Institution: Middlesex University		
Unit of Assessment: UoA 11		
Title of case study: **Digital Twin Specification, Design and Application**		
Period when the underpinning research was undertaken: 2013-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof. Balbir S. Barn	Professor of Software Engineering	2008-onwards
Prof. Tony Clark	Professor of Computer Science	2011-2016
Prof. Huan Nguyen	Professor of Digital Communication Engineering	2011-onwards
Dr Mohsin Raza	Research Fellow	2018-2019
Dr Dang Viet Hung	Research Fellow	2019-2021
Period when the claimed impact occurred: 2016-2021		
Is this case study continued from a case study submitted in 2014? Y/N		

1. Summary of the impact (indicative maximum 100 words)

Middlesex has been advancing digital twin research in programming technologies and applications (Prof. Barn and Prof. Clark (2011-2016) with Tata Consultancy Services (TCS) and in digital twins for structural health monitoring of large-scale infrastructures (Prof. Nguyen).

Impacts have included industry-scale demonstrators for TCS clients, strengthening a robust Java implementation of Enterprise Simulation Language leading to a TCS product TwinX™, design simulations and non-pharmaceutical interventions for managing the COVID-19 Pandemic in Pune, India and software tools to produce a repair and maintenance plan for the Thăng Long bridge in Hanoi, Vietnam resulting in benefits of £9.1 million (£1.5m of savings on repair costs + £7.6m of estimated economy benefit).

2. Underpinning research (indicative maximum 500 words)

Middlesex Computer Science undertakes world-leading research to improve the quality of software systems development. Today, quality of software is dependent upon large-scale, networked, semi-autonomous interdependent systems. Such systems no longer have fixed behaviour and must invariably adapt to achieve their intended function and even change function over time. Consequently, software architects and designers require higher level abstract tools to understand system complexity and interdependencies. Simulation and modelling are core aspects of such work. Beyond software, similar methods of working are also applicable to engineering problems associated with large-scale infrastructures. During this REF research period, these approaches have coalesced around the notion of a Digital Twin (DT). Generally, a DT is a virtual representation of a real-world physical artifact or system that is linked to enable use of real-time data to enable learning, reasoning and dynamically adapting for improved decision making. DTs can be of many types depending upon the features in play and the purpose for which they are defined.

This section describes **two** broad directions of research activity associated with what is now widely known as a Digital Twin (DT): first, our work on software engineering and, second, our more recent work on structural health monitoring. The integration of model-based software engineering and the proving of conceptual advances in complex scenarios is a hallmark of our approach to DT research.

(a) Software Engineering: Barn and Clark's work has developed language-based simulation and modelling techniques to design, analyse and adapt the quality-assured development of complex enterprise systems. After initial research on lightweight methods for enterprise modelling, the entirety of this work has been performed in collaboration with TCS and its research lab in Pune. Critically, it is not *just* an application of research, but much more: it is industry and academia working in collaboration to address emerging industry-scale problems. Barn and Clark's

contribution has led to new methods and technologies, the development of which is described in the rest of this section. The collaboration illustrates how the research has responded and adapted to the emerging sub-discipline of DT that first became significant in 2016.

Existing approaches to digital twin representation of enterprise modelling are not suitable as a basis for simulation and analysis. Barn and Clark's collaborative research directly led to the construction of an executable modelling language called LEAP (Lightweight Precise Enterprise Architecture), together with a toolset for enterprise simulation [R1]. This research was reported in India's premier Software Engineering Conference – ISEC, attended by representatives from most of India's premier industrial research labs. ISEC has an acceptance rate of around 13-15% and is notable for the representation of industrial researchers. The LEAP work was identified by TCS as potential technology that could be exploited by TCS as they embarked on a research strategy focused on idea of the Model Driven Organization (MDO). LEAP thus formed the basis of a collaborative initiative between Middlesex and TCS Research leading to a conceptual research paper published in the Core-ranked A conference - HICSS [R2]. MDO was promoted by a series of dedicated workshops at international conferences. MDO subsequently became integral to the research strategy for TCS software engineering research area.

