD, USA, December 8-11, 2019*, pages 157–168. IEEE, 2019.

[7] Souvik Barat, Ritu Parchure, Shrinivas Darak, Vinay Kulkarni, Aditya Paranjape, Monika Gajrani, and Abhishek Yadav. An agent-based digital twin for exploring localized non-pharmaceutical interventions to control covid-19 pandemic. *Transactions of the Indian National Academy of Engineering*, pages 1–31, 2021.

[8] Balbir Barn, Ravinder Barn, and Franco Raimondi. On the role of value sensitive concerns in software engineering practice. In *2015 IEEE/ACM 37th IEEE International Conference on Software Engineering*, volume 2, pages 497–500. IEEE, 2015.

[9] Balbir S Barn. Mapping the public debate on ethical concerns: algorithms in mainstream media. *Journal of Information, Communication and Ethics in Society*, 2019.

[10] Balbir S Barn and Ravinder Barn. An exploration of resilience and values in the co-design of sociotechnical systems. *International Journal of Systems and Society (IJSS)*, 3(1):1–17, 2016.

[11] Barbara Rita Barricelli, Elena Casiraghi, and Daniela Fogli. A survey on digital twin: Definitions, characteristics, applications, and design implications. *IEEE Access*, 7:167653–167671, 2019.

[12] Sebastian Bittmann, Balbir Barn, and Tony Clark. A language oriented extension to toulmin's argumentation model for conceptual modelling. In *Information System Development*, pages 359–369. Springer, 2014.

[13] Calin Boje, Annie Guerriero, Sylvain Kubicki, and Yacine Rezgui. Towards a semantic construction digital twin: Directions for future research. *Automation in Construction*, 114:103179, 2020.

[14] Alexandra Bolton, Lorraine Butler, Ian Dabson, Mark Enzer, Matthew Evans, Tim Fenemore, Fergus Harradence, Emily Keaney, Anne Kemp, Alexandra Luck, et al. Gemini principles. 2018.

[15] Alan W Brown and Balbir Barn. Enterprise-scale cbd: Building complex computer systems from components. In *STEP'99. Proceedings Ninth International Workshop Software Technology and Engineering Practice*, pages 82–91. IEEE, 1999.

[16] Alan W Brown and Maria H Penedo. An annotated bibliography on integration in software engineering environments. *ACM SIGSOFT Software Engineering Notes*, 17(3):47–55, 1992.

[17] Tony Clark, Balbir Barn, Vinay Kulkarni, and Souvik Barat. Language support for multi agent reinforcement learning. In *Proceedings of the 13th Innovations in Software Engineering Conference on Formerly known as India Software Engineering Conference*, pages 1–12, 2020.

[18] Tony Clark, Vinay Kulkarni, Souvik Barat, and Balbir Barn. ESL: an actor-based platform for developing emergent behaviour organisation simulations. In *International conference on practical applications of agents and multi-agent systems*, pages 311–315. Springer, 2017.

[19] Batya Friedman. Value-sensitive design. *interactions*, 3(6):16–23, 1996.

[20] Sue C Funnell and Patricia J Rogers. *Purposeful program theory: Effective use of theories of change and logic models*, volume 31. John Wiley & Sons, 2011.

[21] Shirley Gregor. The nature of theory in information systems. *MIS quarterly*, pages 611–642, 2006.

[22] Chris Goldspink et al. Modelling social systems as complex: Towards a social simulation meta-model. *Journal of Artificial Societies and Social Simulation*, 3(2):1–23, 2000.

[23] James Hetherington and Matthew West. The pathway towards an information management framework-a 'commons' for digital built Britain. 2020.

[24] David Jones, Chris Snider, Aydin Nassehi, Jason Yon, and Ben Hicks. Characterising the digital twin: A systematic literature review. *CIRP Journal of Manufacturing Science and Technology*, 29:36–52, 2020.

[25] JoAnn Lee and Andrew and Crooks Youth and their Artificial Social Environmental Risk and Promotive Scores (Ya-TASERPS): An Agent-based Model of Interactional Theory of Delinquency *JASS*,24,4,2021.

[26] Kendrik Yan Hong Lim, Pai Zheng, and Chun-Hsien Chen. A state-of-the-art survey of digital twin: techniques, engineering product lifecycle management and business innovation perspectives. *Journal of Intelligent Manufacturing*, pages 1–25, 2019.

[27] Azad M. Madni, Carla C. Madni, and Scott D. Lucero. Leveraging digital twin technology in model-based systems engineering. *Systems*, 7(1), 2019.

[28] Christian Matt, Thomas Hess, and Alexander Benlian. Digital transformation strategies. *Business & Information Systems Engineering*, 57(5):339–343, 2015.

[29] Tsega Y Melesse, Valentina Di Pasquale, and Stefano Riemma. Digital twin models in industrial operations: A systematic literature. *Procedia Manufacturing*, 42:267–272, 2020.

[30] Brent Daniel Mittelstadt, Patrick Allo, Mariarosaria Taddeo, Sandra Wachter, and Luciano Floridi. The ethics of algorithms: Mapping the debate. *Big Data & Society*, 3(2):2053951716679679, 2016.

[31] Enid Mumford. The story of socio-technical design: Reflections on its successes, failures and potential. *Information systems journal*, 16(4):317–342, 2006.

[32] David O?Sullivan, Tom Evans, Steven Manson, Sara Metcalf, Arika Ligmann-Zielinska, and Chris Bone. Strategic directions for agent-based modeling: avoiding the yaawn syndrome. *Journal of land use science*, 11(2):177–187, 2016.

[33] Pawel Pawlewski, Monika Kosacka-Olejnik, and Karolina Werner-Lewandowska. Digital twin lean intralogistics: Research implications. *Applied Sciences*, 11(4):1495, 2021.

[34] Giuseppe Primiero. A minimalist epistemology for agent-based simulations in the artificial sciences. *Minds and Machines*, 29(1):127–148, 2019.

[35] Adil Rasheed, Omer San, and Trond Kvamsdal. Digital twin: Values, challenges and enablers. *arXiv preprint arXiv:1910.01719*, 2019.

[36] Robert G Sargent. Verification and validation of simulation models. In *Proceedings of the 2010 winter simulation conference*, pages 166–183. IEEE, 2010.

[37] Andrew D Selbst, Danah Boyd, Sorelle A Friedler, Suresh Venkatasubramanian, and Janet Vertesi. Fairness and abstraction in sociotechnical systems. In *Proceedings of the conference on fairness, accountability, and transparency*, pages 59–68, 2019.

[38] Christian Stary. Digital twin generation: Re-conceptualizing agent systems for behavior-centered cyber-physical system development. *Sensors*, 21(4):1096, 2021.

[39] Stephen E Toulmin. *The uses of argument*. Cambridge university press, 2003.

[40] Eric J Tuegel, Anthony R Ingraffea, Thomas G Eason, and S Michael Spottswood. Reengineering aircraft structural life prediction using a digital twin. *International Journal of Aerospace Engineering*, 2011, 2011.

[41] Jan-Frederik Uhlenkamp, Karl Hribernik, Stefan Wellsandt, and Klaus-Dieter Thoben. Digital twin applications: A first systemization of their dimensions. In *2019 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)*, pages 1–8. IEEE, 2019.

[42] Jon Weimer. *Handbook of ergonomic and human factors tables*. Prentice Hall, 1993.

[43] M. Young, The Technical Writer's Handbook. Mill Valley, CA: University Science, 1989.