Towards the Essence of Specifying Sociotechnical Digital Twins

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ABSTRACT

Digital Twins are now mainstream technology in the engineering domain. Capabilities and underpinning concepts are well understood and augmented by proven theories from the physical sciences. Nonetheless the design of digital twins in engineering still remains essential a craft. As digital twin technology merges with more traditional computational modelling approaches such as that found in simulation, new application domains are emerging and public policy experts see significant potential in DT for understanding their complex system areas. Such domains have a significant sociotechnical component and as such a new type of digital twin is required, together with a means of specifying such a digital twin. This paper proposes a specification language/method for this purpose. Requirements elicitation for this language utilises a tabletop paper template that serves as a boundary object between domain experts and technical experts. The language is conformant with accepted practice in simulation methods and its semantics provides a route to implementation of a digital twin. We argue that the language is a contribution to a breadcrumb trail for future work in this emerging application area for digital twins.

CCS CONCEPTS

• **Software and its engineering → Domain specific languages**; • **Computing methodologies → Modeling methodologies**; • **Applied computing → Law, social and behavioral sciences**.

KEYWORDS

simulation, digital twin, language engineering, sociotechnical

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1 INTRODUCTION

Digital Twin (DT) research is advancing practice in technical domains such as manufacturing and construction. A consequence of that predominantly engineering focus is that digital twins in those domains have developed capabilities, working definitions and also some largely craft-based approaches to building digital twins. Broadly, we can safely assume that common features are: seamless connection between a real entity and the virtual twin, continuous exchange of multidimensional data, comprehensive descriptions of constructs, and a safe simulation environment for testing and prediction. In particular the conceptual architecture shown in figure 1 formulated at a recent Dagstuhl workshop on Digital Twins, is representative of the state of the art. Technical implementations derived from that conceptual architecture are also well understood.

More recently, though, policy makers have identified that the role of digital twins can be brought to bear in more diverse and differently challenging domains such as decision-making in public policy settings at both a national and international level. It is notable that in the UK, that digital twins and indeed, computational modelling, more generally, is seen as a key tool in public policy decision making. Thus the UK Research and Innovation strategy is specific in positioning the importance of digital twins [1] . The cornerstone of the current UK government for example, the Levelling Up strategy amplifies the point that: "All economies are complex, adaptive systems of many moving, interacting parts, workers, businesses, government and civil society. Each moving part adapts their behaviour in the light of experience and the evolving environment. It is the complexity of these interactions that generates the richness, history, dependence and unpredictability seen in local growth patterns across the UK." [8].

What are the characteristics and capabilities of Digital Twins that can focus on these concerns? It is our proposal that applications of DTs focusing on such a system of systems requires a new class or flavour of digital twin that we refer to as a Sociotechnical Digital Twin (STDT). The term STDT was first introduced in an earlier paper [5] addressing the key challenges facing the development of such types of DT. These included:

- Abstraction Gap: the quality and validity of the conceptual model of the problem.
- Ethical and Epistomlogical concerns: The impact of outcomes from the STDT and the truthness of the STDT.

[1]https://www.gov.uk/government/publications/uk-innovation-strategy-leading-the-future-by-creating-it/uk-innovation-strategy-leading-the-future-by-creating-it-accessible-webpage

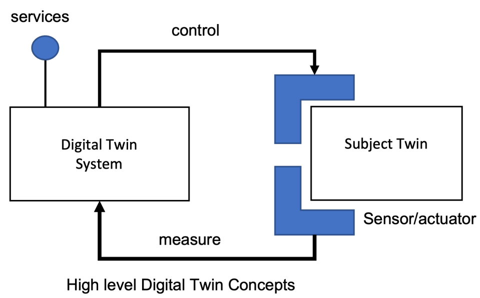

Figure 1: Conceptual Architecture of a Digital Twin System

- Moving from Craft to Engineering: the development of viable methods for designing STDT.

This paper, building upon that prior work, advances a proposal for the methodological challenge posed.

STDT draws it capabilities from two domains of existing research and practice: (1) Digital Twins as understood from the engineering domain; and (2) Established uses of social simulation (see Pilkynas et al. for an example [14]).

