Institution: The University of Manchester		
Unit of Assessment: 10 (Mathematics)		
Title of case study: Making industrial installations safer and more efficient by identifying real and false alarms		
Period when the underpinning research was undertaken: January 2011 – November 2016		
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:**
Tim Butters	PDRA, KTP Associate (now Head of R&D, Argent and Waugh)	2013 – 2016
Stefan Güttel	Lecturer, Senior Lecturer, Reader	2012 – present
Nicholas Higham	Professor	1985 – present
Jonathan Shapiro	Reader	2003 – present
Period when the claimed impact occurred: August 2013 – present		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Large-scale industrial installations - such as oil refineries and power stations - rely on safety-critical systems that employ distributed sensor networks coupled to alarms. A sub-optimal or erroneous alarm configuration at these installations can have catastrophic environmental, health, and economical consequences.

Researchers at The University of Manchester (UoM) and the SME Argent & Waugh Ltd have used new mathematical algorithms and methods to develop an innovative approach to improve alarm configurations that identify redundancies reliably and in real time. The new approach is deployed at industrial sites *via* the widely-used Sabisu software platform, with more than **6,000 individual license owners worldwide**, at companies such as SABIC, Royal Dutch Shell, and Huntsman. For SABIC alone, the savings from using Sabisu are estimated at **GBP1,500,000 *per annum***, resulting from more efficient real-time monitoring of equipment.

Further benefits arise from **increased plant safety** and **reduced operator workload** in the plants, and for Argent & Waugh through increased profits and enhanced capability.

2. Underpinning research

The impact is underpinned by research in numerical linear algebra that has taken place at The University of Manchester (UoM), primarily in the Department of Mathematics, since 2011. The fundamental research on matrix functions was financially supported by an ERC Advanced Grant, while the industrial impacts have been realised through a Knowledge Transfer Partnership (KTP). The approach to identify redundant alarms in networks of industrial scale is based on a combination of key findings in network centrality analysis **[1]** and numerical linear algebra methods for the approximation of large-scale matrix functions **[2, 3]** as detailed below.

Making matrix centrality measure computations feasible in [2]
The new scaling-and-squaring algorithm "`expm_new`" in **[2]** enables computation of the action of a large sparse matrix's exponential onto a vector, instead of computing the (generally dense) matrix exponential explicitly. This work makes calculations of exponential-based centrality measures for large networks, which determine the most important components of the network, computationally feasible and reliable. Extensive numerical tests of "`expm_new`" reported in **[2]** quantify speedup factors of between 3.5 and 321 greater than competing methods based on polynomial expansions for sufficiently large time steps, while achieving the same or better accuracy (speedup factors taken from Table 6.4 in **[2]**).

New insights into the relation between centrality measures from [1]
The research in **[1]** justifies, both theoretically and numerically, that computationally more expensive resolvent-based centrality measures can be replaced by computations of matrix exponentials without affecting the centrality rankings significantly.

Further significant speedup allowing for interactive real-time computations in [3]

Finally, the scaling-and-squaring algorithm "`sexpm`" developed in **[3]** is the one implemented by the KTP Associate under the guidance of the academic team in the Sabisu software marketed by Argent & Waugh Ltd. The algorithm crucially relies on the discovery in **[3]** that the scaling-and-squaring algorithm can be made significantly more efficient for matrices with special spectral properties, which are satisfied for the matrices arising in the context of alarm network modelling.

The efficiency gains obtained with "`sexpm`" enable the computation of centrality measures for alarm networks with many thousands of nodes (a node being an alarm/sensor) within milliseconds in the Sabisu platform. This makes the computation truly real-time and, crucially, interactive (see, *e.g.*, the numerical tests in Figure 7.3 of **[3]** where speedup factors of between 2 and 80 over "`expm_new`" are reported). The new algorithm in **[3]** reduces numerical difficulties associated with over-scaling, making the computation more reliable. This is an important requirement in safety-critical environments such as industrial plants.

