May 2025

Evaluation of Made Smarter Innovation Industrial Strategy Challenge Fund

Final Evaluation – Annex Report

SQW

Contents

1. Introduction 1

Annex A: SIC for Manufacturing and Digital Technologies sectors A-1
Annex B: Consultees B-1
Annex C: Further detail on methodology C-1
Annex D: Theory of Change assumptions D-1
Annex E: Survey analysis E-1
Annex F: Performance on output metrics F-1
Annex G: Performance on outcome metrics G-1
Annex H: Secondary data analysis H-1
Annex I: Econometric analysis I-1
Annex J: Technology trends J-1
Annex K: International comparison K-1
Annex L: Case studies L-1

Contact:
Sarah Brown
Tel: 07436 098652
email: sbrown@sqw.co.uk

Approved by:
Osman Anwar
Director
Date: 20/05/2025

1. Introduction

1.1 This report contains the annexes for the Evaluation of the Made Smarter Innovation Industrial Strategy Challenge Fund Final Report.

Annex A: SIC for Manufacturing and Digital Technologies sectors

A.1 The Challenge documentation does not include a specific definition for the manufacturing sector or digital technology sector. In view of this, for the purpose of the evaluation, SIC codes have been used to define the two sectors, as set out in Table A-1. Although, it is recognised that the two sectors are not always mutually exclusive and there is likely to be some crossover; for example, for companies that manufacture digital technology.

A.2 In terms of SIC classification, the manufacturing Section (C) encompasses numerous Divisions, as set out in the table below. All divisions are incorporated in sector definition for manufacturing. For the digital technology sector, a definition has been taken from an evaluation of Tech Nation.[1] This suggests that the sector broadly includes SIC codes 58 to 63 (Information and Communication - Section J). Some digital technology firms arguably also fall under Professional, Scientific and Technical Activities (Section M).

Table A-1: Sector definitions/SIC codes

Section	Division	Description
Manufacturing Sector:		
Manufacturing (Section C)	10	Manufacture of food products
	11	Manufacture of beverages
	12	Manufacture of tobacco products
	13	Manufacture of textiles
	14	Manufacture of wearing apparel
	15	Manufacture of leather and related products
	16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
	17	Manufacture of paper and paper products
	18	Printing and reproduction of recorded media
	19	Manufacture of coke and refined petroleum products
	20	Manufacture of chemicals and chemical products
	21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
	22	Manufacture of rubber and plastic products
	23	Manufacture of other non-metallic mineral products
	24	Manufacture of basic metals

[1] TECH NATION EVALUATION (publishing.service.gov.uk)

Section	Division	Description
	25	Manufacture of fabricated metal products, except machinery and equipment
	26	Manufacture of computer, electronic and optical products
	27	Manufacture of electrical equipment
	28	Manufacture of machinery and equipment n.e.c.
	29	Manufacture of motor vehicles, trailers and semi-trailers
	30	Manufacture of other transport equipment
	31	Manufacture of furniture
	32	Other manufacturing
	33	Repair and installation of machinery and equipment
Digital Technology sector:		
Information and Communication (Section J)	58	Publishing activities
	59	Motion picture, video and television programme production, sound recording and music publishing activities
	60	Programming and broadcasting activities
	61	Telecommunications
	62	Computer programming, consultancy and related activities
	63	Information service activities

Source: ONS, Standard Industrial Classification (SIC 2007)

Annex B: Consultees

Table B-1: List of consultees

Name	Role	Organisation
Internal consultees		
Dr Bruce Adderley	Director Make and Use – Net Zero	Innovate UK
Mike Biddle	Executive Director for Net Zero	Innovate UK
Dr Ben Farmer	Deputy Challenge Director – Made Smarter Innovation	Innovate UK
Paul Gadd	Deputy Director	Innovate UK
Ezra Kasapoglu	Director of AI and Digital Economy	Innovate UK
Chris Needham	Innovation Lead – Manufacturing Made Smarter	Innovate UK
Dr Katie Daniel	Deputy Director for Regional Partnerships	EPSRC
Prof Jon Dawes	Deputy Executive Chair	EPSRC
External Consultees		
Sonal Bhatt	Head of Manufacturing	Department for Business and Trade
Emma Cole	Head of Manufacturing	Department for Business and Trade
Prof Steve Evans	Director of Research in Industrial Sustainability	University of Cambridge
Prof Tim Minshall	Head of the Institute for Manufacturing	University of Cambridge
Chris Courtney	Chief Executive Officer	National Manufacturing Institute Scotland (NMIS) (HVMC)
Clare Porter	Director for Strategic Engagement	High Value Manufacturing Catapult (HVMC)
Philippa Glover	Director	Independent manufacturing advisor (Philippa Glover)
Prof Jan Godsell	Professor of Operations and Supply Chain Strategy	Loughborough University
Brian Holliday	Managing Director	Siemens
Kiran Krishnamurthy	Chief Executive Officer	IntelliumAI
Graham Malley	Principal Director Digital Manufacturing	Accenture
Prof Linda Newnes	Professor of Cost Engineering	University of Bath
Stephen Phipson	Chief Executive Officer	MAKE UK
Delores Sanders	Co-Chief Executive Officer	Total Control Pro

Name	Role	Organisation
Prof Rab Scott	Director of Industrial Digitalisation	Advanced Manufacturing Research Centre
Jon-Paul Sherlock	Executive Director	Astra Zeneca
Roger Singleton	Chief Executive Officer	Riskoa
Mark Summers	Executive Director of Technology	National Composites Centre

Annex C: Further detail on methodology

Contribution Analysis

C.1 The MSI Challenge is a complex intervention operating in a multifaceted landscape and an evolving and emerging sector. The programme embodies many of the characteristics and factors of complexity described by the Magenta Book.[2] It involves multiple types of interventions, scales and timeframes coupled with a wide range of potential routes to impact, across many beneficiaries. Furthermore, the programme is seeking to address issues (i.e. challenges associated with productivity and clean growth in manufacturing) that have multiple causes and span different policy domains (e.g. research, innovation, enterprise), and there are a wide range of other initiatives taking place with similar aims.

C.2 The Magenta Book highlights how this complexity can create challenges for evaluation, with attribution/causality particularly hard to prove given the multiple influences on impacts. Reflecting these issues, the evaluation will adopt an overarching theory-based approach, which draws on the principles of Contribution Analysis. This is in line with UK Government evaluation guidance set out in the Magenta Book:

Theory-based methods can be used to investigate net impacts by exploring the causal chains thought to bring about change by an intervention … Theory-based evaluation is explicitly concerned with both the extent of the change and why the change occurs. In addition, it often considers the context at the same time that the intervention is being implemented.

HMT Magenta Book, 2020, p.43

C.3 Contribution Analysis is a theory-based approach for assessing causal questions and inferring causality in programme evaluations. It assesses and compares the evidence collected *on what has actually happened* as a result of an intervention, against the intervention's original theory of change and logic of *what was expected to happen*.

C.4 The approach is based on the development of logic models and underlying theory as to how intended outcomes and impacts were to be brought about.[3] It allows evidence to be built to demonstrate the contribution made by the intervention to the outcomes in question (e.g. new IDT solutions developed, employment and turnover generated), while also identifying the other factors which may have plausibly contributed to it (e.g. market opportunities, policy and regulations, challenges and opportunities from the UK's exit from the EU and the Covid-19 pandemic, wider economic conditions). This provides a 'contribution story' and a line of reasoning from which a plausible conclusion can be drawn, with some level of confidence, about the contribution that the intervention itself (instead of other factors) has made to observed

[2] Magenta Book Supplementary Guide: Handling Complexity in Policy Evaluation, March 2020.
[3] Mayne, J. (2001) *Addressing Attribution Through Contribution Analysis: Using Performance Measures Sensibly*, The Canadian Journal of Program Evaluation, Vol. 16 No. 1, pp. 1-24.

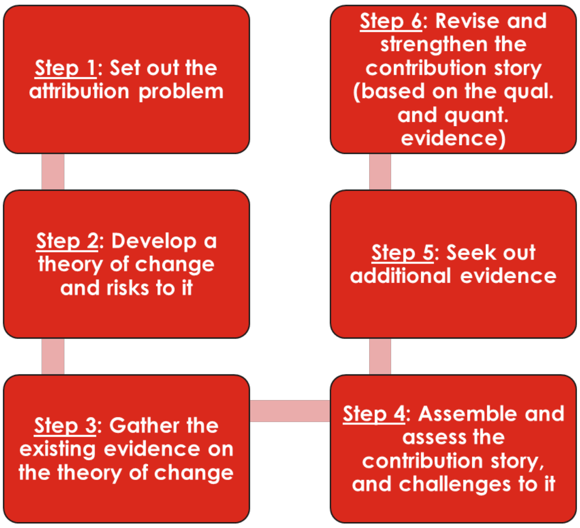
outcomes.[4] This process will draw on bottom-up and top-down research methods, which are set out in more detail below.

C.5 Following the collation and analysis of the evidence, a *plausible association* can be made (or attribution is demonstrated beyond reasonable doubt) if the following are satisfied:[5]

- a reasoned theory of change is set out
- the activities have been implemented as set out in the theory of change
- the chain of expected results, e.g. on direct beneficiaries and the wider sector can be shown to have occurred
- other influencing factors have been shown not to have made a difference, or the decisive difference.

C.6 The process is based on a six-step method to gather evidence and develop the 'contribution story', as summarised in Figure C-1. The findings from the "contribution story/stories" will then be synthesised with wider evidence on how and why effects have been achieved to draw conclusions on the impact to date of the Challenge, the key enablers to this, outstanding issues, and implications for the future.

Figure C-1: Six steps of Contribution Analysis



Source: Mayne, J. (2008) Contribution Analysis: An Approach to Exploring Cause and Effect, ILAC Brief 16

[4] Mayne, J. (2008) *Contribution Analysis: An Approach to Exploring Cause and Effect*, ILAC Brief 16.
[5] White, H. and Philips, D. (2012) *Addressing attribution of cause and effect in small n impact evaluations: towards an integrated framework,* International initiative for Impact Evaluation Working Paper 15.

Annex D: Theory of Change assumptions

Table D-1: Made Smarter Innovation logic model assumptions

	Inputs, activities & outputs	Short-term outcomes	Long term outcomes
Assumptions	The Challenge is widely publicised across the relevant channels Sufficient demand exists from industry, in line with competition scope Industry are willing and able to coinvest Funding does not duplicate other support Assessment of applications by UKRI leads to high quality projects, with realistic, with well-defined aims and objectives There is a robust rationale for public intervention, and activity would not have progressed without MSI (or not at the same speed/scale/type) Projects are able to form and sustain effective consortia (where relevant) Sufficient capacity (financial/time) of industry / academics to participate in project delivery	Collaborative ecosystem leads to increased innovation in IDTs IDT solutions developed are proven to work and benefits demonstrated New technology solutions and digital technology products are sufficiently substantive to make a real difference within participating Businesses have capacity and capability to increase R&D and investment in new technologies Learning generated from the challenge is effectively disseminated to inform future interventions	New digital manufacturing solutions are aligned to market need and demand (UK and globally), and affordable Digital tech companies have the capability and interest to pivot existing products/ business model Manufacturing businesses / partners have the capacity/capability to adopt new IDTs/ supply chain technology Interest and capacity to sustain partnerships / connections / collaborations Technologies are effective in reducing waste / CO2E
Factors that could enable progress	Effective project management/governance by UKRI and Innovation Leads (e.g. EPSRC, ESRC, KTN) Effective engagement and inputs from stakeholders and incumbent networks Effective partnership working within projects	Effective knowledge exchange between project partners / stakeholders Feedback loops and opportunities for iteration in development of IDTs	Awareness, willingness and capability to adopt new digital manufacturing solutions among wider manufacturing sector Technology alignment with relevant strategic activities / priorities

	Inputs, activities & outputs	Short-term outcomes	Long term outcomes
	Facilitation of new collaborations Synergies maximised within and across strands to ensure opportunities are maximised within the Challenge	Wider support/ funding to support business adoption of IDTs Project partners have a good understanding of target market(s) Project partners can secure additional R&D and/or growth finance if required	Effective partnership working / KE networks / diffusion mechanisms (at cross-project and sector level) Good communication with and engagement from manufacturing supply chains
Factors that could hinder progress / cause ToC to break down	Poor communication leads to low demand / awareness of the challenge Lack of ecosystem / stakeholder engagement Co-investment not materialising (or delayed) R&D skills / staff shortages or capacity issues Failure of technology during testing / technical complexities delay progress Outputs (e.g. novel technology solutions) are not achievable over the project timeline	Insufficient evidence to prove the value of digitalisation in the manufacturing sector Failure to secure follow-on funding to progress through to commercialisation Insufficient interest / demand from wider manufacturing sector for IDTs Lack of connection between project and end users Tension between interest of project partners in maintaining control/IP vs. rollout potential if outputs widely shared Ineffective dissemination of learning	New digital manufacturing solutions have limited wider rollout potential, and investor community and sector not interested Failure to secure follow-on investment to support growth Lack of skills / capacity within the sector to adopt / integrate IDTs Lack of effective engagement with wider industry (where required)
Wider external drivers	The influence of economic conditions on the ability to invest in innovation / adoption of IDTs Covid-19 related implications for delivery Other sources of R&D funding including complementary and potentially duplicating interventions Global demand for IDTs / product trends (across different manufactured products) Appetite / trends in private investment market for IDTs Implications of external shocks (e.g. Covid-19 & Brexit) for manufacturing / digital tech sectors		

