Institution: University of Sheffield		
Unit of Assessment: B-12 Engineering		
Title of case study: Boeing Sheffield – A first for Europe		
Period when the underpinning research was undertaken: 2003–2018		
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:**
Scott R.	Professor in Industrial Digitisation	2003–present
Hughes J.	Research Director	2006–present
Ozturk, E.	Senior Technical Fellow	2010–present
Sims, N.D.	Professor of Mechanical Engineering	2000–present
Taylor, C.	Technical Fellow	2006–present
Ridgway, K.	Professor of Design and Manufacture	1988–2019
Turner, S.	Chief Technology Officer	1997–2017
McLeay, T.	Head of Research, The Machining Group	2008–2016
Hughes, R.W.C.	Head of Manufacturing Intelligence	2012–2020
Period when the claimed impact occurred: 2016–2020		
Is this case study continued from a case study submitted in 2014? N		

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

Sheffield's research integrating advanced machining technologies for aerospace alloys with state-of-the-art factory simulation was crucial in Boeing's decision to build its first new build factory constructed worldwide in 30 years. Boeing Sheffield is a £40m, 6,200 m^2 manufacturing facility and has created 87 new high-value manufacturing jobs. Operational since 2018, Boeing Sheffield has created £50m of economic value and placed around £8m of orders with the local supply chain. Sheffield City Region has benefited from growth in both GVA (+1.0%) and employment (+1.4%), the UK Government has heralded its impact on their flagship Aerospace Sector Deal.

2. Underpinning research (indicative maximum 500 words)

In 2016, Boeing initiated a major research & development programme with the University of Sheffield's Advanced Manufacturing Research Centre (AMRC) to develop new manufacturing techniques capable of underpinning a business case for Boeing's first production facility in Europe. This case required a 20% reduction in costs, a 25% reduction in waste, and a 30% increase in productivity for the machining of gear and actuator parts. Sheffield's research programme had two objectives:

1) Develop a cost-effective and futureproof manufacturing method to displace single use machine tools and processes.

2) Integrate this new method with modelling tools that can simulate real-time operations to ensure that the production facility will have the manufacturing capacity and flexibility to meet current and future demands.

The first research objective built on Sheffield's pre-existing fundamental understanding of material removal processes for the machining of aerospace alloys and applied it to Boeing's gear-specific processes for a range of machine tools. Specifically, Sheffield's research into process damping had previously investigated the relationship between vibration and machining feed rate to maximise both stability and speed. Accurate feed rate selection for machining was achieved through development of a milling vibration time-domain model that considered process damping forces created due to interference between the tool flank and the just-cut workpiece surface **[R1]**. Through extensive experimental testing, the influence of tool edge geometry on vibration and consequently production time revealed that variable helix/pitch angles and an increased cutting edge radius improved process damping performance **[R2]**.

Traditional machining dynamics models predict the stability of a process involving a single cutting tool operating at a given point in time. Research at Sheffield had investigated parallel machining dynamics to improve productivity by using multiple cutting tools on a part simultaneously. This research led to an understanding of the interacting dynamics of two simultaneously operating cutting tools **[R3]**.

Sheffield's research into the effects of cutting tool preparation, cutting speed, and feed rate on tool wear/life for a range of different cutting tool geometries and materials led to an understanding of the effects of operating parameters on tool life for a range of aerospace alloys **[R4]**. This knowledge resulted in further improved process efficiency.

Sheffield has developed in-process condition monitoring technology for tool wear using acoustic emission, microphone, vibration, and spindle power sensors. In-process monitoring is essential to achieving the desired dimensional accuracy and surface finish of a machined workpiece and avoids ad-hoc manual interventions. The developed technology allows the condition of the tool to be monitored after each cut of the workpiece and the tool life to be maximised **[R5]**. The ability to correctly determine and track the geometry of the tools used to create the gears informed the tooling strategy and improved productivity.

The second research objective involved the development of a Discrete Event Simulation (DES) model of the new facility to determine whether Boeing had an adequate workforce and resources to support operations and identify whether there would be any bottlenecks in production and to validate production targets against intended operations. Previous research in automated model generation using simplified data capture tools and algorithms to generate a file readable in real time by the DES model allowed rapid simulation of a variety of manufacturing processes and different operational scenarios **[R6]**. The application of this simulation model validated Sheffield's proposed manufacturing method against Boeing's production targets, allowing for a holistic understanding of the factory floor operations before the construction of the facility was completed.

