Institution: Brunel University London		
Unit of Assessment: 11 Computer Science		
Title of case study: Cloud-based High-Performance Simulation Techniques to Reduce Manufacturing and Logistics Costs Through Better Decision Making		
Period when the underpinning research was undertaken: 2016-2019		
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:**
a)Professor Simon J E Taylor b)Dr Anastasia Anagnostou	a)Reader/Professor b)Research Fellow/Lecturer	a) 01/1995-present b) 03/2012 - present
Period when the claimed impact occurred: August 2013 to December 2020		
Is this case study continued from a case study submitted in 2014? N		

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

Brunel researchers' novel cloud-based High Performance Simulation (HPS) techniques have enabled in this REF period: (i) at least 30 SMEs to develop new cloud-based HPS products leading to around GBP13,000,000 increased turnover, (ii) Saker Solutions to increase their turnover to around GBP1,400,000 and delivering some GBP2,000,000,000 – GBP3,000,000 benefit to nuclear, manufacturing, defence and retail industries, (iii) a new cloud-based nuclear waste reprocessing decision support system at Sellafield PLC Saker Solutions (UK SME) and (iv) a new startup (CloudSME UG).

2. Underpinning research (indicative maximum 500 words)

Computer simulation is widely used in manufacturing and logistics from new product design (e.g. continuous simulation (**CS**) used mainly in product design (efficiency of air flow over turbine blades, movement of oil in tankers, etc.) to evaluating improvements in production and logistics (e.g. discrete-event simulation (**DES**) (analysis of factory improvements, supply chain logistics, warehouse organisation, etc.)). Contemporary simulation software systems limit the amount of investigation/experimentation that can be done in a project, and therefore the quality of results (**THEME1**), and model size/reuse (**THEME2**). **THEME1**:**DES** until relatively recently no widespread approaches were used by commercial simulation vendors to speed up experimentation; **CS** simulation software is typically parallelised and uses multiple CPUs to speed up simulations; these need expensive computing clusters to run. **THEME2**:**DES** commercial simulations typically run on a single computer which limits model size.

THEME1:DES/CS - cloud computing enable users to "hire" multiple computational resources that can significantly speed up simulation experimentation through parallel execution. This can result in better results and decision making. Simulation software vendors are typically SMEs. The development of cloud-based High-Performance Simulation (HPS) software is costly and this is a major barrier to innovation. In the FP7 Cloud-based Simulation platform for Manufacturing and Engineering (CloudSME) project (www.cloudsme.eu), research by Taylor/Anagnostou in collaboration with the project leader (Kiss, Westminster) and the CloudSME project team led to the development of the CloudSME Simulation Platform (CSSP) that enabled the rapid creation of commercial cloud-based HPS software solutions on multiple clouds (e.g., Amazon, Azure and European SME cloud providers such as CloudSigma, etc.). Previous experience in HPS enabled Taylor/Anagnostou to bridge between commercial simulation application development with the technical development of the CSSP platform. Taylor/Anagnostou worked with the industrial partners to develop their new cloud-based simulation applications and ensured that the CSSP would fully support these. SMEs use the CSSP's common API to create new cloud applications that can run on different clouds. This avoids potentially redevelopment costs when moving to

another cloud and allows SMEs to exploit savings from the emerging worldwide cloud market. Applications can be web-based or desktop (**REF3**, **REF6**). The Cloud Orchestration at the Level of Application (COLA) project continued this work (project-cola.eu) by leveraging advances in containerisation to produce the auto-scaling Microservices-based Cloud Application-level Dynamic Orchestrator (MiCADO) service. Taylor/Anagnostou worked with Kiss in the COLA project to produce JQueuer that augments MiCADO to enable the optimum use of cloud-based resources in simulation experimentation via deadline scheduling (**REF5**).

THEME2:DES - Large simulations can be composed from a set of linked new/existing smaller simulations running on multiple computers. Taylor led international standardisation efforts with the US-based Simulation Interoperability Standards Organization (SISO) to produce the world's first standard in this area (Standard for COTS Simulation Package Interoperability Reference Models (SISO-STD-006-2010) (**REF1**). The common approach to interoperating simulations (distributed simulation) is specified in other standards. However, these do not capture problems common to commercial simulation applications. This research created methods and interoperability patterns that implemented these standards to enable large-scale simulations consisting of new or reused models. **REF2** describes the methodology based on a non-confidential case study.

Overall, this work has created a foundation for high performance simulation in industry by combining **THEME1** and **THEME2** (see **REF4** for details on the overall "vision").

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

REF1 Taylor, S.J.E., Anagnostou, A., Kiss, T., Terstyanszky, G., Visti, H., Farkas, Z., Kacsuk, P., Sereda, A. and Fantini, N. (2018). The CloudSME simulation platform and its applications: A generic multi-cloud platform for developing and executing commercial cloud-based simulations. Future Generation Computer Systems. 88:524-539.

REF2 Taylor, S.J.E., Anagnostou, A., Kiss, T., Terstyanszky, G., Kacsuk, P., Fantini, N., Lakehal, D. and Costes, J. (2019). Enabling Cloud-based Computational Fluid Dynamics with a Platform-as-a-Service Solution. IEEE Transactions on Industrial Informatics. 15(1): 85-94.

REF3 Kiss, T., DesLauriers, J., Gesmier, G., Terstyanszky, G., Pierantoni, G., Abu Oun, O., Taylor, S.J.E., Anagnostou, A., Kovacs, J. (2019). A cloud-agnostic queuing system to support the implementation of deadline-based application execution policies. Future Generation Computer Systems, 101: 99-111.