From 2013 to date, Barn has been hosted annually by TCS Research in Pune India for two weeks to co-develop research that has had a direct influence on the TCS Research strategy and their interactions with clients. These visits led to the co-creation of a technology-based method for organization modelling and decision-making, reported in the leading ACM/IEEE Models Conference series [R3]. This work was a development derived directly from the original work in LEAP. The key contribution of this work is a conceptual meta-model expressed in terms of goals, execution traces, simulation levers, and agents, for constructing enterprise models that can be used to aid decision-makers. Aspects of this work were also executed by TCS's funding of a distance learning PhD student, a senior scientist at TCS, to undertake doctoral studies at Middlesex. Souvik Barat completed in 2018 and his work, supervised by Barn, led to the development of methodology for enterprise decision making. This annual collaboration, initially seeded by the groundwork of the research published in [R1] has led to new products being marketed by TCS [S7, S8].

To validate the conceptual model, a number of case studies were developed and reported in publications. A particular interest was focused on the use of the technology for modelling socio-technical contexts. Some of that research used ESL and its underlying conceptual model in an exploratory case study examining India's demonetization strategy of 2016. This validation would provide confidence later in the work done on COVID-19 reported below.

Clark led on the development of a technology to support the modelling and decision-making approach. The agent-based technology takes the form of a novel programming language called ESL and an associated development platform called EDB (http://www.esl-lang.org, [R4]) both of which are open source. The platform was then extended and used in a Digital Twin context with research being reported in [R5].

Following expansion and evolution of DT research, in 2019, Middlesex established the London Digital Twin Research Centre Centre (https://dt.mdx.ac.uk/) . Further work now includes: Building Information Management, and Smart Factory (working closely with Festo and Siemens) as well as consolidating work on Structural Health Monitoring. The Centre's ethos is that modelling gains from application, complexity spurs research innovation, and international collaboration enables both.

(b) Digital Twins for Structural Health Monitoring (SHM):

A well-documented use for Digital Twins is in the area of structural health monitoring of large infrastructure artefacts such as bridges and buildings. In 2018, Prof. Nguyen received funding for two international collaboration grants - from the Newton Fund (https://dt.mdx.ac.uk/?page_id=36) and from the UKIERI (https://dt.mdx.ac.uk/?page_id=37).

In collaboration with the University of Transport and Communications (UTC), Vietnam, Prof. Nguyen has been addressing the problem of how to detect damage and predict future maintenance requirements of large infrastructures such as bridges due to aging, environmental change, vehicular loads and other human-induced factors.

The research reported in [R6] addressed the issue of inherent high dimensionality of measured structure data in raw time series sensory signals for SHM using different deep learning techniques to assess the reliability as well as the trade-off between accuracy and of different deep learning models, assisting the relevant stakeholders to make informed decision in maintenance and operation of bridges.

The work in [R7] makes use of physical features embedded in raw data and an elaborated hybrid deep learning model, featuring two algorithms—convolutional neural network (CNN) and long-short term memory (LSTM). Building on advances in algorithms for health monitoring uniting machine learning, structural mechanics and signal processing Nguyen developed a novel hybrid approach that delivered highly accurate results in detecting damage and its severity even for multiple damage scenarios. The resulting method has been a practical end-to-end data-driven framework used for defining a Digital Twin for automatically monitoring the operational state of structures. This framework is reported in the *IEEE Transactions on Automation Science and Engineering* [R7]. These works were integrated in a Cloud based Digital Twin platform (http://3.140.199.12/) that was critical to the repair plan development of the Thăng Long bridge in Hanoi, Vietnam by the Ministry of Transport resulting in savings of £1.5 million on repair costs and benefits of £7.6 million in economy [S12].

3. References to the research (indicative maximum of six references)

[R1] Clark, T., Barn, B.S. and Oussena, S., 2011, February. LEAP: a precise lightweight framework for enterprise architecture. In Proceedings of the 4th India Software Engineering Conference (pp. 85-94). ACM. (doi:10.1145/1953355.1953366)

[R2] Clark, T., Kulkarni, V., Barn, B., France, R., Frank, U. and Turk, D., 2014, January. Towards the model driven organization. In 2014 47th Hawaii International Conference on System Sciences (pp. 4817-4826). IEEE. (doi:10.1109/HICSS.2014.591)

[R3] Kulkarni, V., Barat, S., Clark, T. and Barn, B., 2015, September. Toward overcoming accidental complexity in organisational decision-making. In 2015 ACM/IEEE 18th International Conference on Model Driven Engineering Languages and Systems (MODELS) (pp. 368-377). IEEE. (doi: 10.1109/MODELS.2015.7338268)

[R4] Clark, T., Kulkarni, V., Barat, S. and Barn, B., 2017, June. ESL: an actor-based platform for developing emergent behaviour organisation simulations. In International Conference on Practical Applications of Agents and Multi-Agent Systems (pp. 311-315). Springer, Cham. (doi: https://doi.org/10.1007/978-3-319-59930-4_27)