Our evidence for (1) is drawn from a recently published, exhaustive systematic mapping study that presents characteristics, applications, challenges and research areas for DTs [12]. The mapping study demonstrated the focus on engineering and the very limited work on socio-technical problems. That paper also presented a definition developed from the synthesis of the current body of work on DT from which we define STDT:

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 systemand 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 modelling approaches including agent based simulation.

Critically, there are limited examples of STDTs that both conform to the architectural style of figure 1 and have sufficient validity. A good example is reported in Barat et al. [3], where a city digital twin of Pune, Mahrashtra was developed for modelling the COVID-19 pandemic. Validity and fine-tuning was achieved by developing the underpinning models whilst the pandemic was underway when actual data was available.

In this paper, we propose that the move from physics-based digital twin systems that target engineering domains to ones that address phenomena where human interaction and cyber-physical components are brought together towards some some goal directed behaviour requires additional methodology and accompanying constructs. Hence, this paper contributes a specification language and underpinning conceptual model. The focus of the language is on the specification of sociotechnical digital twins. Validity of the language and conceptual model is based on a design science oriented approach and the use of a case study example.

Upfront, we understand that this paper, on initial examination, appears to be offering a YAM (Yet another method/language) that has been evaluated in a limited way. Our counter argument is the following: we are reporting on *work in progress*; our case study is realistic and has been externally referenced by a UK Government body. On the method and language front, the most recent systematic mapping study on digital twins reports the lack of methodology to support the move from artisanal approaches to engineering [12]. A recent Dagstuhl event focussed on DTs identifies a similar challenge [2]. Contributions to a method and language (with case study examples) can therefore be a necessary first foundational step before software tools can be built. Further, the proposal to develop a conceptual framework alongside language work is consistent with the idea of theory building and that such actions are steps or a journey to building a theory [4]. We also suggest that the case study presented is an excellent candidate for a reference example for digital twin development given its richness and complexity.

The rest of the paper is structured as follows. We begin by first introducing the case study on "**Levelling Up**" to provide a structural frame for the paper. Section 3 presents the specification method containing our main contributions. Section 4 presents some concluding remarks and plans for future work.

2 CASE STUDY: UK LEVELLING UP

In 2019, the Conservative Government, under Prime Minister Boris Johnson, won a landslide general election. A centre piece of that election victory was the promise to "Level Up" regions of the UK which had hitherto been perceived to have been left behind in terms of economic growth and investment. In 2022, the UK.Gov published a strategy to address these disparities in growth of different regions of the UK [8]. The strategy had a number of key objectives:

- **Boost productivity,** pay, jobs and living standards by growing the private sector, especially in those places where they are lagging through greater investment in R&D, better transport infrastructure and increased digital connectivity.
- **Spread opportunity and improve public services**; greater skills and education investment, and a focus on health and wellbeing.
- **Restore a sense of community** by improving housing, decreasing crime and creating a greater pride in place.
- **Empower local leadership** through greater devolution and long-term funding settlements.

The white paper documents at length how disparities are played out. Salient examples include: Salary difference, and eduational qualifications are highest in London and lowest in the North East; Life expectancy is best in the South East, while those in the North East have reduced life expectancy by 3.5 years.

To address these objectives, the underlying theory being utilised is drawn from Economic Growth theory where prominence is given to the role of productivity (the amount produced per unit of input) [16]. Productivity drivers that are directly correlated with increase in productivity include investment in a range of capitals such:

Physical capital: machines, housing, infrastructure [7];
Human capital: skills and experience of the workforce;
Intangible capital: innovation, ideas, patents [10];
Financial capital: access to funds [11];
Social capital: measures of social infrastructure, connectedness and an engaged community;

[2]https://www.dagstuhl.de/en/program/calendar/semhp/?semnr=22362

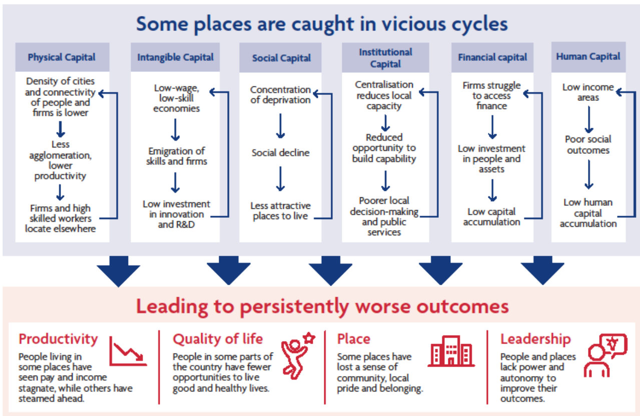

Figure 2: Levelling up Capitals Framework

Institutional capital: degree of centralisation in decision making.