REF4 Taylor, S.J.E., Turner, S.J., Strassburger, S. and Mustafee, N. (2012). Bridging The Gap: A Standards-Based Approach to OR/MS Distributed Simulation. ACM Transactions on Modeling and Computer Simulation. 22(4): Article 18.

REF5 Anagnostou, A., & Taylor, S. J. E. (2016). A distributed simulation methodological framework for OR/MS applications. Simulation Modelling Practice and Theory, 70, 101-119. doi:10.1016/j.simpat.2016.10.007

REF6 Taylor, S.J.E. Distributed Simulation: State-of-the-Art and Potential for Operational Research. (2019). European Journal of Operational Research. 273(1):1-19.

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

This research has had impact in many areas of manufacturing and logistics in terms of enabling better decisions through the use of faster experimentation (**THEME1**) and larger simulations (**THEME2**). It has therefore enabled (i) many commercial cloud-based high-performance simulation (HPS) systems, (ii) a major high-performance simulation industrial application of large scale simulation and associated innovations, and (iii) contributions to standardisation. Overall, based on substantial industrial experience, the major impact of this work has been to create a foundation for future industrial high performance simulation systems by combining both themes.

(**THEME1**) The impact of cloud-based HPS has been to enable vendors to create new products/services with a knock-on impact to their clients through more detailed analyses within project timescales. A diverse range of applications include business process simulation, footwear design, emissions reduction, inventory management and freight transportation. Overall, the impact so far has been evidenced by 30 European SMEs from 12 countries that reported the following estimated economic impact as a result of this work: a cumulative turnover increase of approximately GBP13,000,000, leading to the development of around 150 new products or services in manufacturing & logistics and contributing to the creation of around 100 new jobs. Additionally, these companies reduced the time to market for new products and improved business processes, customer satisfaction and business practices. The above numbers are evidenced in official project reports/deliverables of the CloudSME and COLA projects submitted to the European Commission and provided by executives of the involved companies (**E1, E2**). The CSSP is also being used in other large projects (e.g. the H2020 Cloudifacturing project involving around 200 SMEs). These figures can be considered to be a lower bound.

The FP7 CloudSME project also led to the founding of CloudSME UG in 2015, a new start up to continue to develop new cloud-based HPS (**E3**). With Taylor as a scientific advisor, the company now has 4 employees and an annual turnover of approximately GBP133,000 since 2017 (primarily through contracts in manufacturing) and made its first profit in 2019. The impact of Brunel's work is further supported by two videos created for the European Commission that demonstrates the results of their ICT for Manufacturing SMEs (I4MS) programme (CloudSME was funded under this). The video by Hobsons Brewery, a UK-based SME craft-brewer, shows how cloud-based simulation made their business more efficient (**E4**). The video by Podoactiva, a Spanish SME manufacturer of tailored foot insoles, shows how the technology enabled them to increase their market by enabling new insole design applications for podiatrists. These projects also enabled Saker Solutions, Hobsons Brewery and Taylor/Anagnostou to successfully bid for an InnovateUK project (CraftBrew) that facilitated the development of a low-cost enterprise management system for small brewers.

(**THEME1 and THEME2**) Taylor/Anagnostou have worked with Saker Solutions (SME, UK) and Sellafield PLC to develop many discrete-event simulations of nuclear waste reprocessing. The impact of **THEME2** (large models) comes from training Saker to create large distributed simulations. Taylor/Anagnostou worked with Saker Solutions and Sellafield PLC to develop a distributed simulation of the Magnox Swarf Storage Silo (MSSS) system. This is the only distributed simulation used in the nuclear industry (**E6**). This reuses and links six previously developed simulations to form a large-scale simulation of nuclear waste recycling in this area. SAKERGRID, a high-performance simulation system previously developed with Taylor to manage and deploy simulation experiments on a computing cluster (and now cloud) has been significantly extended through the above research and deployed at both Saker and Sellafield (**THEME1**). This has led to an increased turnover at Saker of GBP1,400,000 since 2014 with some GBP2,000,000 – GBP3,000,000 of benefit mainly to the nuclear industry (Sellafield) but also manufacturing, defence and retail sectors. In addition, there are unquantified savings arising from the reduced turnaround time of experimentation enabled by the use of SAKERGRID which both reduces project lead time and increases the number of scenarios which can be examined. The upgrading of SAKERGRID to cloud also enabled Saker to continue working effectively during the COVID pandemic (**E7**).

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

E1: CloudSME deliverable D4.6 IPR management/monitoring and exploitation/use 2, 31st March 2016, submitted by the CloudSME project to the European Commission, pages 13-21 containing exact impact figures of participating companies.

E2: COLA deliverable D3.3 First commercial exploitation and sustainability report, 21st December 2017, submitted by the CloudSME project to the European Commission, pages 30-33 containing exact impact figures of participating companies.

E3: Evidence provided by CloudSME UG (Germany).

E4: Impact video by Hobsons Brewery and Company Limited - https://www.youtube.com/watch?v=TGYE9l5cHs0

E5: Impact video by Podoactiva SL - https://www.youtube.com/watch?v=ymhplrZWj_Q

E6: Description of the MSSS distributed simulation in Sellafield PLC, The 2017 Technology Development and Delivery Summary, p.18.

E7: Evidence provided by Saker Solutions Ltd (England).