[R5] Barat, S., Kulkarni, V., Clark, T., Barn, B. (2019) An Actor Based Simulation Driven Digital Twin for Analyzing Complex Business Systems. Proceedings of the 2019 Winter Simulation Conference, 2019, Maryland, USA.(doi**:** 10.1109/WSC40007.2019.9004694)

[R6] H. V. Dang, M. Raza, V. T. Nguyen, T. T., Bui, and H. X. Nguyen, "Deep Learning-Based Detection of Structural Damage Using Time-Series Data," *Structure and Infrastructure Engineering*, 2020. DOI: 10.1080/15732479.2020.1815225

[R7] H. V. Dang, H. Tran-Ngoc, N. V. Tung, B. T. Thanh, G. De Roeck, H. X. Nguyen, "Data-Driven Structural Health Monitoring using Feature Fusion and Hybrid Deep Learning," *IEEE Transactions on Automation Science and Engineering*, Nov. 2020. DOI: 10.1109/TASE.2020.3034401

4. Details of the impact (indicative maximum 750 words)

International and industry collaborations have shaped Middlesex's leadership in applied digital twin research. It has been arrived at from two different starting points but shares the underlying principle of *model based design*. This section outlines the impacts from both strands of work.

(a) Impacts arising from our Software Engineering research:

The work in software engineering, closely developed with TCS, is an example of a pioneering research collaboration in an emerging area of technology between academia and industry where knowledge transfer is continuous and facilitated by annual sabbatical residencies, presentations to TCS staff, joint publication, and supervision of TCS research staff.

TCS Research is a pioneer in core technology infrastructure to support Model Driven Engineering (MDE) and has delivered several large business critical software systems using this infrastructure for almost 20 years. They recognized that MDE could be applied to address all aspects of an enterprise such as vision, mission, goal, strategies and operational processes. These research questions were congruent with the LEAP research conducted by Barn and Clark [R1] and it is this that shaped the collaboration. The [S1] letter from the Executive Vice President and Chief Technology Officer of TCS confirms the basis of the collaboration, the ongoing work and the benefit of contributions of Barn and Clark to TCS activity.

After the initial influence of R1, the research collaboration between Middlesex and TCS was formally noted in a memorandum of cooperation. A co-designed research agenda was initiated, with the aim that it should lead directly to products for creating agent-based simulation models of enterprises. The research roadmap was conceptualized in the MDO vision paper [R2] and then formalized into a research roadmap report for TCS customers and shareholders [S3].

As a result of this research collaboration, TCS has been able to raise their profile in the area of enterprise modelling and simulation. This has had a positive impact on client satisfaction and loyalty, the generation of new revenue streams and their reputation for research-led innovation. Specific examples include:

- Development of the TCS world-leading digital twin product – TwinX™ based on the meta model developed by Barn and Clark. The TwinX™ product is now being being provided as solution by TCS to companies such as VodafoneZiggo and has a product manager assigned – Kaustav Bhattacharya [S2].
- Proof-of-concept demonstrators. The technology arising from the research has been showcased by TCS using proof-of-concept demonstrators [S1]. Case studies covering various business optimisation requirements based on ESL [research reported in R7] were developed. These included: Optimizing operation of a parcel sorting terminal; Optimization of order-to-activation process of a telecommunications company using digital twin based on ESL; and Optimized stock-replenishment for shops in a retail supply chain using digital twin based on ESL.
- New Business. The extension of ESL with machine learning capabilities described in [R5] has been applied by TCS Research to a commercial problem provided by a European supermarket client. The company has, to date, been using a system-dynamics approach to simulation which takes several weeks to stabilize and produce a solution. Using the ESL-based machine learning simulation, TCS Research has been able to demonstrate the reduction of the stabilization time to a matter of hours. In this case, both the approach and the ESL technology have supported TCS in promoting TCS Research to existing and new clients [S1].
- Conceptual scope in company R&D. TCS research labs incorporated MDO as one of their research themes as described in their promotional literature to clients and shareholders [S2].
- Barn and Clark co-supervised a TCS Research employee on a doctoral programme at Middlesex from 2015-18. [S4]. The successful PhD has diffused ESL knowledge within the TCS through the recruitment of three new researchers specifically to develop local expertise in ESL. This was seen as critical for transferring research knowledge to the end user and building capacity in digital twin simulation at TCS.