The white paper proposes an explanatory framework for describing how disparity in regions manifests itself. This framework is essentially a consolidated theory of "**Levelling up**" that is built up from granular theories from economics. Figure 2 illustrates the various capitals and their inter-play. While each capital as a driver is important, the real significance is derived from their interdependence and interaction with each other as part of a complex, adaptive economic ecosystem - a system of systems in other words.

Behavioural factors causing a spillover between capitals might include the decisions people make about where they live. The location in turn depends upon job availability, but also family ties, schools, housing and transport. Work is a key driver and workers make decisions based on their qualifications and job preferences and availability. Preferences change over time. Thus workers are prepared to move around to acquire new skills at the beginning of a career.

From this description of a "**Levelling up**" strategy, thought experiments can be designed and be subject to experimentation through simulation. The challenge is establishing a robust methodological approach that can specify and design a sociotechnical digital twin to enable exploration in this space.

3 SPECIFICATION METHOD

In developing a method, we consider a design science perspective offered by Peffers et al. [13]. and execute three essential design science research cycles. We motivate the reasons and value of the method; we develop the artefacts of the method and we evaluate the method output. The latter two cycles utilise the case study presented earlier.

3.1 Motivation

Our prior work in developing tools and techniques for decision making in the enterprise space provides the underpinning research and evidence base. Up to now, work has completed in developing frameworks of conceptual models and their implementation to describe decision making processes and to enact experimental scenarios for conducting what-if, if-what type of scenarios [2]. Further technology has been developed to provide an overlay of machine learning to enhance the decision-making capabilities [6]. Critically, the technology has been seen as an aid to decision making. Humans remain centre-stage in the decision making process but with a reduced cognitive burden. Hence, issues around ethical concerns are diverted. While there has been some effort in developing digital twin based simulations of sociotechnical problems, for example demonetization [1] and Covid-19 pandemic planning [3], developing specific methods for such systems remains a significant and important research gap. One reason for this is the particular set of characteristics that contribute to the defining of a sociotechnical digital twins such the interconnectedness of systems, emergent behaviours of agents, the need for adaptation, the heterogeneity of key actors and the recognition that there may be multiple means of achieving system goals.

A tangential objective is to recognise that specification and design of a sociotechnical DT requires close collaboration with domain experts who are not modelling experts and therefore modelling needs to be implicit and should be expressed in the language of the domain expert. We propose the use of a tabletop paper template of the form shown in figure 5 that supports participatory enterprise modelling approaches (PEM) [9] in that domain experts focus on providing knowledge and the act of modelling is mostly deferred.

3.2 Method Artefacts

The case study content has been used in two ways in an iterative process. It has both contributed to the meta concepts (also termed the STDT Specification meta language and the actual model for the case study. The concepts are exemplified in the tabletop template.

Table 1: Sociotechnical DT Specification Meta Language Concepts

Concept	Description
Assumption	Used for defining the scope of the subject and target digital twin system
Validation	Underpinning external references to theories for justification of model elements
Constraint	Domain level rule constraining behaviour (invariant)
Goal	Objective / purpose of the DT
Measure	Property of the domain model that is quantifiable in some way
Lever	Property of the domain model of the DT that can be changed through external control
Regulation	Enforceable policy such as a planning rule
Domain Model	Concepts from the problem domain - key business objects
Actions	Behaviour (operation specifications) assigned to domain concepts in the domain model

The modelling language can then be represented as a conceptual model. In figure 3, the concepts from table 1 are represented diagrammatically to include relationships and some further essential