Further work arising from [1-3]
The underpinning academic research was tailored to the application and presented in a number of engineering conferences. Paper **[4]** reports on a numerical study on real-world alarm data provided by SABIC Petrochemicals UK, quantifying the benefits that can be achieved with the newly developed approach. Paper **[5]** introduces an intuitive visualisation of alarm clusters based on animated graphs and sparsity plots of associated matrices. While sparsity plots are widely used in numerical linear algebra and network analysis, their utilisation in the context of alarm systems is novel. Paper **[6]** introduces a new approach to real-time fault detection, based on sensor anomalies, allowing alarm faults to be traced back to their root-cause using historical time series data available from sensor readings.

3. References to the research

The key research related to this impact case was published in leading journals, including top journals in the field in Scientific Computing and Numerical Analysis (SIAM Journal Scientific Computing and SIAM Matrix Analysis and Applications). The practical aspects were presented at project management and engineering conferences and published in peer-reviewed proceedings. The research was supported by ERC Advanced Grant MATFUN 267526 and Innovate UK Knowledge Transfer Partnership #9315. UoM authors are highlighted in bold text.

Key journal papers: [Google Scholar (GS) citations as of 5 March 2021]

[1] **M. Aprahamian**, D. J. Higham, and **N. J. Higham**: "Matching exponential-based and resolvent-based centrality measures." *Journal of Complex Networks* 4(2):157–176, **2016**. DOI: 10.1093/comnet/cnv016 [GS citations: 27]

[2] A. H. Al-Mohy and **N. J. Higham**: "Computing the action of the matrix exponential, with an application to exponential integrators." *SIAM Journal on Scientific Computing* 33(2):488–511, **2011**. DOI: 10.1137/100788860 [GS citations: 362]

[3] **S. Güttel** and Y. Nakatsukasa: "Scaled and squared subdiagonal Padé approximation for the matrix exponential." *SIAM Journal on Matrix Analysis and Applications* 37(1):145–170, **2016**. DOI: 10.1137/15M1027553 [GS citations: 11]

[4] **T. D. Butters**, **S. Güttel**, and **J. L. Shapiro**: "Detecting and reducing redundancy in alarm networks," in *Proceedings of the IEEE International Conference on Automation Science and Engineering (CASE),* p1224–1229, **2015**. DOI: 10.1109/CoASE.2015.7294265 [GS citations: 3]

[5] **T. D. Butters**, **J. L. Shapiro**, **S. Güttel**, and T. J. Sharpe: "Statistical cluster analysis and visualisation for alarm management configuration," in *Proceedings of the 2014 Asset Management Conference,* The Institute of Engineering and Technology, **2014**. DOI: 10.1049/cp.2014.1027 [GS citations: 6]

[6] **T. D. Butters**, **S. Güttel**, **J. L. Shapiro**, and T. J. Sharpe: "Automatic real-time fault detection for industrial assets using metasensors," in *Proceedings of the 2015 Asset Management Conference,* The Institute of Engineering and Technology, **2015**. DOI: 10.1049/cp.2015.1717 [GS citations: 1]

4. Details of the impact

Context

This research has addressed a core challenge of identifying and reducing redundant alarms in complex industrial installations. Alarm systems play a critical role for the efficient and safe operation and control of plants. They alert plant operators to unexpected behaviour and perform forced shut-downs if a severe danger is detected. Failures in alarm systems can have catastrophic consequences, with incidents such as the partial nuclear meltdown at Three Mile Island and the Texas City refinery explosion both having root-causes directly linked to suboptimal alarm configuration and management. Typical configurations can easily have thousands of sensors measuring physical quantities such as pressures, temperatures, or flow rates. For example, the SABIC system studied in **[4, 5]** has 1,433 sensors, which over a two week period can trigger more than 50,000 alarms. Many of these alarms will be redundant or noise, but global standards for alarm management configuration, like International Society of Automation (ISA) SP18 and Engineering Equipment and Materials Users Association (EEMUA) 191, allow a plant operator to investigate at most one alarm signal every 10 minutes. The detection and removal of redundant alarms is therefore crucial to avoid operator overload, allowing them to focus on alarms that are genuinely important for the safe operation of a plant.

