Institution: Loughborough University		
Unit of Assessment: B12: Engineering		
Title of case study: Transforming manufacturing by deploying adaptive intelligent monitoring and knowledge-sharing methods		
Period when the underpinning research was undertaken: 2008 – 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:**
Andrew West	Professor of Intelligent Systems	1995 – present
Bob Young	Professor of Manufacturing Informatics / Visiting Professor	1989 – 2016 / 2016 – present
Paul Conway	Professor of Manufacturing Processes	1990 – present
Period when the claimed impact occurred: 2015 – 2020		
Is this case study continued from a case study submitted in 2014? No		

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

The competitive advantage of the UK's manufacturing industry is underpinned by its ability to make rapid, cost-effective decisions. Research on how to improve the decision-making ability of manufacturing by ensuring that the right knowledge was provided to the right people at the right time has 1) provided economic benefits and savings totalling £75M+ across global (e.g., Ford) and SME (e.g., S2S Ltd. and Control 2K Ltd.) businesses, and 2) enabled Ford and Rolls Royce to introduce new methods to achieve systems interoperability. In addition, the underlying principles of knowledge sharing that enable such interoperability has 3) underpinned development of a new international standard (ISO20534:2018) for Interoperability that enables smart manufacturing to achieve the vision of Industrie 4.0.

2. Underpinning research (indicative maximum 500 words)

Manufacturing decisions have traditionally been based upon a combination of observations and ad-hoc monitoring informed by human experience. Solutions were typically developed on a case-by-case basis to a high level of sophistication but were not reusable, transferrable or adaptable to new problems. The research of Professors West, Conway and Young (nine research projects of value £13.5M to Loughborough University from 2011-2020) focused on improving the decision-making ability in UK manufacturing by ensuring that the right knowledge was provided to the right people at the right time through the hardware and software solutions that enable this to happen.

First, the team identified that the next generation of intelligent manufacturing systems would require a holistic systems approach to monitoring, analysing, re-coding and presenting information to provide actionable insights. Their research delivered optimal **structures and compositions** of intelligent manufacturing monitoring systems that have enabled **new knowledge about industrial products and processes to be generated from embedded sensors' data**. Prior to this, industry lacked both the specialist knowledge and supporting software services to guarantee robust systems operation within harsh manufacturing environments. The research established a set of common intelligent building blocks, that could be configured and adapted for different domains such as automotive and electronics and were demonstrated to be effective for both global and small companies (e.g. Ford and S2S Ltd.). The key elements of the system were embedded software to collect the sensor information (i-ii), interoperable software services to analyse the sensor information in terms of key business performance indices (iii-v), and software and hardware to optimise the communications performance of the embedded solutions in harsh manufacturing environments (vi):

(i) **Configurable software state machines** embedded within physical assets that capture industrial automation best practices **[R2, R3, R4]**;
(ii) A **service bus** to integrate a network of distributed assets enabling robust communications **[R4]**;
(iii) **Reconfigurable process-based analytical and management services** to select data capture, filtering and analytics functionality as required, and ensure that services can be configured, scheduled and managed independent of location **[R3, R4]**;
(iv) Interoperable **software simulation engines** to predict business performance gains **[R1, R2]**;
(v) **Process mining services** to evaluate the real processes adopted by industry **[R4]**;
(vi) **Optimal antennas** designed via electromagnetic simulations and experimentally evaluated for proven robust communications operation within specific manufacturing environments **[R1, R4]**.

The monitoring system solutions, based on these building blocks, can operate at both the manufacturing (i.e., beginning of life) and final recycling (i.e., end of life) lifecycle stages of products and can be modified in real time to support continuous learning. This learning is, in turn, used to aid process improvements for the business.

Second, to enable **sharing and reuse of manufacturing knowledge**, our research established an ontological framework **[R5]** to organise the concepts and rules associated with knowledge from both manufacturing and throughout product subsequent life cycles and supply chains **[R6]** that can also be used throughout supply networks. The novelty lies in the logical structure of the ontology (i.e. the formally constrained hierarchy of concepts and relationships that can be traced from generic roots to specific manufacturing instances) which enables knowledge relevant to particular manufacturing domains to be specialised to suit the needs of specific manufacturing businesses and their supply chains (e.g. aerospace - Rolls Royce; automotive – Ford; electronics - S2S Ltd.; automation and systems integration – Control 2k Ltd.). Potential conflicts in semantics that inhibit interoperation of manufacturing systems are eliminated by adopting this approach. In this way, the application of our resulting Manufacturing Reference Ontologies provides effective knowledge infrastructures that can be expanded and developed to revolutionise the impact of future manufacturing software tools and services **[R5, R6]**.