	Inputs, activities & outputs	Short-term outcomes	Long term outcomes
	General labour and skills availability, as well as prices, exchange rates, profit margins in manufacturing / digital tech Wider political, regulatory, economic drivers across the sectors		

Source: SQW based on information from the Made Smarter Innovation Challenge

Annex E: Survey analysis

Beneficiary survey

Profile of respondents

E.1 In total there were 43 respondents. Characteristics of respondents included the following:

Table E-1: Characteristics of beneficiary survey respondents (n=43)

Characteristic	Count	%
Project Lead?		
Project Lead	25	58%
Project partner	18	42%
Organisation type		
Manufacturer	17	40%
Digital technology developer	11	26%
Research Institute	4	9%
Technology intermediary	4	9%
Other	4	9%
Commercial lab or private R&D institution	1	2%
Consultancy	1	2%
University	1	2%
Number of employees (FTE)		
1-4 FTEs	12	28%
5-9 FTEs	2	5%
10-49 FTEs	10	23%
50-99 FTEs	3	7%
100-199 FTEs	4	9%
250-999 FTEs	4	9%
1000+ FTEs	3	7%

Characteristic	Count	%
Don't know/no response	5	12%
In the three years prior to applying for MSI funding for this project, did your organisation…		
invest in R&D for the purposes of manufacturing innovation?	24	56%
receive any other form of public sector support?	24	56%
co-operate on innovation activities with any other organisations?	28	65%

Source: SQW analysis of beneficiary survey data

E.2 Of the 43 respondents, 23 were able to comment on why the project had not previously been viable. Of these 23, the majority (15) were unable to secure finance. Other common reasons prevent project progression included difficulties in finding suitable collaborators and lack of capacity to manage the project:

Table E-2: Which of these, if any, prevented you from taking forward the project prior to applying for MSI funding? (n=23)

Reason preventing	Count	%
Unable to secure finance	15	71%
Difficulties in finding suitable collaborators	9	43%
Lack of management time	8	38%
Lack of access to necessary facilities	5	24%
Had not considered this type of project before becoming aware of the MSI funding	4	19%
Lack of knowledge of market opportunities	3	14%
Other	3	14%
Lack of technical and/or innovation skills	3	14%
Lack of information about potential new technologies	3	14%

Source: SQW analysis of beneficiary survey data

E.3 Roughly half (12) had considered other sources of funding to progress the project. Sources considered include:

Table E-3: What other sources of funding were considered? (n=12)

Source of finance	Count	%
External equity finance (e.g. business angel, venture capital)	7	58%
Public sector grant	5	42%
Other	1	8%
Don't know	1	8%

Source: SQW analysis of beneficiary survey data

Activity additionality

E.4 Approximately half of respondents (22 out of 43) felt that the project would have either probably would not or definitely would not have progressed without MSI funding. This was higher (60%) among 'other' organisations (e.g. research institutes, technology intermediaries), but lower among manufacturers (41%). Only a fifth of the projects definitely would have gone ahead without MSI funding.

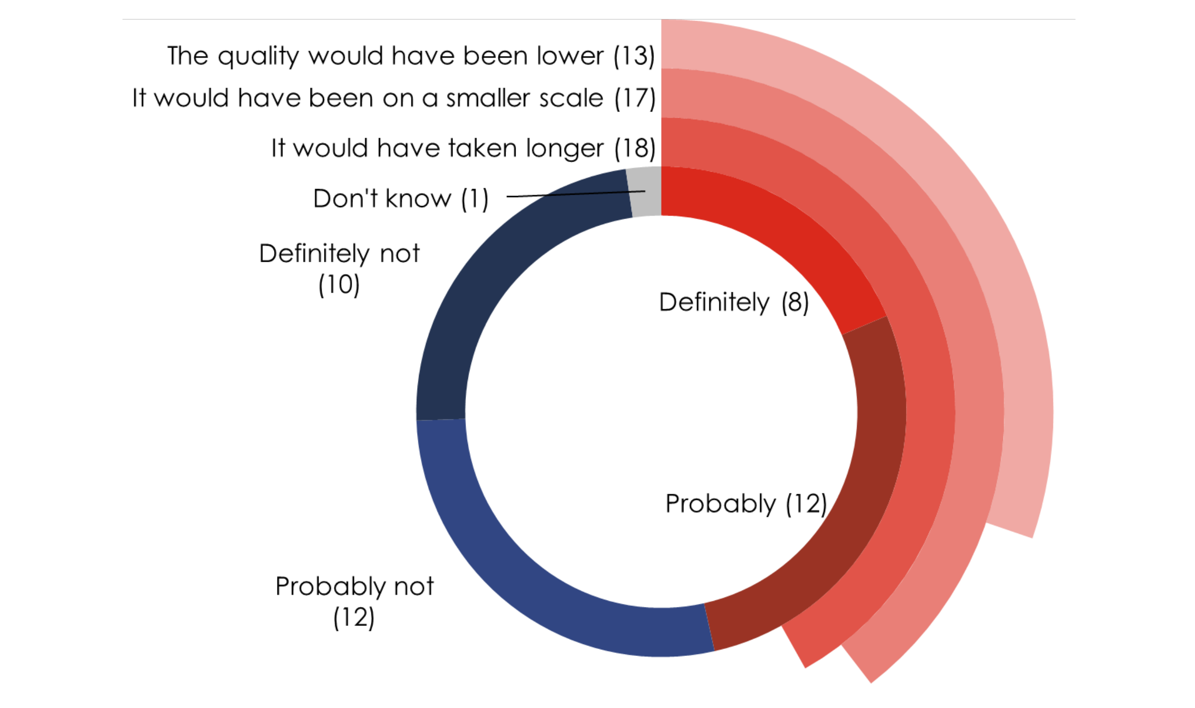
Table E-4: Would you have taken forward this or a similar project if you had not been successful in your application for MSI funding? (n=43)

	Manufacturer (% of manufacturers)	Digital technology developer (%)	Other (%)	Total (%)
Definitely	4 (24%)	2 (18%)	2 (13%)	**8 (19%)**
Probably	6 (35%)	2 (18%)	4 (27%)	**12 (28%)**
Probably not	6 (35%)	3 (27%)	3 (20%)	**12 (28%)**
Definitely not	1 (6%)	3 (27%)	6 (40%)	**10 (23%)**
Don't know	0 (0%)	1 (9%)	0 (0%)	**1 (2%)**
Total	**17**	**11**	**15**	**43**

Source: SQW analysis of beneficiary survey data

E.5 For the 20 respondents whose projects were likely to have gone ahead anyway, all have realised enhanced project delivery because of MSI funding – either in terms of speed (18), scale (17), or quality (13).

Figure E-1: Would you have taken forward this or a similar project if you had not been successful in your application for MSI funding? (n=43)



Source: SQW analysis of beneficiary survey data

Process

E.6 Project monitoring, support from partners and good financial/technical support were all felt to be important factors contributing towards successful project delivery.

Table E-5: Which aspects of MSI's design and delivery processes have worked well and helped your project to progress? (n=43)

Row Labels	Count	% of respondents
Project monitoring and management incl. review / audit	13	30%
Support from partner(s)	13	30%
Good support incl. financial / technical	13	30%
Straightforward web-based process	11	26%
Access to information / data	3	7%
Don't know	8	19%
Other	2	5%

Source: SQW analysis of beneficiary survey data

E.7 Most respondents either believed there were no factors hindering project progress, were unsure if any factors hindered progress, or identified very specific factors that did. Difficult programme processes and limited funding flexibility were the most common processes felt to hinder project delivery.

Table E-6: Which aspects of MSI's design and delivery processes have worked less well or hindered project progress, and could be improved? (n=43)

Row Labels	Sum of Count	Sum of %
Don't know	10	23%
Nothing - it's fine as it is	7	16%
Other	7	16%
Time consuming / difficult processes	7	16%
Flexibility on funding / timing limits	7	16%
Access to support e.g. faster responses to queries	4	9%
Clear and timely communication	4	9%
Not applicable	3	7%

Source: SQW analysis of beneficiary survey data

Progress

E.8 Of the beneficiaries, 33 respondents were able to comment on how their technology had progressed as a result of their MSI-funded project. Most (85%) projects had resulted in at least some TRL progression, and nearly half (15) had progressed by more than three TRLs. MSI has typically supported early-stage technologies (20 of the 33 respondents reported technology initially at TRL 3 or below).

Figure E-2: TRL progression of MSI-funded projects (n=33)

	Current TRL								
TRL prior to MSI application	1	2	3	4	5	6	7	8	9
1 Basic Principles				4		1		4	2
2 Developing hypothesis			1	1					
3 Specifying and developing PoC				2			3	1	1
4 PoC demonstrated in test site	1			1	3	1			
5 Validated in relevant environment								1	1
6 Validated in operational environment						2	1		
7 System complete and qualified									
8 Product/technology being implemented									1
9 Product/service on commercial release/ process deployed									1

Source: SQW analysis of beneficiary survey data

E.9 Ten out of 25 project leads had reported further financial investment into the MSI-funded project. Of these, half had been investment between £10k-£100k, and there were three instances of investment greater than £100k. Overall, this totalled £1.1m – an average of £110k for each business.

Table E-7: Has there been any further financial investment in this project (excluding the initial investment)? (n=25)

	Count	%
Yes	10	40%
Additional private investment	10	40%
• Less than £10k	• 2	• 8%
• Between £10k-£100k	• 5	• 20%
• More than £100k	• 3	• 12%
Additional public investment	2	8%

Source: SQW analysis of beneficiary survey data

E.10 Among the 25 cases covered by project leads, 18 (70%) had developed or tested new technology solutions, while new IP and spin-outs are less likely to date. To date, they had collectively tested 35 technology solutions across 63 manufacturers. For those which were expecting the project to lead to a commercially available new product/service, most anticipated that the product/service would be launched in the next two years (17 out of 20).

Table E-8: Benefits as a result of the project (n=25)

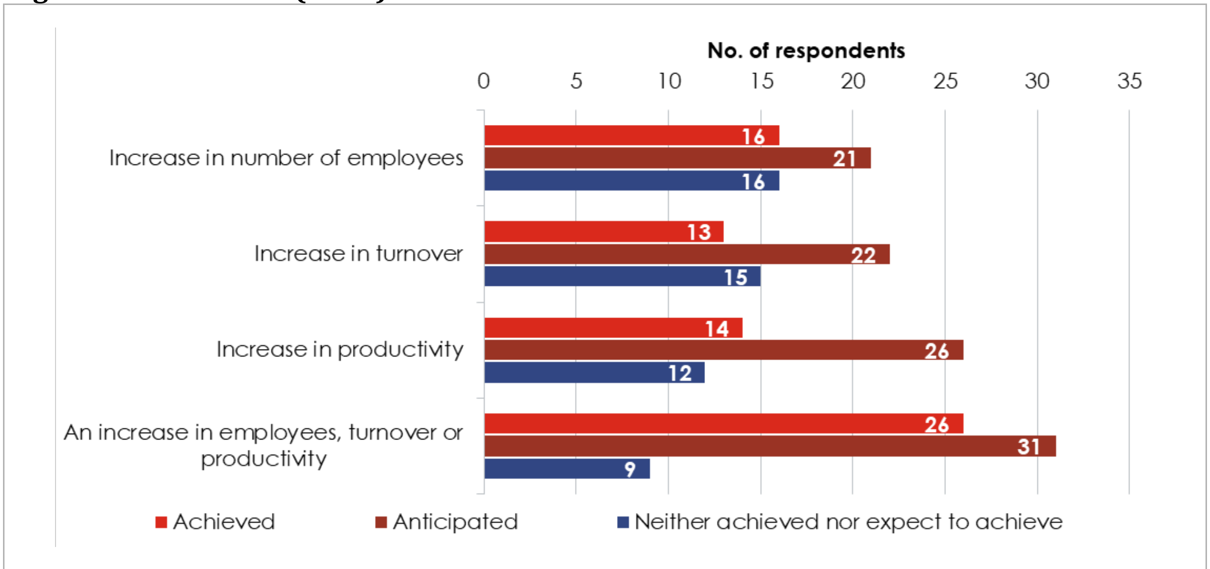
	Achieved	Expect in future	Will not experience	Don't know / refused
New technology solutions tested or developed	16	6	1	2
New standards developed	10	4	9	2
A commercially available new product/service	8	20	12	3
Publications	4	7	12	2
New spin-outs or start-up companies	2	6	14	3
Applied/secured patents/IP	2	4	18	1

Source: SQW analysis of beneficiary survey data

Impact

E.11 Most (79%) participants have achieved (or expect to achieve) an increase in jobs, turnover or productivity within the next 3 years, as a result of MSI projects. More than half (60%) have already achieved one or more of these. Manufacturers are more likely to report improvements in productivity, while technology developers are more likely to report increases in turnover.

