REF2021

Institution: Aston University

Unit of Assessment: UoA11 Computer Science

Title of case study: Digital Twins for Complex System Engineering

Period when the underpinning research was undertaken: 2018-2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s): Professor Tony Clark	Role(s) (e.g. job title): Deputy Dean	Period(s) employed by submitting HEI: 2018-present

Period when the claimed impact occurred: 2018-2020

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact

Research at Aston University has developed a new agent programming technology for simulating and analysing complex enterprise systems using digital twin principles. The results have influenced the strategic direction of Tata Consultancy Services (TCS) Research and have been used in the field by TCS to improve their ability to provide client demonstrators and commercial solutions. The technology has been productized by TCS as TwinX™.

2. Underpinning research

Aston's Software Engineering Research Group (SEA) undertakes world-leading research that aims to improve the quality of software systems development. Businesses are increasingly connected to a range of clients and services and their reliance on software is leading to large-scale, networked, semi-autonomous interdependent systems. Execution of a new system involves interacting with previously unknown systems requiring the new system to be future proofed in terms of maintaining its own goals. The new system may also need to take advantage of new situations presented by the ecosystem. It is no longer possible to consider a single system as having a fixed behaviour: it must learn to adapt in order to achieve its intended function and even change its function over time.

Clark's work within SEA has developed simulation and modelling techniques that are used to design, analyse, and adapt the quality assured development of complex enterprise systems. Much of this work has been achieved in collaboration with partners, particularly TCS Research. Clark's contribution has led to new methods and technologies. The contribution is ongoing and builds directly on a history of collaboration that is described in the rest of this section. Areas of impact are forward and backward referenced using (**NAME:IMPACT_ID**), sources of evidence are referenced as [**S_ID**] and references are given as [**R_ID**].

Existing approaches to enterprise modelling are not suitable as a basis for simulation and analysis. Clark's earlier work on the Unified Modelling Language and a resulting commercial spin-out led to the construction of an executable modelling language called LEAP together with a collaborative initiative: 'The Model Driven Organization' (MDO) co-founded with TCS Research that was adopted as a research theme by TCS Research as evidenced by their publicity material [**R2**] [**S3**] (**MDO: I1**).

Clark has been hosted annually by TCS Research in Pune India for a week 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 as a development of 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 (**Decision-Making: I2**).

Since joining Aston, Clark has led on the development of a technology to support the modelling and decision-making approach (**I2**) that has been jointly delivered with TCS Research as tutorials at leading international conferences [**R5**] [**S2**] (**Profile**: **I3**). 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) both of which are open source (**ESL**: **I6**).

ESL provides a number of novel features compared to other agent-based simulation technologies including the application of temporal patterns over simulation histories [**R1**], and an ability to perform system adaptation through agent monitors. Part of this research was undertaken by a TCS Research employee PhD thesis co-supervised by Clark [**R6**] [**S5**] (**Temporal Processing**: **I4**).

Recent research at Aston has significantly extended ESL with adaptation technology in the form of machine learning [**R4**] producing a novel approach to the use of agents in the construction of a digital twin for complex business system simulation [**R3**] (**Digital Twins**: **I5**). This addresses a major issue faced by enterprise modelling that arises from the lack of information: it is generally only possible to construct a partial simulation model. Machine learning can be used to adapt the partial agent-based model to satisfy an overall system goal without knowing a-priori the complete system behaviour.

3. References to the research

[R1] **Clark, T**., Barn, B., Kulkarni, V. and Barat, S., 2019, February. Making Sense of Actor Behaviour: An Algebraic Filmstrip Pattern and its Implementation. In Proceedings of the 12th Innovations on Software Engineering Conference (formerly known as India Software Engineering Conference) (p. 13). ACM. (**I4, I6**)
https://doi.org/10.1145/3299771.3299783

[R2] **Clark, T**., 2018. Introduction to the Special Issue on Model-Driven Organisations. Enterprise Modelling and Information Systems Architectures (EMISAJ)–International Journal of Conceptual Modelling: Vol. 13, Nr. 3. (**I1**, **I2**) **DOI:** 10.18417/emisa.13.3

[R3] 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. (**I2**)
DOI: 10.1109/WSC40007.2019.9004694

[R4] **Clark T**., Barn B., Kulkarni V., Barat S. (2020) Language Support for Multi Agent Reinforcement Learning. Proceedings of the 13th Innovations in Software Engineering Conference, Jabalpur, India. (To be presented). (**I5**, **I6**)
https://doi.org/10.1145/3385032.3385041

[R5] Kulkarni, V. and **Clark, T**., 2019, May. Towards Adaptive Enterprises Using Digital Twins. In 2019 13th International Conference on Research Challenges in Information Science (RCIS) (pp. 01-05). IEEE. (**I5**) **DOI:** 10.1109/WSC40007.2019.9004956

[R6] Barat, S., Barn, B., **Clark, T**. and Kulkarni, V., 2020, November. OrgML- A domain specific language for organisational decision-making. In IFIP Working Conference on The Practice of Enterprise Modeling (pp. 155-170). Springer, Cham. (**I4**)
https://doi.org/10.1007/978-3-030-63479-7_11

4. Details of the impact

Aston research has had a direct influence on the direction of TCS Research starting with the creation of the MDO research theme (**I1**) leading to the development of an approach to handle complex decision making in organisations (**I2**), establishing the idea of a Digital Twin based on novel agent-based approaches (**I3**) [**S1**]. In 2019 this work won a TCS Innovation Award in competition with over 6000 entries. The PhD research in collaboration with Aston led to the design of a domain specific language that TCS are building into a product (**I4**).