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

R1 Segura Velandia, D. M., Kaur, N., Whittow, W. G., Conway, P. P. and West A. A. (2016). Towards industrial internet of things: Crankshaft monitoring, traceability and tracking using RFID. *Robotics and Computer-Integrated Manufacturing*, 41, pp. 66- 77. DOI: https://doi.org/10.1016/j.rcim.2016.02.004

R2 Pease, S. G., Trueman, R., Davies, C., Grosberg, J., Yau, K. H., Kaur, N., Conway, P. P. and West, A. A. (2018). An intelligent real-time cyber-physical toolset for energy and process prediction and optimisation in the future industrial internet of things. *Future Generation Computer Systems*, 79 (3), pp. 815-29. DOI: https://doi.org/10.1016/j.future.2017.09.026

R3 Sharpe, R. G., Goodall, P. A., Neal, A. D., Conway, P. P. and West, A. A. (2018). Cyber Physical Systems in the re-use, refurbishment and recycling of Used Electrical and Electronic Equipment. *Journal of Cleaner Production*, 170, pp. 351-61. DOI: https://doi.org/10.1016/j.jclepro.2017.09.087

R4 Neal, A. D., Sharpe, R. G., Conway, P. P. and West, A. A. (2019). smaRTI-A cyber-physical intelligent container for industry 4.0 manufacturing. *Journal of Manufacturing Systems*, 52 (A), pp. 63-75. DOI: https://doi.org/10.1016/j.jmsy.2019.04.011

R5 Palmer, C., Usman, Z., Canciglieri Junior, O., Malucelli, A. and Young, R. I. M. (2018). Interoperable manufacturing knowledge systems. *International Journal of Production Research*, 56 (8), pp. 2733-52. DOI: https://doi.org/10.1080/00207543.2017.1391416

R6 Usman, Z., Young, R. I. M., Chungoora N., Palmer, C., Case, K., and Harding, J. A. (2013). Towards a formal manufacturing reference ontology. *International Journal of Production Research*, 51 (22), pp. 6553-72. DOI: https://doi:10.1080/00207543.2013.801570

The research described in Section 2 has been supported by 9 UKRI-industry-collaborative research projects (2011-2019) and 2 EU projects, altogether totalling £13.5M to Loughborough University: under *EP/E002323/1* Interoperable Manufacturing Knowledge Systems; *EP/J501748/1* Intelligent Embedded Components for Enhanced Supply Chain Observability and Traceability; *EP/H03014X/1* Design for Increased Yield in the Electronics Manufacturing Supply Chain; *EP/K018191/1* Knowledge Driven Configurable Manufacturing; *EP/K014137/1* Adaptive Informatics for Intelligent Manufacturing; *EP/P027482/1* Future Connected Smart Manufacturing Platform in Embedded Integrated Intelligent Systems; *EU FoF-ICT-2011.7.3 -285541* Premanus: Product-Service System for Remanufacturing; *EU-FP7-NMP-608627* FLEXINET: Intelligent Systems Configuration Services for Flexible Dynamic Global Production Networks.

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

Loughborough research has enhanced decision-making processes for global automotive and aerospace manufacturers and SMEs by the provision of new information from intelligent distributed monitoring systems. It has also enabled interoperability through methods for sharing multiple related sources of knowledge, providing a framework by which these benefits can be freely implemented globally. This has resulted in a series of significant economic benefits, improved company practices and the creation and publication of an international standard.

Impact 1: Economic benefits of deploying intelligent industrial monitoring systems

Our research underpinned the design of a platform technology comprising monitoring components and analytical services that have been deployed within manufacturing facilities. The reach of our platform technology has been demonstrated through its effective implementation across different sectors (e.g., automotive and electronics) and across large (e.g., Ford) and small (e.g., S2S Ltd.) businesses.

When implemented to serve the specific needs of Ford, the system allowed the location, environmental status and cleanliness of intelligent containers that transport components between machining and assembly facilities to be determined for the first time. Since its implementation in 2015 it has "*led Ford to eradicate a global engine warranty issue that had cost the company in excess of £30M*" **[S1]**.

By designing and deploying novel miniaturised RFID tags and supporting software services to trace high-value portable components in manufacturing plants, Ford reported that physical losses were reduced:

> "*One of the main advantages of Loughborough's technology over that on the market was the size and range of the tag which allowed Ford to implement an effective deterrent significantly reducing the losses […] from theft and counterfeit of high value powertrain components […] valued at £0.28M/month/facility*" **[S1]**.