Figure E-3: Has participating in the MSI project led to any of the following in your organisation to date? (n=43)



Source: SQW analysis of beneficiary survey data. Note: total exceeds 43 as some organisations have both achieved benefits and anticipate achieving further benefits in future.

E.12 The scale to which respondents had experienced or anticipated experiencing these benefits varied across organisations. Cumulatively, respondents reported that MSI funded projects had resulted in an additional 28 employees, and an anticipated 68 additional employees in the next three years. Effects on turnover varied significantly too, with some anticipating that outcomes from their project will result in more than £1m in additional turnover.

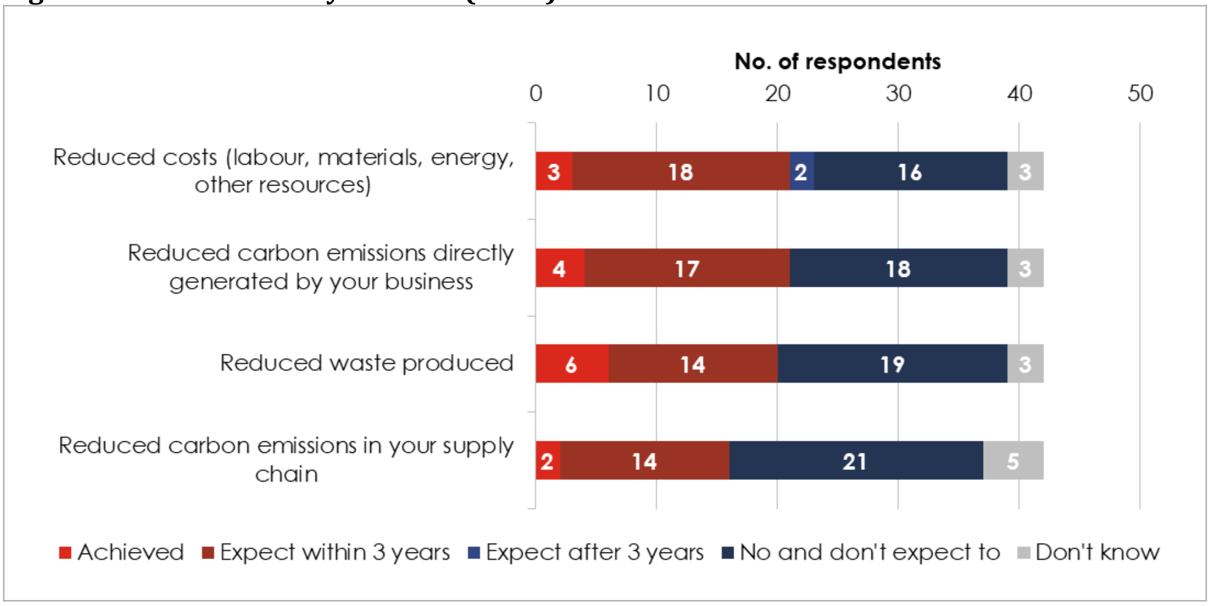
Table E-9: Scale of benefits resulting from MSI-funded projects (n=43)

Benefit	Achieved (no. respondents)	Achieved (scale of benefit)	Anticipated (no. respondents)	Anticipated (scale of benefit)
Employees	16	28	21	68
Turnover	13	• £5k-9k: 1 • £10k-£99k: 4 • £100k-£499k: 4 • Don't know: 4	22	• £10k-£99k: 1 • £100k-£499k: 6 • £500k-£999k: 5 • £1m-£10m: 5 • Don't know: 5
Productivity	14	N/A	26	N/A

Source: SQW analysis of beneficiary survey data

E.13 Although not a primary aim of MSI-funded projects, some respondents reported that they have achieved or expect to achieve sustainability benefits, particularly in relation to reduced waste and reduced carbon emissions.

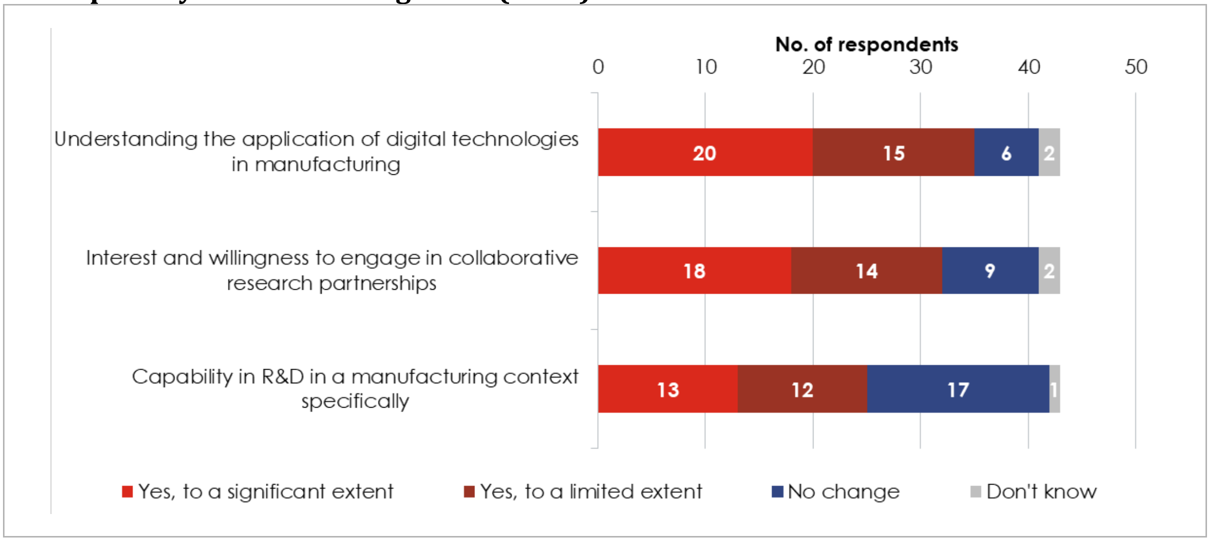
Figure E-4: Sustainability benefits (n=43)



Source: SQW analysis of beneficiary survey data

E.14 MSI projects have also contributed towards increased skills and understanding among participant organisations, most commonly in understanding the application of digital technologies in manufacturing. The majority (77%) reported that staff had developed new skills (via formal or on-the-job training) due to the project, totalling 943 employees (an average of 29 employees per organisation which experienced this benefit).

Figure E-5: Has engaging in the project raised your organisations' understanding, skills and capability in the following area? (n=43)



Source: SQW analysis of beneficiary survey data

Outcome additionality

E.15 Of the project lead organisations, all (that were able to comment) felt that the MSI funding contributed towards the outcomes they had experienced. In most cases, the outcomes would have taken longer to achiever, or been at a smaller scale, although there were a couple of instances where none of the outcomes would have been achieved without MSI.

Table E-10: Without this support from MSI, which of the following would have happened? (n=24)

Additionality	Number of respondents
Complete (i.e. none of these benefits would have happened)	2
Partial (i.e. benefits would have happened, but not to the same extent)	22
Don't know	1
Types of partial additionality	
Benefits would have taken longer to achieve	19
Benefits would have happened on a smaller scale	16
Benefits would have been of a lower quality	5
Length of time to achieve same benefits	
Up to a year	3

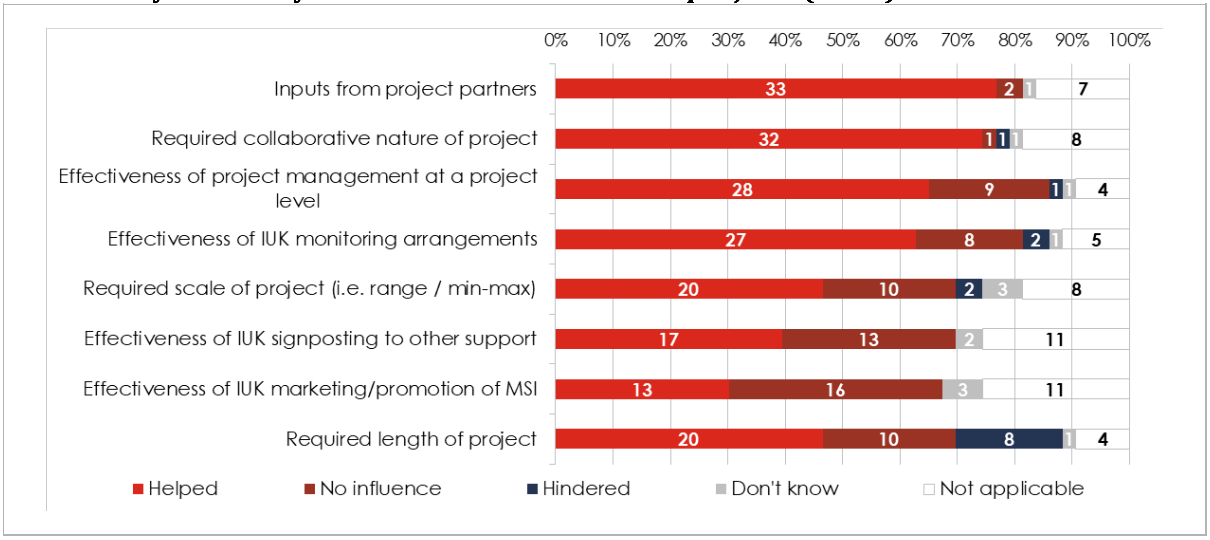
Additionality	Number of respondents
One to two years	12
Three to five years	4
Proportion of outcomes which would have been achieved without MSI	
25% or less	3
26%-50%	6
51%-75%	2
76%-99%	3
Don't know/refused	2

Source: SQW analysis of beneficiary survey data

Contribution

E.16 Input from project partners and collaborative nature of projects were the two largest internal factors which aided project delivery.

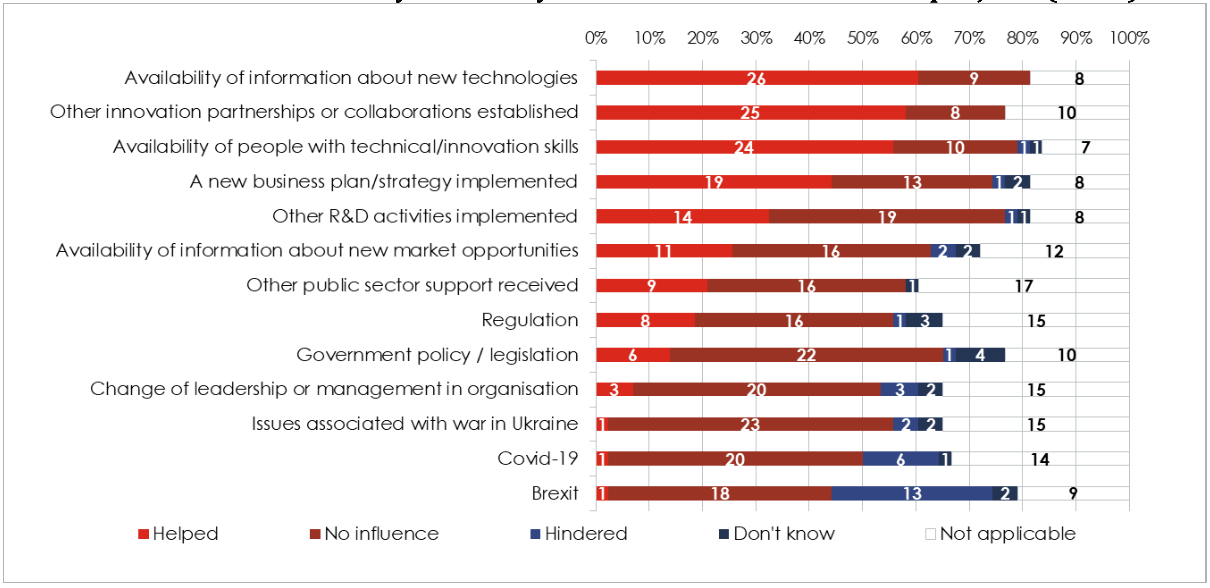
Figure E-6: Have any of the following factors relating to design and delivery of MSI influenced your ability to realise benefits from the project? (n=43)



Source: SQW analysis of beneficiary survey data

E.17 The availability of information, collaboration external to MSI and availability of people with the right skills were all additional factors which aided project delivery. External factors felt to have hindered delivery of MSI included Brexit and the Covid-19 pandemic.