To reach a broader audience beyond research, Barn is a co-editor of a book initiated by TCS Research 'Advanced Digital Architectures for Model-Driven Adaptive Enterprises' with IGI-Global. The book contains by-invitation contributions from industry leaders in the field and aims to establish TCS as a thought leader in the field of model driven enterprises and simulation-based methods [S5]. The book is aimed at practitioners seeking to understand digital twin technology. It was promoted via a post by Sankha Som, Chief Innovation Evangelist to his 500+ connections on LinkedIn. His post reported on the collaboration with Middlesex regarding Enterprise Modelling and stated how this "**area has already made its way into Enterprise Digital Twins that we are developing for various domains such as Telecom…"** [S8].

Our earlier research had already indicated that the design approach and the ESL technology was viable in socio-technical systems [R6]. In early April 2020, colleagues at TCS developed a local

Java implementation of ESL that originally developed at Middlesex. The TCS implementation has been productized as the Java TwinX™ Library. This software has been used to model scenarios for non-pharmaceutical interventions for the COVID-19 pandemic in the Pune region by working closely with a local Pune based NGO (PrayasPune.org). The fine-grained analysis of COVID-19 pandemic management was led by Dr Souvik Barat using the TwinX™ Java library based on ESL. Details of the simulation are described in [S7] where the role of Dr Barat as lead on the TCS team is documented. This (ongoing – March 2021) activity has been reported in a Pune-based newspaper and in national newspapers and is shown in [S6]. On 03/03/2021, the national TV channel, MirrorNow, ran a debate about Maharashtra's recent COVID-19 pandemic spike in infections (available at: https://www.youtube.com/watch?v=x48G7-bOvPY). On this programme, Dr Abhay Shukla (national convenor, the People's Health Movement-India), noted:

"The TCS-Prayas model that has been published, it has predicted the second wave back in mid-December, at a pretty accurate level." [S9]

(b) Impacts from Digital Twins for Structural Health Monitoring:

The digital twin developments arising from the TCS collaboration and collaboration with Prof. Nguyen led to the Faculty of Science and Technology establishing the London Digital Twin Research Centre (LDTRC). Research outputs [R6, R7] from an international collaboration funded by the Newton Fund and UKIERI were brought to the attention of Ministry of Transport of the Vietnamese Government. The Ministry of Transport collaborated with a project team from Middlesex and the University of Transport and Communications, Hanoi. Using the conceptual and modelling developments reported in section 2. The collaboration has led to:

- Preparation of a repair plan by the research team for the Thăng Long bridge in Hanoi, Vietnam by the Ministry of Transport resulting in savings of £1.5 million on repair costs.
- Early re-opening of the Thăng Long bridge helped reduce traffic flow resulting in an estimated further benefit to the economy of Hanoi of around £7.6 million.
- Policy development in digital transformation for infrastructures in Vietnam. The Ministry of Transport intends to use the digital twin technology developed by Middlesex and UTC on other bridges including Nhật Tân bridge, Cần Thơ bridge, and Mỹ Thuận bridge

The engagement and utilisation of the research [R6, R7] was essential in reducing the maintenance costs and was reported as critical in policy development in helping Vietnam towards digital transformation for infrastructures [S10], which was reported on the national TV programme "Digital Nation" in Vietnam on 7th March 2021 [S11].

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] Corroborating letter from the Chief Technology Officer of TCS Research. (PDF)

[S2] TCS Digital Transformation and TwinX™. (PDF)

[S3] Research strategy (Conceptual Scope Document) (PDF)

[S4] Staff development at TCS (PhD): http://eprints.mdx.ac.uk/26456/

[S5] Advanced Digital Architectures for Model-Driven Adaptive Enterprises – Edited Book for Practitioners. https://www.igi-global.com/book/advanced-digital-architectures-model-driven/226277

[S6] Newspaper articles from "The Week" and "Hindustan Times". (See generated PDF)

[S7] COVD-19 Simulation report from PrayasPune Last accessed: https://prayaspune.org/health/images/galleries/Brief%20digital%20twin%20covid.pdf

[S8] LinkedIn Post by Sankha Som, Chief Innovation Evangelist at TCS. (see generated PDF).

[S9] Discussion of the TCS-Prayas Agent based Model on Indian National TV. https://www.youtube.com/watch?v=x48G7-bOvPY

[S10] Corroborating letter from Ministry of Transport, Vietnam. (PDF)

[S11] Digital Twin work reported on National TV programme 'Digital Nation': https://vtv.vn/video/quoc-gia-so-07-3-2021-488990.htm