The versatility of the underpinning platform technology is also illustrated by its application to resolve and eradicate "*a significant safety issue*" **[S1]** associated with machine gantry failures in which the flexible tracks supporting the power and communications cable distribution were failing catastrophically without warning that resulted in "*significant production losses due to inspection downtime*" **[S1]**. The "*multisensory telemetry system with associated 'self-learning' algorithms*" developed from Loughborough research resulted in global savings of "*>£45M in the first year of deployment*" **[S1]**.

In addition to successful implementation within Ford, the system also brought substantial economic benefit to S2S Ltd: an SME specialised in end-of-life electronics processing. Indeed, "*S2S Ltd. is now the market leader in end-of-life processing of sensitive (in terms of stored data) waste electrical and electronic equipment*" **[S2]**.

The Loughborough system, operational since 2016, has, according to the Managing Director of S2S

> "*increased our customer base by 30%, increased our throughput capability by a factor of 10, contributed to increased profits of over £1Mpa and enabled us to provide a unique product services business that is generating more than £500k pa*" **[S2]**.

Trakk-IT Ltd. – the jointly owned spinout company established to translate Loughborough research findings into industrial solutions – received a Global Industry Innovation Award from ADISA (the global accreditation body specialising in risk management and data protection in asset retirement) in 2018 **[S2]**.

Impact 2: Improved company practices for manufacturing, maintenance and systems interoperability

In addition to the direct economic benefits described in Impact 1, Ford reported that the information provided by the embedded intelligence approaches, such as for the containers deployed within the Loughborough system, was

> "*a major contributing factor towards Ford's Industry 4.0 manufacturing and maintenance global programme (>$1B) and traceability standards based on solutions incorporated into Ford's Global 'Bill of Process' defining best practices for manufacturing programmes*" **[S1]**.

In addition, our system design, analysis and simulation research when applied to root cause analysis of manufacturing defects from a crankshaft machining transfer line "*significantly reduced business and manufacturing risk (>£64M/year) for crankshaft quality*" **[S1]** by analysing the performance, associated risk and business case of alternative embedded monitoring solutions and analysis services to identify sources of variability in the production of crankshafts.

Our formal manufacturing reference ontologies for knowledge sharing and improved cross-systems connectivity have led to the introduction of new methods for systems interoperability at Rolls-Royce plc. that have

> "*become a core part of cutting edge digital connectivity solution thinking for the company's extended supply chain*". These "*solutions for interoperability are estimated to provide cost savings opportunity to the business in the order of £60M over the next 3 years*" **[S3]**.

Our reference ontology research has also supported the practices of Control 2K Ltd: an SME business that provides training for production/assembly operators, web-based e-commerce and business productivity tools, as well as systems integration services linking front-end office applications with industrial processes to support enhanced stock control, order scheduling and energy monitoring **[R5, R6]**. Here, our research has

> "*provided a crucial input to Control 2K Limited in developing radically new manufacturing software platforms*" and, in addition, these have "*the potential to provide cost savings to manufacturing businesses in the order of £200,000 per business*" **[S4]**.

Impact 3: A new International Standard for Interoperability that underpins smart manufacturing

To maximise the benefits and reach of ontologies as applied to manufacturing, there is a requirement for recognised international standards to provide the common underpinning approaches. We extended the impact, reach and value of our reference ontology work by driving an international standardisation effort culminating in the creation and publication of the international standard, ISO 20534 in 2018. This standard is founded upon the core elements of our reference ontology, encompassing critical revisions from experts across six nations: UK, France, Spain, Germany, USA and South Korea **[S5]**.

This is an important and recognised step towards defining an ontological infrastructure to support the effective knowledge sharing required by industry, as reported by the Convenor of ISO TC184 SC4 WG8:

> "*such formal ontology standards, of which ISO 20534 plays a significant role, are fundamental to the effective achievement of Smart Manufacturing and the vision of Industrie 4.0"* **[S5]**.

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

S1 Dr Leslie Lee: Maintenance Operating Systems & Industry 4.0 Powertrain Manufacturing Engineering, Ford of Europe
S2 Mr Alan Dukinfield: Managing Director S2S Ltd
S3 Dr. Neil Hastilow: Head of Digital Manufacturing – Civil Aerospace, Rolls-Royce plc
S4 Mr Gash Bhullar: Managing Director Control 2K Limited and Sematronix Limited, Director and Chairman of TANet Limited
S5 Prof. Anne-Francoise Cutting-Decelle, Centre Universitaire D'Informatique, Universite de Geneve, Geneve, Switzerland and Convenor of ISO TC184 SC4 WG8