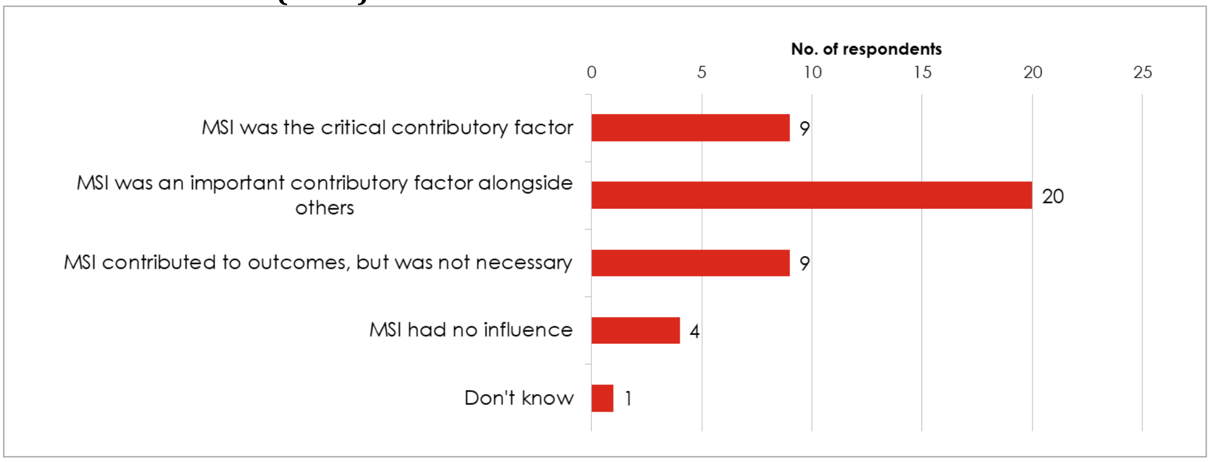
Figure E-7: Have any of the following other factors relating to your organisation and/or the wider context influenced your ability to realise benefits from the project? (n=43)



Source: SQW analysis of beneficiary survey data

E.18 The majority (29 out of 43) of respondents felt that MSI was either the critical or an important contributory factor to respondents experiencing the outcomes they had achieved.

Figure E-8: What has been the role of MSI in achieving the outcomes described relative to these other factors? (n=43)



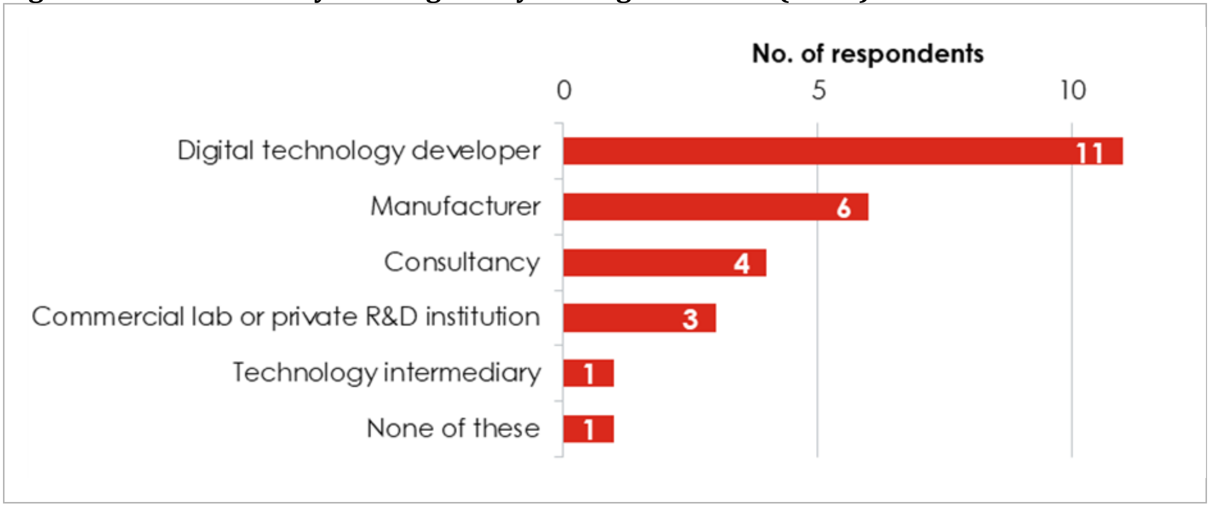
Source: SQW analysis of beneficiary survey data

Non-beneficiary survey

Profile of respondents

E.19 There were 26 respondents to the non-beneficiary survey. Most unsuccessful applicants which responded were either digital technology developers or manufacturers.

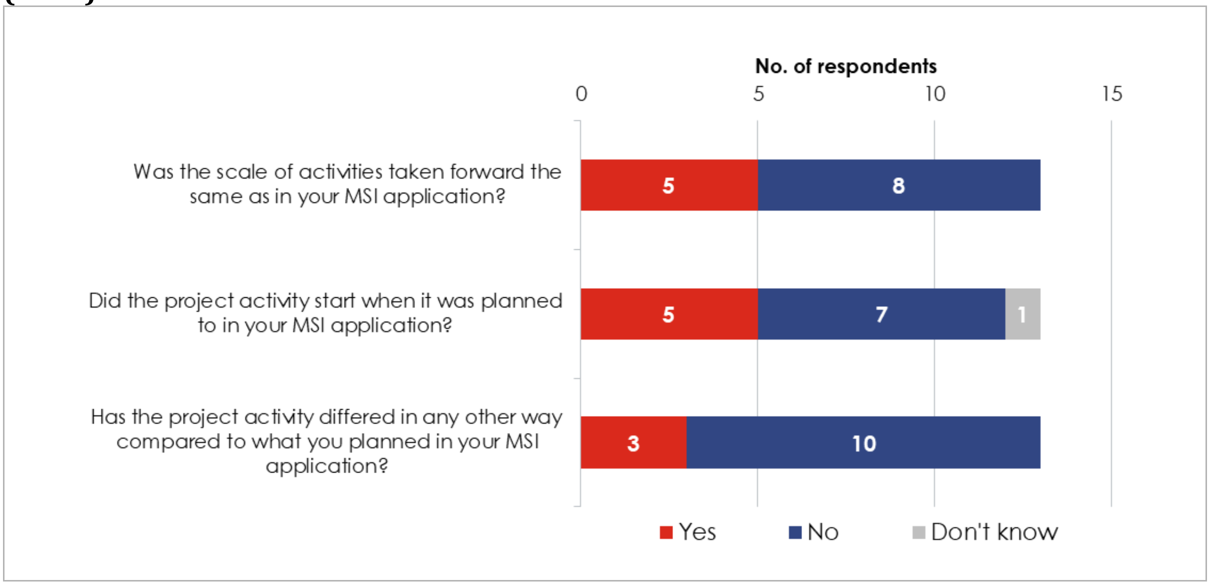
Figure E-9: How would you categorise your organisation? (n=26)



Source: SQW analysis of non-beneficiary survey data

E.20 Most had not received public sector support in the last three years but had worked with others on innovation activity.

Figure E-10: During the three years prior to applying for MSI funding for this project… (n=26)

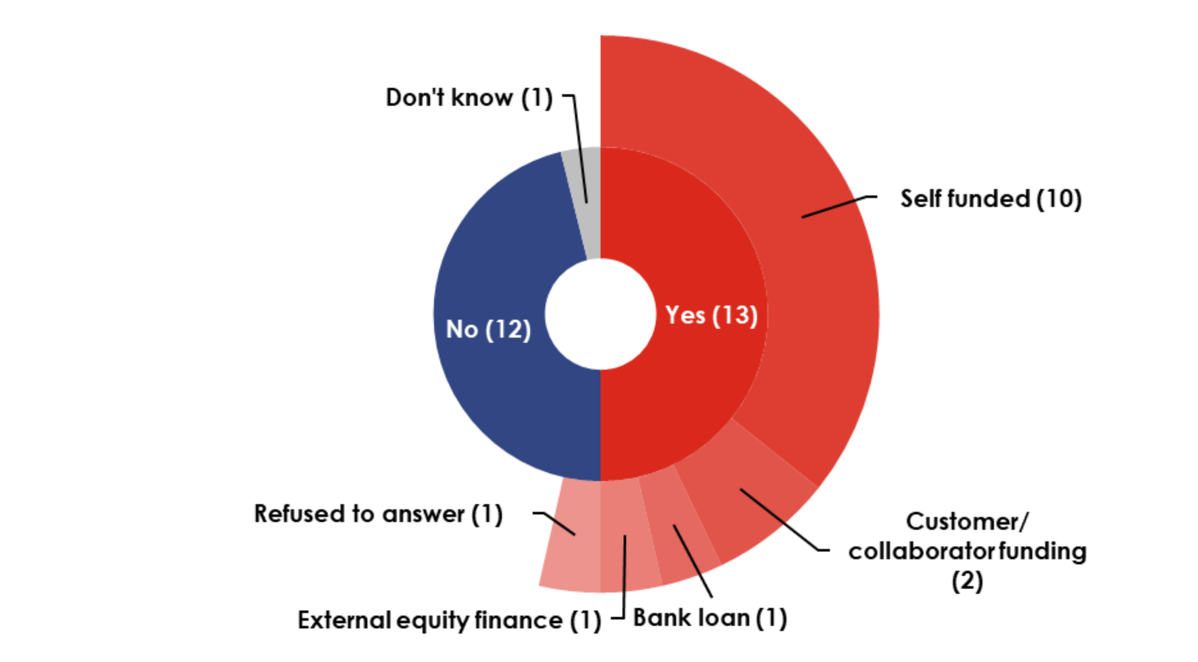


Source: SQW analysis of non-beneficiary survey data

Implementation

E.21 Half of respondents were able to progress their project without MSI funding.

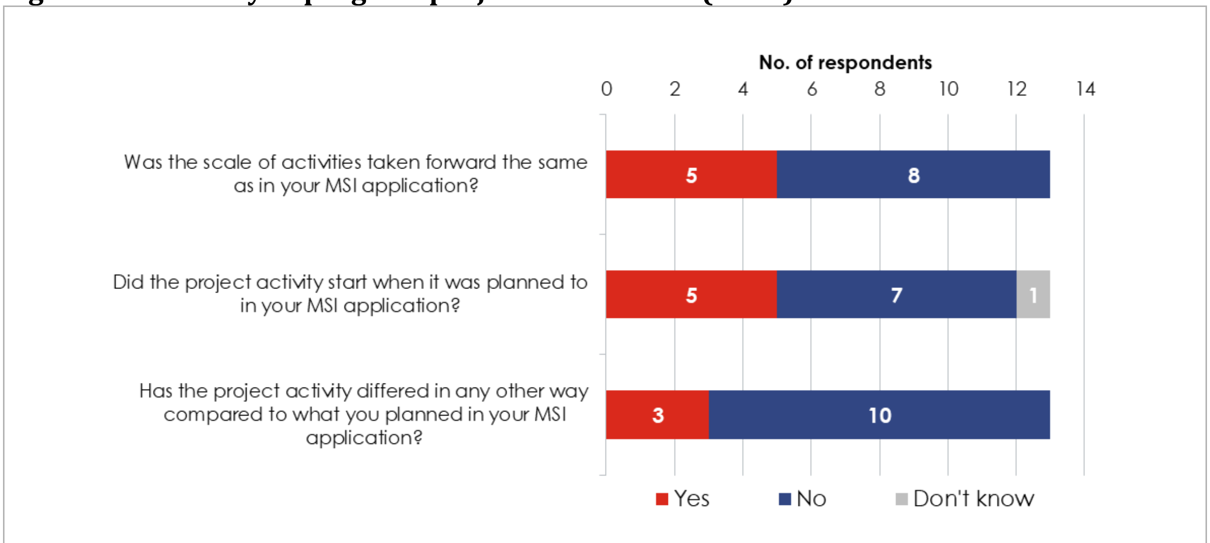
Figure E-11: After your unsuccessful application to MSI, has the proposed project activity been taken forward without MSI funding? If yes, how was the project activity funded without MSI funding? (n=26)



Source: SQW analysis of non-beneficiary survey data. Note: Total of funding sources exceeds number of respondents which progressed their project, as some respondents reported multiple sources of funding.

E.22 For those which were able to take their project forward without MSI funding, the majority noted how the project was either smaller, started later, or differed compared to what was planned as part of their MSI application. Of all 13, only one project was delivered in full and without differences compared to what was planned under MSI.