Pathway to impact

The impacts have been achieved through a Knowledge Transfer Partnership (KTP) with Argent & Waugh Ltd (July 2013 – November 2016) and KTP Associate Tim Butters, who implemented the algorithms developed in the underpinning research within the Sabisu analytical platform, and has since been employed as Head of Research & Development by Argent & Waugh Ltd post-KTP. The research was published in high-quality peer-reviewed journals **[1, 2, 3]** and presented at international conferences **[4, 5, 6]** to a wide audience of engineers and managers. The visualisations developed in **[5]** have been implemented in the Sabisu platform. The quorum-voting algorithm developed in **[6]** is used in conjunction with the new alarm network analysis within the Sabisu analytical platform.

Reach and significance of impact

With around **6,000 users distributed globally**, the Sabisu analytical platform is in wide use from small biofuels sites to multi-site petrochemicals organisations. Argent & Waugh customers include global leaders in the chemical processing industries like ENSUS, Huntsman, LNG Canada, SABIC, Shell, and Südzucker **[A]**. SABIC alone, one of Argent & Waugh's main customers, is the world's 98th-largest corporation on the Forbes Global 2000 ranking. More details on the significance of impact are given below, grouped by impact area.

<u>Real-time alarm analytics and work load reduction for plant operators</u>

The new alarm analytics capability based on the underpinning research is marketed by Argent & Waugh as a product called "SEION" **[B]**. The SEION user interface allows operators to perform alarm analytics in real-time and trace back faults to their root-cause using historical sensor readings. The system has been demonstrated to **reduce the average load per plant operator by up to 12%**, meaning that valuable time is freed up for the operators to monitor and address safety-critical alarms **[4]**. Although SEION relies on sophisticated numerical algorithms, it does not require any complex configuration and can be implemented easily in any industrial sensor network. According to Argent & Waugh, "*this solution is highly portable, leading to very short set-up times and a high level of cost effectiveness*" **[C]**.

<u>Improved early warning of maintenance requirements</u>

An engineer at SABIC Petrochemicals UK reports that SEION "*has allowed us to identify and track 'events' associated with individual cylinders; giving us early warning of maintenance requirements, allowing us to* ***consolidate work packages and minimise production losses****. However, the secondary benefits from accurate prediction of maintenance workload, including the* ***management of spare parts*** *and* ***balancing of production capacity with sales****, cannot be disregarded*" **[D]**.

<u>Savings for costumers and competitive advantages for Argent & Waugh</u>

Sabisu's analytics capabilities are a main focus for Argent & Waugh customers, and so the underpinning research and its implementation through the KTP had a transformative effect on

the company. According to the then-Head of R&D at Argent & Waugh **[E]**, "*As well as providing income to the company, the systems* [Sabisu and SEION] *have saved* [SABIC] *more than £3M over the last two years. In particular the real-time redundancy reduction capabilities enabled by Dr Güttel and Prof Higham's research on matrix functions, have been extremely popular with our customers.*" According to CEO Tim Sharpe, "*Through application of advanced mathematical expertise to model/analyse/interpret and manipulate historical data, Sabisu is now capable of providing customers with new levels of visual management, predictive control and management capability, and outperforms existing software solutions on the market in terms of visualisation, innovativeness (using new mathematical models and data analysis techniques), capability, and speed*" **[B]**.