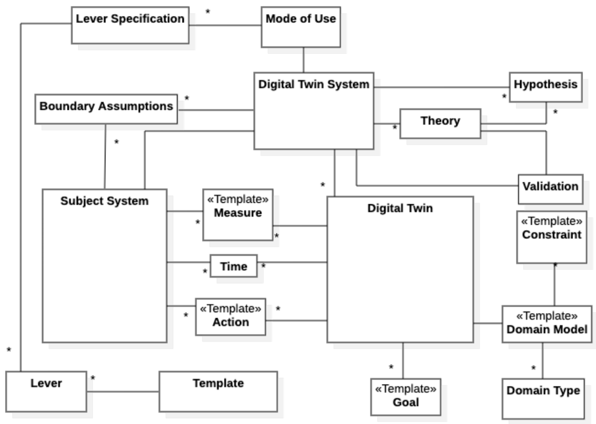

Figure 3: Conceptual Model

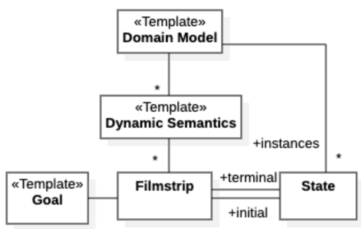

Figure 4: Model Semantics

elements, for language design purposes rather than domain requirements are introduced. A *Template* stereotype denotes a conceptual element that can contain *levers*. A *Lever* denotes a named slot that can be supplied with a value. A lever value represents a parameter for the *Digital Twin System*. Each lever used in the system has a *Lever Specification* that states whether the lever is to be supplied before the twin is used or whether one or more lever values are to be produced as result of executing the twin.

3.2.1 Semantics. The *Dynamic Semantics* of the Conceptual Model presented in figure 4 is a collection of traces or Filmstrips that contain snapshots of instances of the Domain Model. The Filmstrip is therefore a description of a Goal that has been subjected to an application of a Lever. The state change of the domain model from an initial model to a terminal model represents the change as a result of the Lever being applied. Additionally there are well-formed rules that determine how an instance model is deemed to be correct with respect to the conceptual model.

3.3 Evaluation

The starting position is to first consider how a sociotechnical DT conforms to the conceptual architecture shown in figure 1. From the case study, The subject twin is the set of UK regions at different stages of productivity. The mechanism by which the the DT system controls the subject twin are the public policies introduced for levelling up as a result of experimental actions. The sensors and actuators are the Levelling Up Capitals Framework shown in figure 2. The measures are values that are attributable to the capitals.

Our primary mode of evaluation is the use of the constructs forming the DT specification language through an exercise of specifying a sociotechnical digital twin for the levelling up case study detailed earlier. The tabletop template is used as boundary object [17] to identify the key concepts for driving the implementation of the digital twin. The tabletop template provides shared interpretive flexibility, but also sufficient information structures that support downstream design work. Method engineering in Information systems field is relatively stable and all methods follow a basic iterative process of Analysis<>Design<>Implementation<>Test-and-Deploy cycle. The tabletop template provides both an analytical and design tool. Further, the use of a meta language that has both syntax (the conceptual model) and semantics provides a clear route through to implementation. The proposed approach is also in alignment and is an enhancement to work in methods in Simulation such as that developed by Sargent [15]. By introducing first order constructs for *Validation* and *Theory* (see Figure 3) we provide a clear route for engineering argumentation approaches. An example of the tabletop template is shown in figure 5, use where sections populated with some workings out. Note that this is an iterative purpose.

For our case study experimentation, the tabletop template example (figure 5) generates the following theory: . Regions have a notion of "aggregated" capital. People have satisfaction levels derived from living in a region and a set of economic circumstances. Regions can be improved with investment and region capital is proportionately related to the level of economic circumstances and level of satisfaction. People move between regions if their economic circumstance allow and will move if their satisfaction levels dip below a given level. People move to regions which have a better level of capital.

A simple, abstracted goal is an equilibrium (levelling up) where no one moves and we have spent no more than X, where X is a target amount or measure. Actions in this context are to simply spend money to increase capital. Levers are what to spend on regions to improve their capital.

Execution of this simulation specification with three indicative regions (London, Coventry, and Middlesborough) with increasing initial levels of investment and capital between them led to a situation that shows citizens move to London in line with both theory and evidential data.

Internal and external validity challenges on the conceptual model remain. We are not able to claim certainty. However our experiential evidence is that the language presented is sufficient for *capturing* the design of a sociotechnical DT. The language has drawn from our previous research reported earlier, see for example, the sociotechnical case study on the Indian Demonitization in 2016 [1].