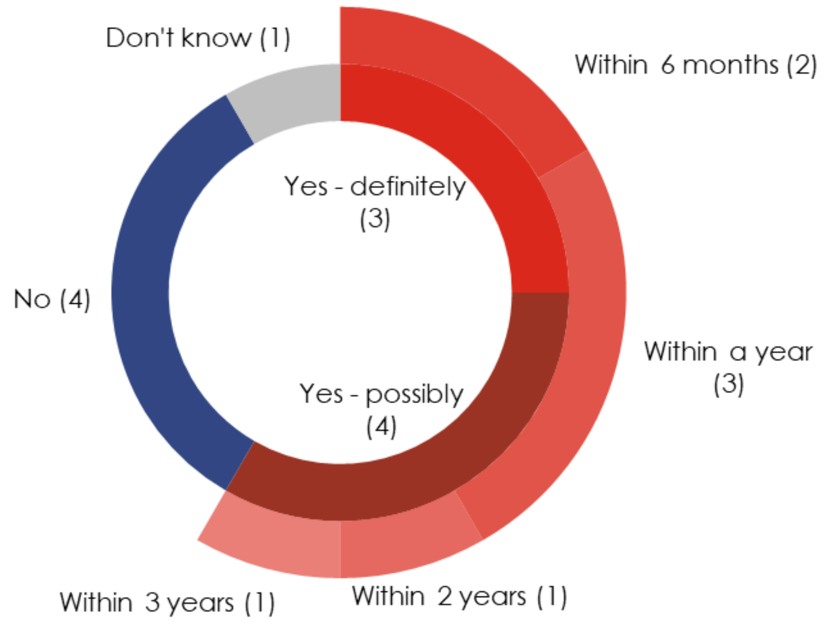
Figure E-12: Ability to progress project without MSI (n=13)



Source: SQW analysis of non-beneficiary survey data

E.23 Of the 12 which were unable to progress their project, just over half (58%) intend to progress their project at some point in the next three years.

Figure E-13: Do you still intend to take forward the project activity at some point in future?



Source: SQW analysis of non-beneficiary survey data

Outcomes

E.24 The table below shows how non-beneficiary projects have progressed. Despite not receiving MSI funding, two projects have resulted in a product/service on commercial release/process deployed (TRL 9), and another two have resulted in a product/technology in manufacture/process being implemented (TRL 8).

Table E-11: Which ONE of the following describes the stage your technology/system started and where you anticipate your technology/system will reach by the END of the project?

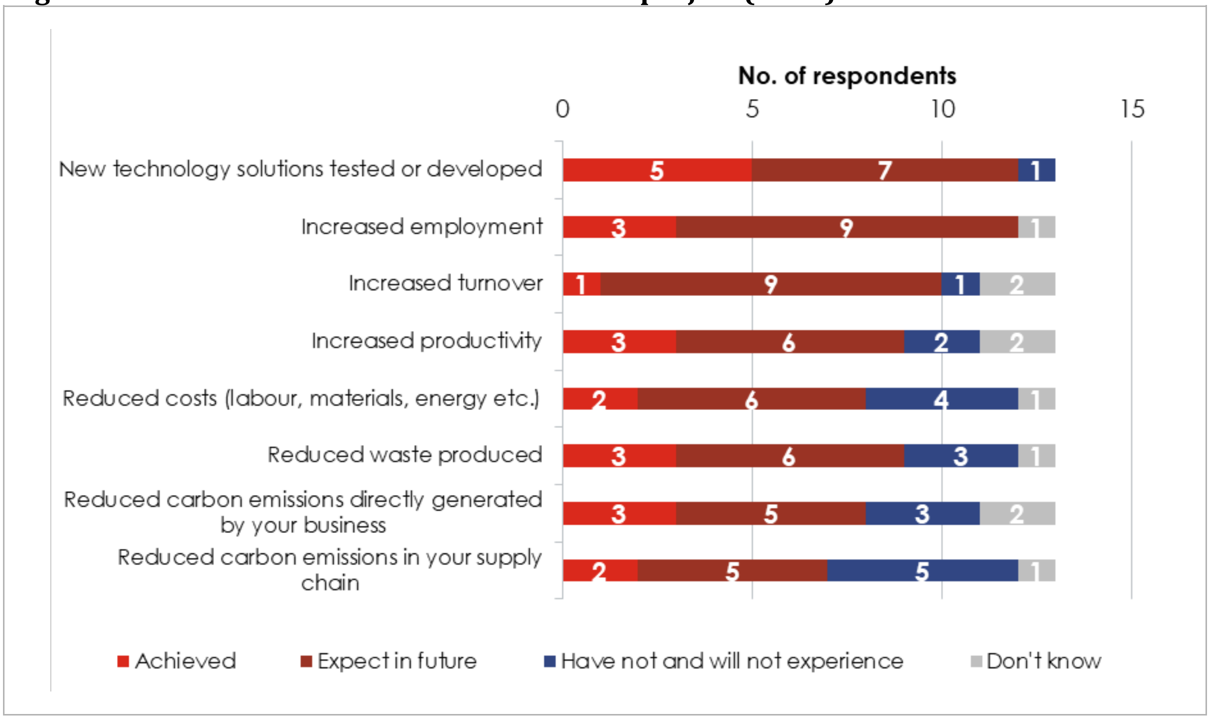
After>	1	2	3	4	5	6	7	8	9
TRL before									
1						1			
2		1	1	2				1	
3									1
4						2			1
5				1		1			
6								1	

After>	1	2	3	4	5	6	7	8	9
TRL before									
7									
8									
9									

Source: SQW analysis of non-beneficiary survey data

E.25 The figure below shows the benefits realised by the 13 non-beneficiaries which have been able to progress their projects. Less than half have achieved benefits to date, and of those which have, these typically related to a new technology solution being tested/developed, increased employment, increased productivity, reduced waste and reduced carbon emissions.

Figure E-14: Benefits realised as a result of the project (n=13)



Source: SQW analysis of non-beneficiary survey data

Annex F: Performance on output metrics

F.1 The table below shows how the MSI has delivered against each of the logic model output metrics.

Table F-1: Achievement on Logic Model Outputs

<table>
<tr><th>Output metric name</th><th colspan="2">Achievement</th></tr>
<tr><td>CO1: Number of projects funded by work strand (and technology)</td><td colspan="2">76 CRD projects
49 projects related to AI/machine learning (38) and/or data analytics (11)
31 projects related to digital twins
28 projects related to IoT
16 projects related to robotics
8 projects related to additive manufacturing
6 projects related to distributed ledger technology (including block chain)
1 project related to extended reality (augmented reality/virtual reality/mixed reality).</td></tr>
<tr><td>CO2: Value of projects funded by work strand (public/private)</td><td>Public - ISCF
Total - £111.6m
CR&D - £46.14m
Innovation Hubs - £30.63m (DSCH - £11.97m, SMDH - £18.66m)
InterAct - £4.99m
Research Centres - £24.01m
Accelerators - £3.68m
Networks - £1.45m</td><td>Non ISCF (public and private, Forms 1 and 2)
Total - £111.2m
CR&D - £52.58m
Innovation Hubs - £45.47m (DSCH - £12.85m, SMDH - £31.87m)
Research Centres - £11.53m
Accelerators - £1m</td></tr>
</table>

Output metric name	Achievement
	Global - £0.63m Standards - £0.08m
CO3: Number of organisations engaged (by work strand)	Number of organisations that are partners in CRD projects: 340 (total), 272 (unique)
CO3: Number of organisations engaged (by sector)	Number of organisations that are partners in CRD projects by SIC code (total number of organisations followed by unique organisations in brackets) Manufacturing - 112 (94) Information and communication - 75 (63) Professional, scientific and technical activities - 86 (48) Administrative and support service activities - 9 (7) Construction - 4 (4) Other service activities - 15 (11) Wholesale and retail trade; repair of motor vehicles and motorcycles - 15 (14) Mining and Quarrying - 2 (2) Real estate activities - 1 (1) Financial and insurance activities - 2 (2) Education - 3 (1) Public administration and defence; compulsory social security - 1 (1) Activities of extraterritorial organisations and bodies - 1 (1) Transportation and storage - 3 (3)

Output metric name	Achievement
CO3: Number of organisations engaged (by size)	Number of organisations that are partners in CRD projects by size (total number of organisations followed by unique organisations in brackets) Micro/Small - 126 (112) Small - 1 (1) Medium - 33 (25) Large - 95 (79) RTO - 8 (5) Academic - 45 (28) Public Sector Research Establishment – 2 (2) Public Sector Organisation - 5 (5) Catapult - 15 (6) Non-UK - 1 (1) Unknown - 9 (9) 168 SMEs engaged in Hubs 99 SMEs engaged in RCs
CO3: Number of organisations engaged (by region)	Number of organisations that are partners in CRD projects by region (total number of organisations followed by unique organisations in brackets) West Midlands - 47 (31) Scotland - 25 (22) North West - 29 (20) North East - 28 (18) South West - 23 (19)

Output metric name	Achievement
	South East - 49 (43) London - 84 (60) East of England - 34 (25) East Midlands - 29 (21) Wales - 8 (8) Yorkshire and The Humber - 29 (22) Northern Ireland - 14 (11)
CO4: Collaborations (by work strand, type and size)	Number of collaborations among CR&D projects: 894 (calculated by counting the number of collaborations on each project e.g. if a project had 4 partners, there were 6 collaborations (6 unique pairings). Collaborations are not unique and are summed across all projects). • 198 collaborations between SMEs and large companies • 185 collaborations between manufacturing firms and technology companies • 174 collaborations between businesses and academics/research organisations.
CO5: Number and type of people engaged (Networks)	12,731 (Members registered in the Made Smarter Innovation Network WorkBooks folder) 17,421 (participants engaged with at campaigns) 10,540 links clicked in email newsletter (Made Smarter Innovation Network WorkBooks folder)
CO6: Number/type of events held/attendances	61 held by MSI Network 92 held by RCs 35 by InterAct 25 events spoken at (MSI Network)
CO7: New and increased use of facilities	No data available
CO8: Number of manufacturers testing IDT solutions	13 (value available for the RCs only)

Output metric name	Achievement
CO9: Additional private sector investment (additional to match funding)	£102m (total non-ISCF funding, Forms 3 and 4)
CO10: Use/business cases developed	570 (491 CRD, 69 Hubs, 10 RCs)
CO11: Demonstrators developed	334 (275 CRD, 24 Hubs, 35 RCs)
CO12: Number of digital tech businesses developing IDT solutions	15 (No. of spin-outs / start-ups formed – reported directly by UKRI)
CO13: Number of publications produced and their reach	470 papers (204 RCs, 114 CRD, 97 Hubs, 15 InterAct)
CO14: New connections made (by type)	1,350 (for the MSIN, total introduction per the CRM tab between Nov 2022 and Nov 2024)
CO15: New research partnerships formed (by type)	76 academics engaged (outside consortia – RCs) 40 institutions (InterAct) 28 academic organisations (CRD)

Source: SQW based on data from Made Smarter Innovation

Annex G: Performance on outcome metrics

G.1 The tables below provide an overview of how MSI has contributed towards short-term and long-term outcomes identified in the logic model, as captured by monitoring data.

Table G-1: Achievement on Logic Model Short-Term Outcomes

Outcome	Achievement	Comment
STO1: Better understanding of IDT use and benefits	81% beneficiary survey respondents reported increased understanding of IDTs	
STO2: Increased adoption of new IDTs	601	Reported directly by UKRI
STO3: Increased investment in IDTs	£112m (public and private) £104m (public and private - £1.7 & £102.5m respectively)	Form 1&2 Form 3&4
STO4: TRL progression	55% beneficiary survey respondents progressed at least 3 TRLs	
STO5: Number of new IDT solutions developed for manufacturers	356	Reported directly by UKRI
ST06: Number of IDT providers selling to manufacturers for first time	15 spin outs / start ups	Reported directly by UKRI
ST07: IP applied for or registered	39	
ST08: Follow-on investment in IDT solutions produced by the programme	£1.7m £102.5m	Form 3 funding Form 4 funding

Outcome	Achievement	Comment
ST09: Increased skills in the use, development and application of IDTs	6,936 people with increased IDT skills	
ST10: Greater awareness of use of IDTs in manufacturing (tech companies, manufacturers, academics)	81% beneficiary survey respondents reported increased understanding of IDTs	
ST11: Knowledge transfer/collaboration benefits	23/43 beneficiary survey respondents worked with new partners	
ST12: Stronger academic capability & capacity in IDTs	76	Defined as number of academics (outside RC) engaging with the RC

Source: SQW analysis of MI data

Table G-2: Achievement on Logic Model Long-Term Outcomes

Metric	Monitoring Data Value	Comments
LT01: Net change/ increase in: Productivity, GVA, Employment		
Average improvement in productivity	10% increase	Reported directly by UKRI
Average decrease in costs	n/a	n/a
Increase in employment	459 jobs	Reported directly by UKRI
LT02: Reduction in waste	11% reduction in waste	Reported directly by UKRI
LT03: Reduction in greenhouse gases/CO2E	15% reduction in CO_2e	Reported directly by UKRI
LT04: Increased skills and capability of manufacturers using IDTs	6,936 people with increased IDT skills	

Metric	Monitoring Data Value	Comments
LT05: Increase in IDT providers (inc. start/up and spin outs)	15	Reported directly by UKRI
LT06: Increase in employment in IDT providers	n/a	
LT07: Value of sales of new IDT solutions	n/a	
LT08: Increase in export sales of IDTs in digital tech companies	£4.26m	
LT09: Sustained network of partnerships, connections and collaborations	4	Joint Venture created through the programme and companies that have gone onto other programmes at Digital Catapult, available for Accelerators only
LT10: Greater academic engagement in IDT innovation	-	
LT11: Coordinated ecosystem linking relevant stakeholders, networks and capabilities	-	

Source: SQW analysis of MI data

Annex H: Secondary data analysis

Data sources

H.1 Table H-1 details the data sources used in Section 3 of the main report in the sub-section 'Secondary data analysis of key indicators'.