Quantification of financial benefits for Argent & Waugh

The overall financial benefits for Argent & Waugh in 2016 resulting from the KTP (which finished at the end of 2016) are quantified by the CEO as "*£300,000 increased profit before tax, with new additional analytics capabilities driving sales with companies such as Shell*" **[B]**. Specifically attributable to the research in **[1, 2, 3]** and its implementation in the SEION analytics system are "*sales profits of £100,000 from existing customers directly attributable to the research,* [a] *further £60,000 from license sales to new customers specifically asking for the new analytics capabilities, and monthly savings of £650 from reduced cloud-computing costs due to more efficient algorithms*" **[E]**.

Capability growth of an SME through KT and job creation

Following the successful completion of the KTP, which was graded "Outstanding" by the KTP Panel **[F]**, in 2017 Argent & Waugh created a Research and Development (R&D) division to support the continuous growth of analytics capabilities, led by former KTP Associate Dr Tim Butters. Two CASE PhD students supervised by Güttel and Shapiro continue to work on the Sabisu platform. In the words of Tim Butters (in his role as Head of R&D at Argent & Waugh): "*I personally have benefitted immensely from this partnership with the academic team, equipping me with new mathematical skills and knowledge, and I am now being trusted with a leading role within the Sabisu development team"* **[E]**.

Argent & Waugh Ltd was incorporated in Feb 2009 and acquired by Aspen Technology Inc. (NASDAQ: AZPN, based in MA, USA) in June 2019 for an undisclosed fee.

Outreach and exposure

Success of the KTP and rapid implementation of novel algorithms within deployed systems has shown the impact of ongoing mathematical work in this area. Similarly, the transition of the KTP Associate to Head of R&D within Argent & Waugh speaks to the importance of bringing these skills into the company workflow. This change in understanding led to Argent & Waugh engaging in outreach directly to mathematics students, sponsoring prizes for three "Sabisu Coding Challenges" organised by the SIAM Student Chapter and the academic team, in which more than 200 mathematics students from all around the UK participated **[G]**. These challenges used industrial alarm data provided by ENSUS and SABIC. For Argent & Waugh, "*these challenges have significantly increased our visibility among young Manchester mathematics undergraduates, and already resulted in several student summer internships and short projects*" whilst additionally benefiting the students taking part **[E]**.

Argent & Waugh have received several awards and wide cross-disciplinary exposure as a consequence of the new analytics capabilities embedded into Sabisu, including the Real IT Awards 2018 **[H]**, and through presentations at industrial conferences (*e.g.*, in 2018 at the American Institute of Chemical Engineers' Annual Meeting and the Global Petroleum Show) **[E]**.

5. Sources to corroborate the impact

[A] Sabisu online case studies, list of global customers, and briefing note as retrieved on 2019/03/14 from http://www.sabisu.co/case-studies/: http://www.sabisu.co/wp-content/uploads/2015/05/Sabisu-Briefing-Note.pdf

[B] Final report on the Knowledge Transfer Partnership, with 2016 financial benefits of the project summarised by Tim Sharpe, Managing Director of Argent & Waugh Predictive Alarm

[C] Analytics website and white paper as retrieved on 2019/03/14 from http://www.sabisu.co/wp-content/uploads/2015/05/alarm-management.pdf

[D] Letter from Simon Whitfield, Machines Engineer at SABIC UK Petrochemicals
[E] Letter from Dr Tim Butters, Head of Research and Development at Argent & Waugh
[F] Assessment certificate from Ian Brotherstone, KTP Manager for Innovate UK
[G] Announcements of the winners of the Sabisu Coding Competitions in 2015–2018 as retrieved on 2019/03/14 from https://www.manchester.ac.uk/discover/news/winners-of-the-sabisu-coding-competition-2018-announced/
http://www.maths.manchester.ac.uk/~siam/sabisu1511/
http://www.maths.manchester.ac.uk/~siam/sabisu1505/
[H] Real IT Awards 2018 news article as retrieved on 2019/03/14 from https://www.gazettelive.co.uk/business/business-news/teesside-firms-celebrate-after-winning-14775382