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

University of Sheffield staff and students in **bold**

R1. **Sims, N. D.,** & **Turner, S.** (2011). The influence of feed rate on process damping in milling: modelling and experiments. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 225*(6), 799–810. https://doi.org/10.1243/09544054jem2141. Winner of the 2011 IMechE Joseph Whitworth Prize. Cited by 11.

R2. **Yusoff, A. R., Turner, S., Taylor, C. M.,** & **Sims, N. D.** (2010). The role of tool geometry in process damped milling. *The International Journal of Advanced Manufacturing Technology, 50*(9–12), 883–895. https://doi.org/10.1007/s00170-010-2586-6. Cited by 24.

R3. **Ozturk, E., Ozkirimli, O.,** & **Turner, S.** (2015). Parallel Machining Dynamics with Multiple Time Delays. *IFAC-PapersOnLine, 48*(12), 346–351. https://doi.org/10.1016/j.ifacol.2015.09.402.

R4. **Hughes, J. I., Sharman, A. R. C.,** & **Ridgway, K.** (2006). The Effect of Cutting Tool Material and Edge Geometry on Tool Life and Workpiece Surface Integrity. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 220*(2), 93–107. https://doi.org/10.1243/095440506x78192. Cited by 53.

R5. **Harris, K., Triantafyllopoulos, K., Stillman, E., & McLeay, T.** (2016). A Multivariate Control Chart for Autocorrelated Tool Wear Processes. *Quality and Reliability Engineering International, 32*, 2093-2106. https://doi.org/10.1002/qre.2032. Cited by 8.

R6. **Hughes, R.W.C., Scott, R. & Ridgway, K**. (2013). Automatic simulation model generation for supporting facility planning in SMEs. *Proceedings of the European Simulation and Modelling Conference*. 23 Oct 2013. Lancaster, UK. Onggo, S. & Kavicka, A. (eds.), 62-67. http://eprints.whiterose.ac.uk/171423/

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

Boeing is the world's largest aerospace company and the US's largest manufacturing exporter. More than 10,000 Boeing-built commercial jetliners are in service accounting for almost half the world's fleet. Boeing directly employs more than 2,500 people in the UK and co-founded The University of Sheffield's AMRC in 2001 **[S1 p2].**

In 2018, Boeing's first new-build factory constructed worldwide in 30 years was opened adjacent to the AMRC. The President of Boeing Europe and the Managing Director for the UK and Ireland stated, "*The innovative technology and discrete event simulation modelling for the machining of aircraft gear and actuator parts, developed with the AMRC, were crucial in enabling Boeing's decision in 2016 to create its first manufacturing facility in the UK"* **[S3]**. He noted, *"The overall value of the University's* [Sheffield] *research, including investments, enhanced manufacturing processes and productivity well exceed £50 million"* **[S3].**

Examples of Sheffield's research contributions and its impact on enhancing manufacturing processes and productivity are given below:

- Research into parallel machining dynamics **[R3]** led to an improved manufacturing method which has reduced cycle times for actuator yoke components from 94.5 minutes to 49.5 minutes **[S3]**.
- Research into material removal processes, vibration, tool edge geometry, tool life and in-process monitoring **[R1, R2, R4, R5]** enabled 'right first time' processes for components such as hypoid pinion and tension blocks through optimal tooling selection, fixturing approaches, and machining strategies **[S3]**.
- Research into cutting tool geometry and in-process monitoring **[R4, R5]** underpinned the development of new technology solutions for gear manufacturing, which allow single setup production, automation of processes, and balancing of operations across the machine tool **[S3]**.

Sheffield's DES research **[R6]** underpinned the development of a 'virtual factory' simulation model, which through value stream mapping, factory layout optimisation, and virtual reality representation helped validate effective processes and technology routes for increasing productivity. This resulted in a robust prediction of the 'should cost' of the new facility and provided Boeing with the confidence to invest £40m in the 6,200 m² Sheffield facility **[S3]**. A Manufacturing Engineer for Boeing Research and Technology stated, "*Through the collaboration with the AMRC, we have been able to look at whether we had invested in the right number of machines for the workshop floor, to check we had the adequate workforce and resources availability to support operations and look at any bottle-necks in production to validate our targets against our intended operations"* **[S4 p3]**.