Table H-1: Data Sources

Metric	Source	Detail
GVA	ONS (2025) GDP output approach – low-level aggregates	Seasonally adjusted, chained volume measure
GVA as % of whole economy	SQW calculation from ONS (2025) GDP output approach – low-level aggregates	Seasonally adjusted, chained volume measure
Employment - GB	ONS (2024) Business Register and Employment Survey – obtained from Nomis portal	-
Employment as % of whole economy - GB	SQW calculation from ONS (2024) Business Register and Employment Survey – obtained from Nomis portal	-
GVA – GB	ONS (2024) Regional gross value added (balanced) by industry: all ITL regions	Current price estimates – inflation adjusted
Productivity (GVA per employment) - GB	SQW calculation: GVA GB divided Number of employees	GVA in 2022 prices
Jobs	ONS (2025) Workforce jobs by Industry	Seasonally adjusted
Business expenditure on R&D	ONS (2024) Business enterprise research and development, UK	Inflation adjusted, in 2023 prices
Business expenditure on R&D, as a proportion of GVA	SQW calculation from 'Business Expenditure on R&D' and 'GVA'	-
% of engineering manufacturing "innovation active"	DBT (2024) UK Innovation Survey 2023	-
% of non-engineering manufacturing "innovation active"	DBT (2024) UK innovation survey 2023	-

Metric	Source	Detail
GHG emissions (000s tonnes of CO2 equivalent)	ONS (2024) Atmospheric emissions: greenhouse gases by industry and gas	Mass of air emissions per annum in thousand tonnes of carbon dioxide equivalent 2023 figure is provisional Residence basis
Energy use all sources (million tonnes of oil equivalent)	ONS (2024) Energy use: by industry reallocated to final consumer and energy intensity	Reallocated energy use in million tonnes of oil equivalent (Mtoe)
Value of manufacturing exports (£ billion)	ONS (2025) Monthly Business Survey turnover in production industries	Current prices, non-seasonally adjusted, inflation adjusted in 2024 prices
Value of Digital Technologies exports (£ billion)	ONS (2024) UK trade in goods by industry, country and commodity, exports	Current prices, inflation adjusted in 2022 prices
Value of manufacturing exports, as a % of all exports	SQW calculation from ONS (2024) UK trade in goods by industry, country and commodity, exports	Current prices
GHG emissions intensity (000s tonnes of CO2 equivalent/£m)	ONS (2024) Atmospheric emissions: greenhouse gas emissions intensity by industry	2023 figure is provisional Residence basis

Source: See table

Manufacturing

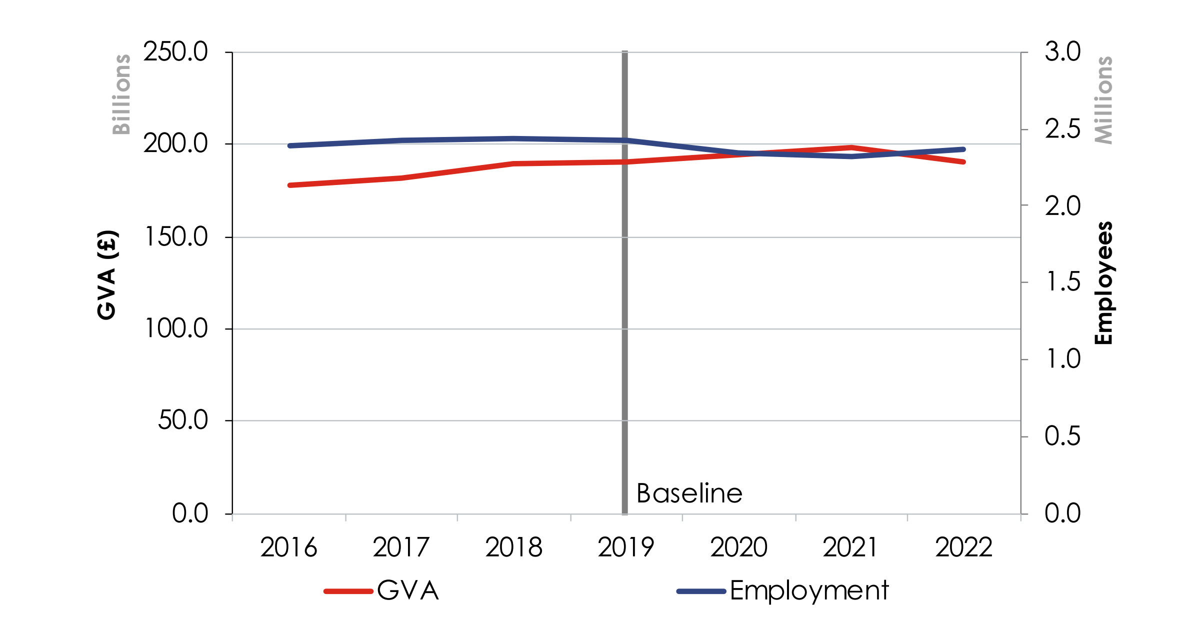
GVA and Employment

H.2 In 2024, Manufacturing accounted for approximately £207bn of GVA, c. 9% of the UK's total. This has remained approximately constant since 2009 (when it was 10%) but is significantly lower than the 1998 value of 16%. Since the baseline, the proportion that manufacturing contributes to total UK GVA has decreased from 9.8% to 8.8%.

H.3 In 2023, there were 2.4m employees in the manufacturing sector in Great Britain, a figure virtually unchanged since 2015[6] - however, given the increase in the total number of employees over that time this represents a gradual fall in the proportion, from 8.1% of all employees at the baseline in 2019 to 7.5% in 2023.

[6] Excluding a slight decrease to 2.3m in the years 2020 and 2021, likely as a result of the Covid-19 pandemic.

Figure H-1: Manufacturing employees and output (GVA) – Great Britain

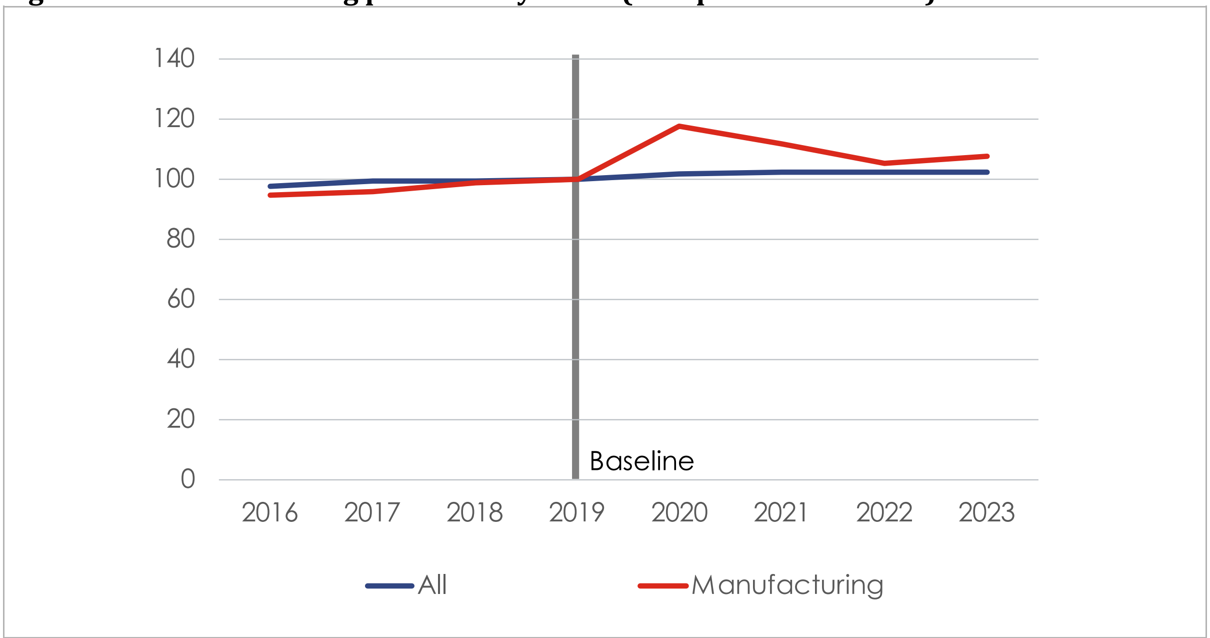


Source: ONS (2024) Business Register and Employment Survey and ONS (2024) Regional gross value added (balanced) by industry: all ITL regions
Note: GVA in 2019 prices

Productivity

H.4 The productivity of the manufacturing sector, as measured in GVA per hour worked, is 7% higher than the productivity of the UK as a whole and is growing at a faster rate. Whilst the UK's productivity in 2023 is approximately 2% higher than it was at the baseline (2019), the manufacturing industry's productivity is 8% higher.

Figure H-2: Manufacturing productivity index (GVA per hour worked)



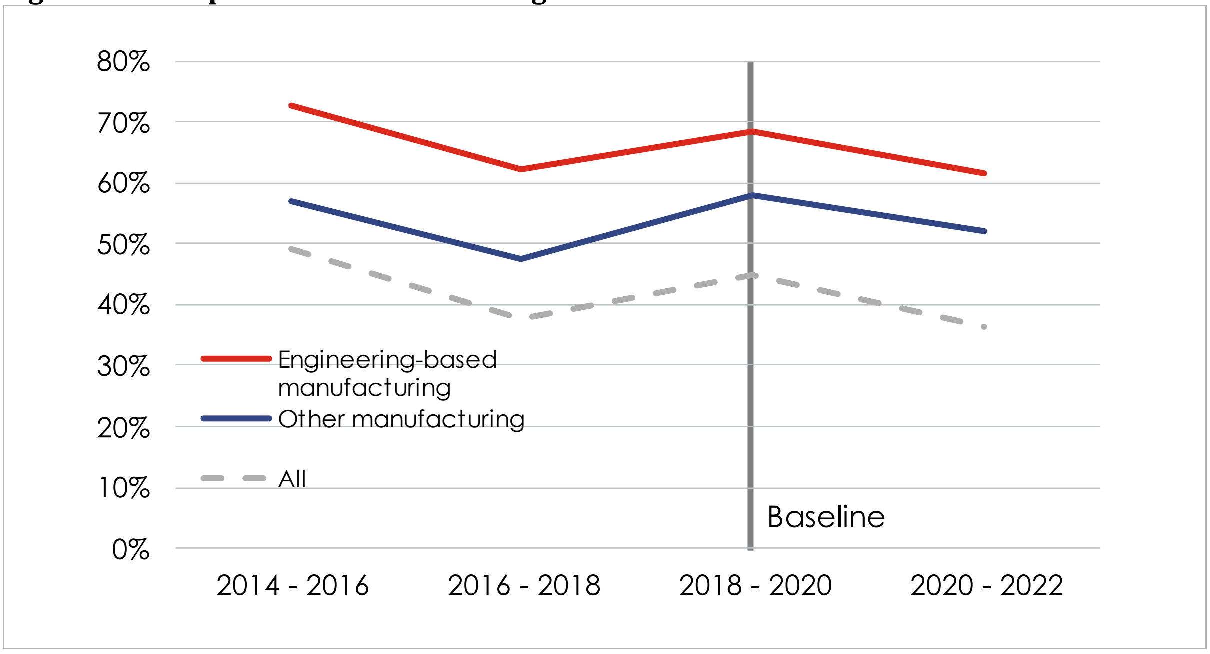
Source: OECD (2025) OECD Productivity Database
Note: Constant prices, 2015 = 100

Innovation

H.5 UK Manufacturers spend a disproportionate amount on R&D, compared to their GVA or employee counts. In 2023, the UK manufacturing sector spent c. £11bn on R&D, 21% of the total spent in any industry (£50bn).[7] This is mirrored in the proportion of businesses that are innovation active – from the latest 'Innovation Survey', 36% of all UK businesses are 'Innovation Active',[8] compared to 62% of engineering-based manufacturing businesses and 52% of other manufacturing businesses. For both types of manufacturing, the main factor driving innovation was 'improving quality of goods or services'.