The approach and associated technology (**I5,I6**) for digital twins has been used by TCS research to develop a collection of real-world proof of concept demonstrators that have been used to engage with commercial clients and acquire new business conducted in [**S1**]:

- Optimizing operation of a Parcel Sorting Terminal in the face of dynamism and uncertainty.

- Customer Engagement optimization across the customer life-cycle through multi-modelling and co-simulation to drive CLV maximization.

- Optimization of order to activation process of a telecommunications company using digital twins based on ESL.

- Optimized stock-replenishment for shops in a retail supply chain using digital twin based on ESL.

The MDO initiative was led by Clark and co-developed with TCS Research and other partners. This had a direct impact on the research strategy of the TCS research labs which incorporated MDO as one of their research themes as described in their promotional literature to clients [**S3**].
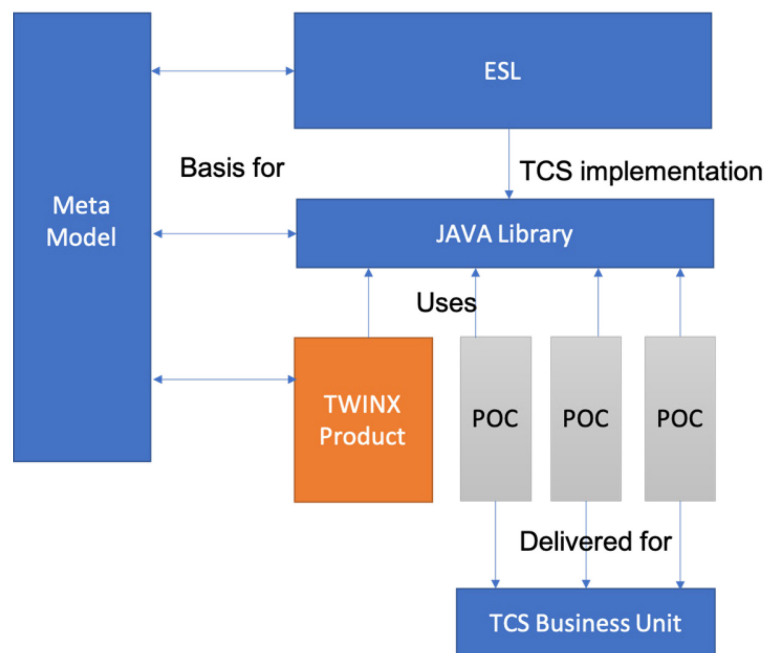

Figure 1 ESL Meta model and TCS TwinX

In order to deliver these case studies to their clients, TCS has used the underlying meta model architecture, design of ESL language to inform and lead directly to the development of their own world leading digital twin product – TwinX ™ as shown in figure 1. The TwinX™ product is now being evangelized by TCS partners [**S5**] and has a dedicated commercial product manager [**S5**].

The extension of ESL with machine learning capabilities described in [**R4**] has been applied by TCS Research to a commercial problem provided by a European supermarket client. The client is interested in improving the efficiency of their supply chain network in terms of product wastage and customer starvation. 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 leading to strong commercial interest from the client. In this case, both the approach and the ESL technology have supported TCS in acquiring new business.

As a result of the research collaboration, TCS has been able to raise their profile in the area of enterprise modelling and simulation. In addition to ongoing co-publication of research results, Clark has co-delivered tutorials on the approach with TCS researchers at leading international conferences including MODELS and RCIS [**S2**].

Clark co-supervised a TCS Research employee to study for PhD (awarded 2019). The PhD research developed an extension to ESL including a novel mechanism for defining temporal

features in a simulation model [**S4**]. The successful PhD has embedded ESL knowledge within the TCS through the recruitment of new researchers specifically to develop local expertise in ESL. This was seen as critical for transferring research knowledge to the end user.

Clark 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 research leaders in the field and aims to establish TCS as a thought leader in the field of model driven enterprises and simulation-based methods [**S6**].

In early April 2020, colleagues at TCS used the approach to examine issues around the COVID-19 pandemic to model scenarios for the Pune, India region by working closely with local authorities. [**S1**]

5. Sources to corroborate the impact

[**S1**]   Corroborating letter from Executive Vice President and Chief Technology Officer, Tata Consultancy Services (TCS) Research

[**S2**]   Tutorial Slides:

   a. Tutorial Slides Delivered at RCIS Conference (2019).

   b. Tutorial Slides Delivered at MODELS Conference (2018).

[**S3**]   Model Driven Organisation Promotion:

   a. https://modeling-languages.com/tata-consultancy-services-model-driven-development-model-driven-organization/

   b. https://www.tcs.com/content/dam/tcs/pdf/discover-tcs/research-book/Towards%20Adaptive%20Enterprises.pdf

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

[**S5**]   TwinX Promotion:

   a. https://www.tcs.com/tm-forum-digital-transformation-asia-2019

   b. https://www.linkedin.com/posts/kaustav-bhattacharya-9b0b4b19_tcstwinx-digitaltwins-tatainnovista-activity-6723248068197777408-2vJf

[**S6**]   Advanced Digital Architectures for Model-Driven Adaptive Enterprises: Authored book based on work with TCS - https://www.igi-global.com/book/advanced-digital-architectures-model-driven/226277