We accept that designing rather than specifying sociotechnical digital twins will also require methodological techniques. Our contribution so far is the language definition and a tabletop technique for supporting outcomes using that language. This remains a future project. Similarly tool support is necessary to further progress from craft to engineering.

4 CONCLUDING REMARKS

Existing research evidence suggests that, while digital twins have achieved silver bullet status, the design of development of digital

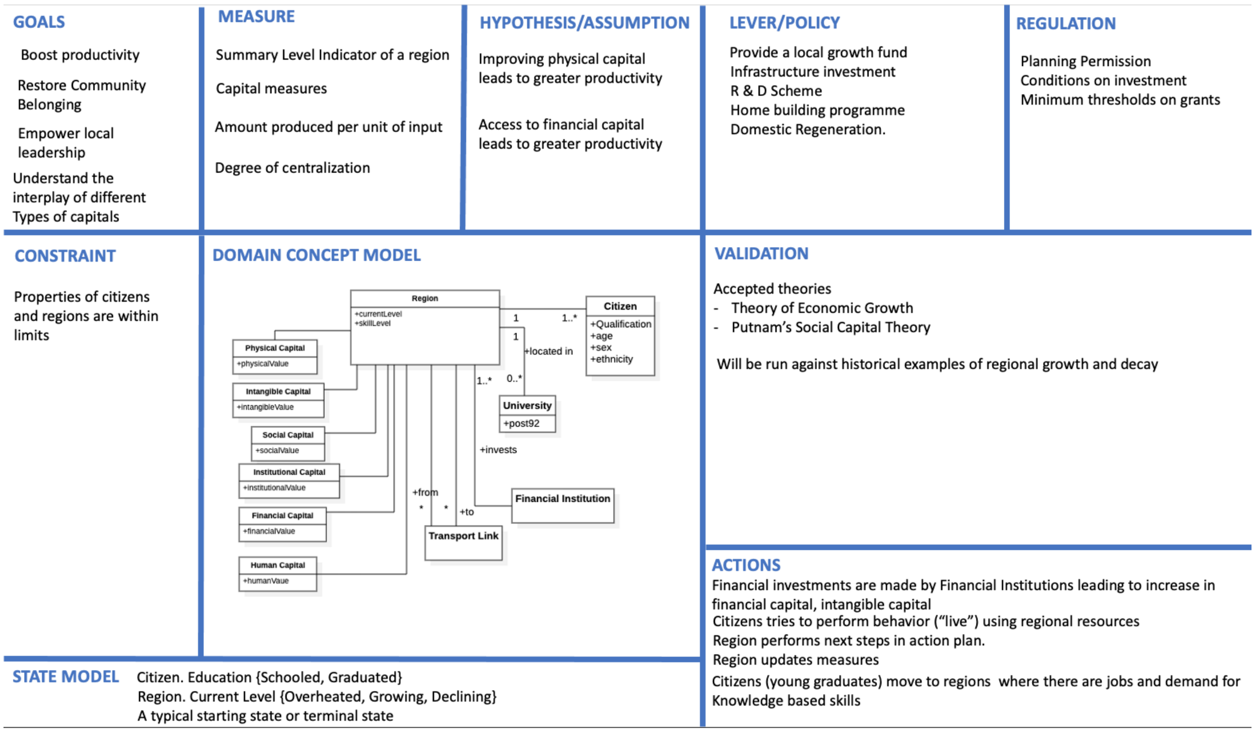

Figure 5: Boundary Object: TableTop Template

twins remains a craft-based enterprise. For the engineering community, this is mitigated by the recognition that the engineering community is able to draw upon established laws of physics as a foundational form. Digital twins are now finding new domains of application and digital twins for the sociotechnical domain are particularly challenging. In this paper, we lay down breadcrumbs for specifying such types of digital twin in the form of a meta language for specification of digital twins. The language, coupled with a boundary object tabletop paper tool, serves to sketch out the essence of a sociotechnical DT. Our future steps are to continue with further validation efforts by reverse engineering the specification of earlier case study examples with a view to enhancing our language through a process of induction. Other future initiatives will focus on software tools to support the tabletop exercises and to provide an implementation route to digital twin environments such as Anylogic or similar tools.

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