H.6 Since the baseline, there has been a slight decrease in the proportion of manufacturing businesses (both 'engineering based' and 'other') recorded as innovation active, down from 68.5% and 57.8% respectively, to 61.6% and 52.0%.

Figure H-3: Proportion of businesses regarded as 'innovation active'



Source: Department for Business and Trade (2024) United Kingdom innovation survey 2023

Exports

H.7 As well as innovating more than other businesses, the UK Manufacturing sector makes up a disproportionate proportion of the UK's exports. In 2022, just under half the UK's exports (50%) were from the manufacturing industry, a proportion that has remained relatively constant since 2008. Manufacturing exports in 2022 were higher in real terms than in any previous year (since 2008), and £5bn higher than they were at the baseline. However, the proportion has decreased since the baseline, from 53% to 50%. Whilst there was a slight decrease in the proportion of

[7] ONS (2024) Business enterprise research and development, UK: 2022.

[8] 'Innovation active' is defined as a business either introducing new products/services, introduced new business processes to produce or supply goods, or engaging in innovation projects that are not yet complete or abandoned.

exports that manufacturing comprises from 2021 to 2022, this was as a result of a recovery in the exports from other sectors post-pandemic.

Figure H-4: Manufacturing exports (inflation adjusted)

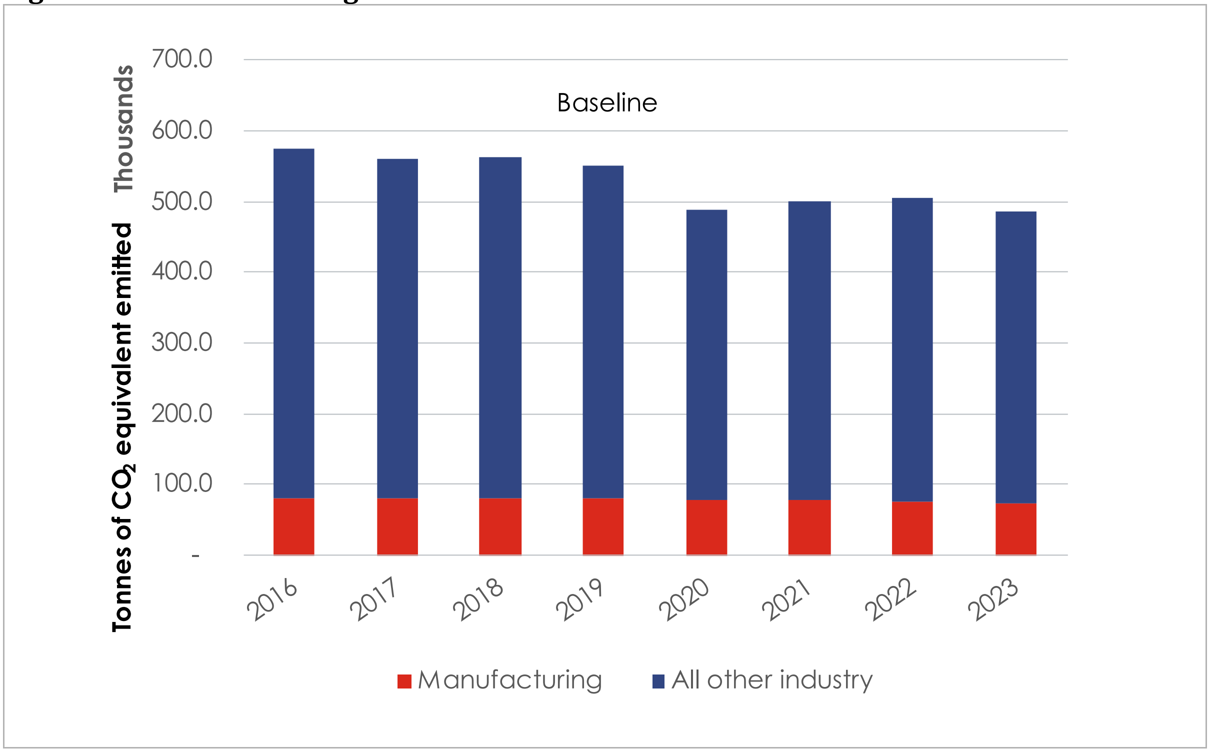
Source: ONS (2024) UK trade in goods by industry, country and commodity, exports~
Note: Export values are in 2022 prices

Emissions

H.8 Like R&D spend, the manufacturing sector emits a disproportionately high proportion of the UK's emissions, relative their GVA – in 2023 the manufacturing industry emitted 73m tonnes of CO_2 equivalent (including other greenhouse gasses like CH_4 and NO_2), 15% of the UK total (487m tonnes)[9]. Since the baseline, CO_2 emissions have decreased in the manufacturing sector less than for the UK as a whole – between 2019 and 2023 total emissions fell by 11%, whilst emissions in the manufacturing sector fell by only 8%. As a result, the proportion of the UK's total emissions accounted for by the manufacturing sector has increased from 14.6% to 15.1% over the period.

[9] At time of writing the emissions statistics for 2023 were 'provisional'. It was 17% in 2022.

Figure H-5: Manufacturing and UK emissions



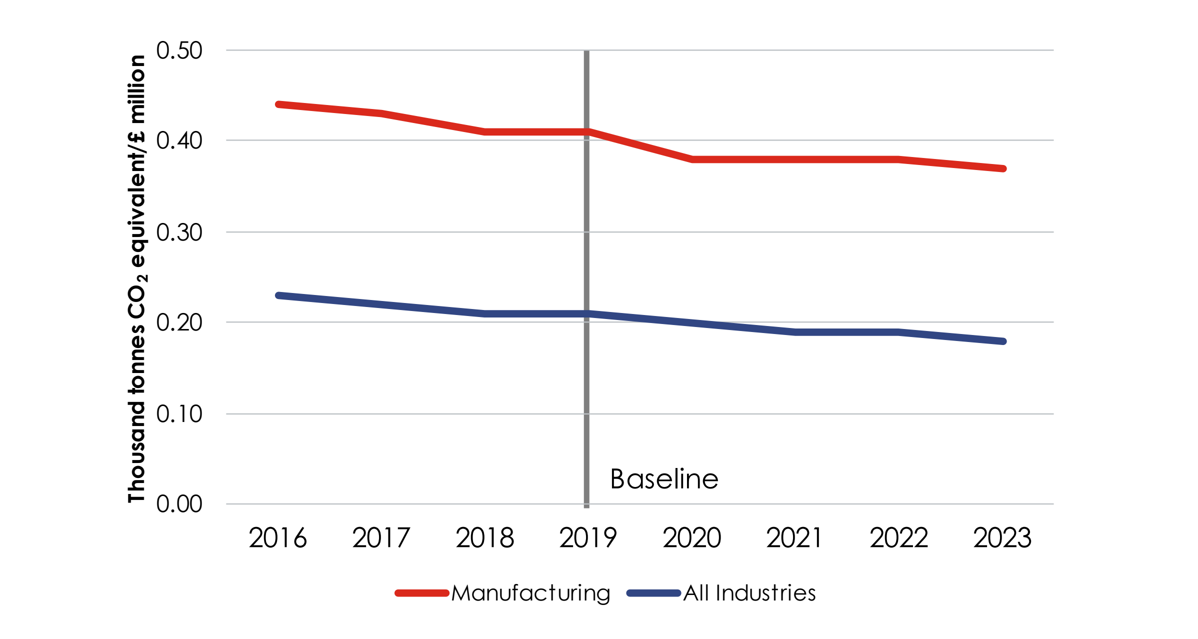
Source: ONS (2024) Atmospheric emissions: greenhouse gases by industry and gas

H.9 Considering both GVA and CO2 emissions, the manufacturing sector has a higher emissions intensity[10] than the UK as a whole (Figure H-6). Across all sectors, in 2022, 192 tonnes of CO_2 was emitted per £m of GVA created, whilst in the manufacturing sector the figure was 351, 84% higher. Since the baseline in 2019, emissions intensity for the UK have decreased 18%, whilst for manufacturing it has decreased by 12%.

H.10 Likewise, the energy use of the Manufacturing sector has decreased from 38.0 Mtoe (Mega tonnes of oil equivalent) in 2019 to 34.7 Mtoe in 2022.[11]

[10] Thousand tonnes of CO_2 emissions produced per £m of GVA generated.
[11] ONS (2024) Energy use reallocated and energy intensity in the United Kingdom

Figure H-6: Emissions intensity, UK and total



Source: Source: ONS (2024) Atmospheric emissions: greenhouse gases by industry and gas; ONS (2024) Regional gross value added (balanced) by industry: all ITL regions

Digital technologies

H.11 This evaluation uses a definition of the 'digital technology' sector used in the 2020 Tech Nation impact evaluation.[12] This definition is comprised of six two-digit SIC codes, as detailed in the table below.

Table H-2: Digital technology sector definition

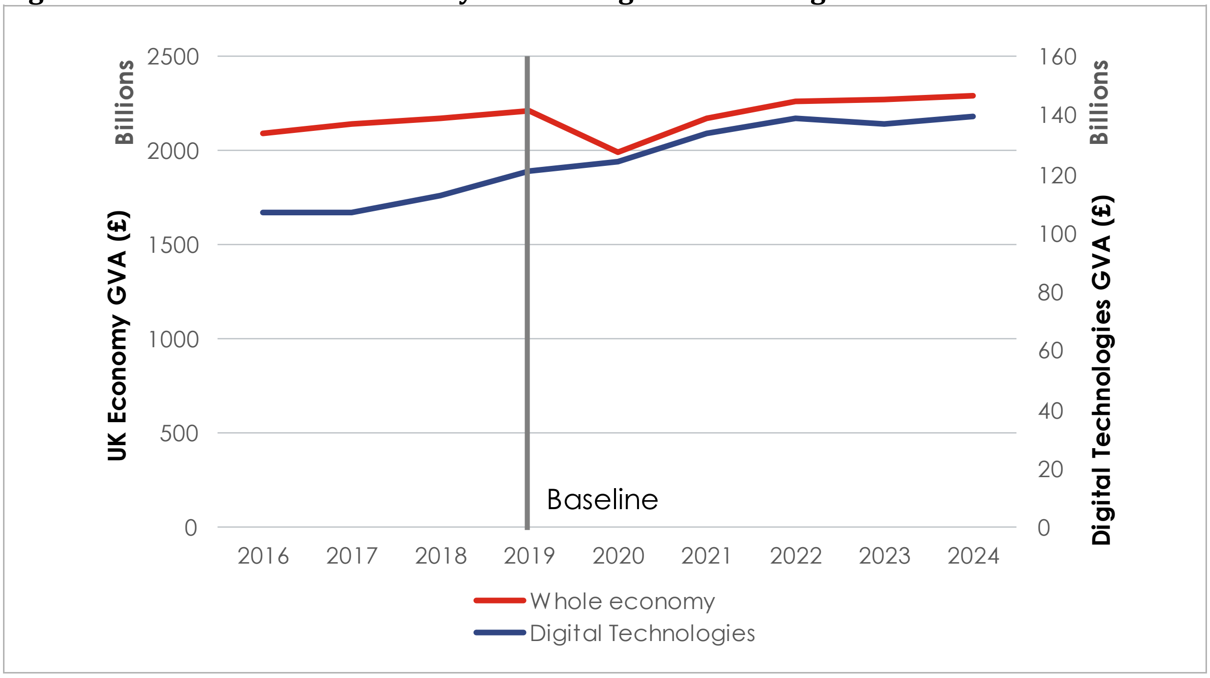
	Division	Description
Information and Communication (Section J)	58	Publishing activities
	59	Motion picture, video and television programme production, sound recording and music publishing activities
	60	Programming and broadcasting activities
	61	Telecommunications
	62	Computer programming, consultancy and related activities
	63	Information service activities

[12] Tech Nation Impact Evaluation (2020) Frontier Economics

Source: ONS, Standard Industrial Classification (SIC 2007), based on [Tech Nation Impact Evaluation](#)

H.12 The GVA of the Digital Technology sector comprises approximately 7% of the UK's total GVA.[13] The economic impact of the Digital Technology sector has grown faster than the UK economy as a whole. Since the baseline in 2019 to 2022, the GVA of the UK economy has grown by 13% and the GVA of the Digital Technologies sector has grown by 17% - as a result the proportion of the UK's GVA comprised of the digital technologies sector has increased from 6.3% to 6.5%.