Socio-economic impact

To date, 87 high-value manufacturing jobs have been created at Boeing Sheffield. These include 30 machinist apprentices, and the employment of eight former AMRC engineers to strengthen knowledge transfer **[S3]**.

Boeing has placed approximately £8m of orders in the local supply chain where proximity is a distinct advantage due to a 'Just in Time' requirement **[S3]**. The UK Sales and Business Director at Boeing supplier NIKKEN stated, "*the contract with Boeing Sheffield has had an enormous impact on NIKKEN, generating [text removed for publication] revenue since 2018. It has resulted in corporate expansion and job creation, [text removed for publication]. NIKKEN has also invested [text removed for publication] in capital equipment to deliver the contrac*t" **[S5]**. Similarly, the Commercial Director at [text removed for publication], another supplier, commented that since 2017, "*the contract with Boeing has significantly boosted our revenue* [text removed for publication]*, business reputation and capabilities* [text removed for publication]*, and serves as a platform for growth and corporate development"* **[S6]**.

Boeing Sheffield's construction has resulted in major benefits for the regional and national economies. The Mayor of the Sheffield City Region said, "*Boeing's choice of location is a strong sign of confidence in our advanced engineering excellence. The opportunities for our communities, for business, for researchers and for the workforce of the future are limitless"* **[S2 para. 6].** More specifically, he stated, "*Following Boeing's arrival in Sheffield, the region's employment levels and GVA have notably increased: in Q3 of 2019, for example, employment growth reached 1.4% and annual GVA increased by 1.0%"* **[S7]**.

Impact on practitioners within the aerospace industry

The improvements in manufacturing methods, specifically with respect to research to achieve a connected digital factory environment, has extended knowledge, expertise, and capabilities within the Boeing Company **[S3]**.

Impact on public policy

Sheffield's research has helped to realise the aims of the Aerospace Growth Partnership, a strategic partnership between the UK Government, industry, and other key stakeholders. Set-up to tackle barriers to growth, boost competitiveness and exports, and grow the number of high-value jobs in the UK, it is responsible for implementing the Aerospace Sector Deal and states its strategy is to "*Make the UK the most attractive aerospace location in the w*orld". The Secretary of State for Business, Energy, and Industrial Strategy commented, "*Boeing choosing the heart of South Yorkshire as its first European home is testament to our capabilities, talent pool and strong manufacturing supply chains which are vital to job creation and creating value for local economies"* **[S2 para. 4]**.

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

S1. Overview of Boeing's position in the UK (2020). Confirms UK employment figures and ongoing research relationship with University of Sheffield. (Accessed 3 Dec 2020). http://www.boeing.com/resources/boeingdotcom/company/key_orgs/boeing-international/pdf/ukbackgrounder.pdf

S2. Boeing press release on Boeing Sheffield Opening (2018). Provides quotes from Boeing about their decision to choose Sheffield (para. 14), Sheffield City Region Mayor on the regional benefit (para. 6), and Secretary of State for Business, Energy, and Industrial Strategy about the National impact (para. 4). (Accessed 14 Oct 2020). https://www.boeing.co.uk/news-media-room/news-releases/2018/october/boeing-opens-new-aircraft-part-factory-in-sheffield.page

S3. Confidential testimonial from The President of Boeing Europe and the Managing Director for the UK and Ireland (2020). Corroborates a) decision to choose Sheffield, b) direct economic impact c) process improvements, d) jobs created, e) local supply chain benefits & f) application of techniques across Boeing.

S4. Joint AMRC / Boeing case study on the "Virtual simulation of new Boeing facility based in Sheffield". Page 3 provides a quote from Boeing on the technical benefits of the research. (Accessed 3 Dec 2020). https://www.amrc.co.uk/files/document/241/1542814525_AMRC_BOEING_case_study.pdf

S5. Confidential testimonial from the UK Sales and Business Development Director at NIKKEN (2020). Corroborates a) revenue, b) corporate expansion, and c) job creation.

S6. Confidential testimonial from the Commercial Director at [text removed for publication], (2020). Corroborates a) revenue, b) business reputation c) increased capabilities & d) growth and corporate development.

S7. Confidential testimonial from the Sheffield City Region Mayor (2021). Corroborates the regional impact of Boeing Sheffield.