Figure H-7: GVA of the UK economy and the Digital Technologies sector



Source: ONS (2024) Regional gross value added (balanced) by industry: all ITL regions
Note: Chained Volume Measure

H.13 In 2023, there were 1.4m employees in the Digital Technologies sector. The number of employees has grown by 9% since 2019, significantly higher than the UK as a whole (4%). In that time, the GVA per worker in the digital sector has increased by approximately 8%.

Beauhurst

H.14 Data from Beauhurst, an online database of UK companies, was analysed to further understand the context. The data was downloaded in March 2025 and has been compared to the baseline report, with downloaded data from February 2022. To gain an understanding of the advanced manufacturing business context, data was downloaded for companies tagged with one of more of the following Beauhurst 'buzzwords': 3D printing, artificial intelligence, augmented reality, Internet of Things, robotics and virtual reality. There are 10,293 businesses with a HQ in the UK that are tagged with at least one off these buzzwords, an almost 400% increase on the number at the baseline stage (2,132). This very large increase has mostly been driven by a large spike in the

[13] In 2022

number of businesses tagged with 'Artificial intelligence' which has increased from 1,318 to 7,661 (a 481% increase). Full details can be found in Table H-3.

Table H-3: Beauhurst 'buzzwords' tagged to companies (n = varies)

	Baseline (2022) (n = 2132)		Final (2025) (n = 10,293)		Change, Baseline to Final	
	Number of firms	Percentage of firms	Number of firms	Percentage of firms	Number change	Percentage increase
3D printing	90	4%	221	2%	↑	146%
Artificial Intelligence	1,318	62%	7661	74%	↑	481%
Augmented reality	208	10%	403	4%	↑	94%
Internet of Things	389	18%	985	10%	↑	153%
Robotics	158	7%	914	9%	↑	478%
Virtual reality	282	13%	762	7%	↑	170%
Any	2,132	-	10,293	-	↑	383%

Source: SQW analysis of Beauhurst data 2025 and 2022 (https://www.beauhurst.com/).
Note, firms can be tagged to more than one 'buzzword'.

H.15 Notably, the raw number of companies tagged with all buzzwords has increased by at least 94%. The two largest increases are in businesses tagged with 'Artificial Intelligence' (481%) and 'Robotics' (478%). Separate Beauhurst Analysis suggests that in the period 2022 to 2024, the number of active businesses in the UK has increased from 5.24m to 5.63m,[14] an increase of 7% - even considering the different time periods, it is clear that the growth in the businesses tagged with the above buzzwords (and by proxy the advanced manufacturing sector) are growing at a faster rate than the business base as a whole. Whilst a large proportion of this increase can be attributed to growth solely in the 'Artificial Intelligence' buzzwords, all show an increase.

H.16 The Fundraising efforts by buzzword show a variation in the ability to secure finance and the amount of finance secured, as shown in Table H-4. Whilst this has been compared to the data at the baseline stage, the 2022 figures presented do not reflect inflation, and thus in real terms will be larger than presented in the table.

[14] New Start Up Index 2024 (2025) NatWest.

Table H-4: Fundraising data of Beauhurst 2025 (2022)

3D printing	Artificial Intelligence	Augmented reality	Internet of Things	Robotics	Virtual reality
Average number of fundraisings					
1.4 (1.7)	**0.9** (2.3)	**1.5** (1.5)	**1.6** (2.4)	**0.6** (1.7)	**1.0** (1.4)
Median value of fundraisings					
£430k (£1.3m)	**£450k** (£1.3m)	**£410k** (£700k)	**£370k** (£1.2m)	**£340k** (£1.1m)	**£350k** (£500k)
Average value of fundraisings					
£2.0m (£2.8m)	**£3.3m** (£8.0m)	**£3.6m** (£5.5m)	**£2.5m** (£9.7m)	**£3.9m** (£14.0m)	**£2.9m** (£3.4m)
Total value of fundraisings					
£590m (£150m)	**£22.0bn** (£8.0bn)	**£2.1bn** (£656m)	**£3.8bn** (£2.7bn)	**£1.9bn** (£1.2bn)	**£2.2bn** (£530m)
Increase in total value of fundraising 2022 - 2025					
300%	**180%**	**210%**	**40%**	**60%**	**310%**

Source: SQW analysis of Beauhurst data 2025 and 2022 (https://www.beauhurst.com/).

H.17 The fundraising data again indicates the large increase in the number of businesses tagged with each buzzword since 2022. A larger, younger, business base will have conducted fewer fundraisings and raised less money, pushing the averages down on the baseline, whilst the total raised will only have increased. It is notable that the total increase in the volume of funding in some cases exceeds the increase in the growth in the number of businesses (e.g. 3D printing, Augmented reality), whilst for others it is smaller.

Gateway to Research

H.18 To understand wider research trends, including how many projects are being undertaken and how much grant funding they have received, the UKRI 'Gateway to Research' database was analysed. The database provides data on the number of publicly funded projects and the grant funding they received.

H.19 Using 22 search terms (detailed in Table H-5) in combination with the words "manufacturing" (for example "AI systems" AND "manufacturing"), the abstracts and titles of research projects were filtered and extracted into five broader categories.

H.20 Between 2016 and 2025, a total of 3,762 projects were supported that related to at least one of these five categories, and a total of £2.6bn grant funding was awarded. In summary:

- The Median amount of funding received by these projects was £137k (or £325k when those receiving no funding were excluded). The maximum amount received by any one project was £28.5m – a research grant lead by the University of Birmingham.
- The three main funding bodies were EPSRC (46% of projects and 46% of total awarded funding), Innovate UK (32% and 33%) and ISCF (8% and 11%). All other funding bodies supported 5% or less of the projects and funding.
- By **number of projects**, the most frequent 'type' of supported projects are: Studentship (29% of projects), Research Grant (22%) and Collaborative R&D (21%). By **award value** the most funded 'type' of projects include:[15] 'Research Grant' (38% of total awarded funding), 'BEIS-Funded Programmes' (18%) and 'Collaborative R&D' (16%). The highest average funding (total awarded funding divided by number of projects) was for 'Training Grants'.
- By region, the South East (14%), London (13%) and the South West (12%) received the most awarded funding.
- The top 34 organisation that lead these projects are all universities, with the most common leading these projects being the University of Nottingham (131 projects), Imperial College London (127 projects) and the University of Sheffield (121 projects).

H.21 The total number of unique projects and grant funding across all five of these of these categories is shown in Figure H-8, whilst the number of unique projects and funding within each category can be found in Figure H-9 to Figure H-13.

Table H-5: Search terms for Gateway to Research

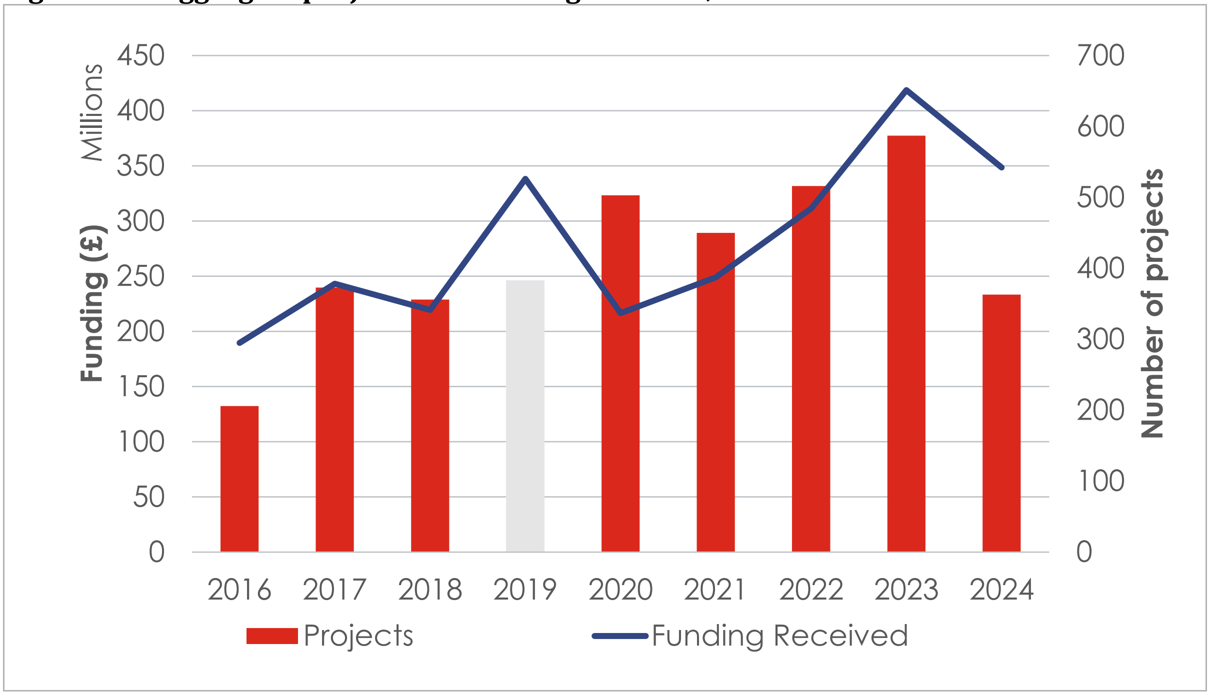
Category	Search terms
Artificial Intelligence (including Machine Learning and Data Analytics)	AI systems artificial intelligence neural network big data data analytics machine learning digital twins simulation
artificial intelligence	3D printing additive manufacturing
neural network	automation automated

[15] 'Studentships' are not awarded any funding.

Category	Search terms
	autonomous robotics robot
big data	Internet of things
data analytics	virtual reality artificial reality augmented reality AR VR sensors

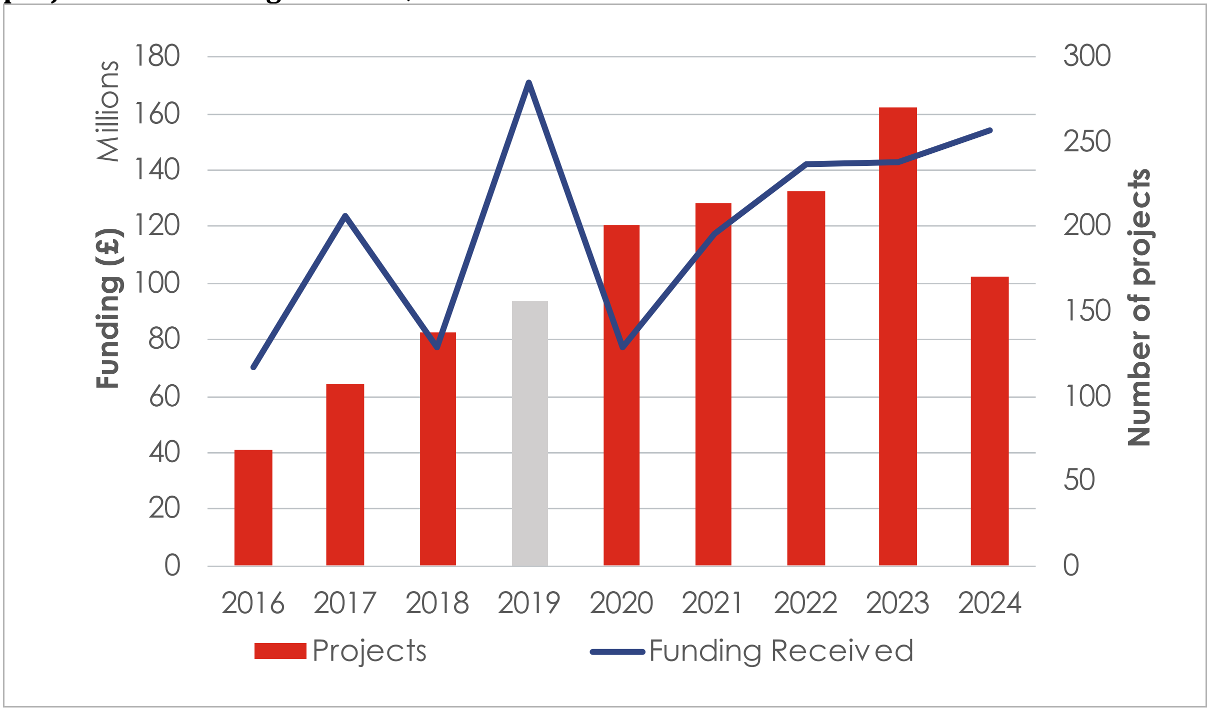
Source: SQW

Figure H-8: Aggregate projects and funding awarded, 2016 to 2024



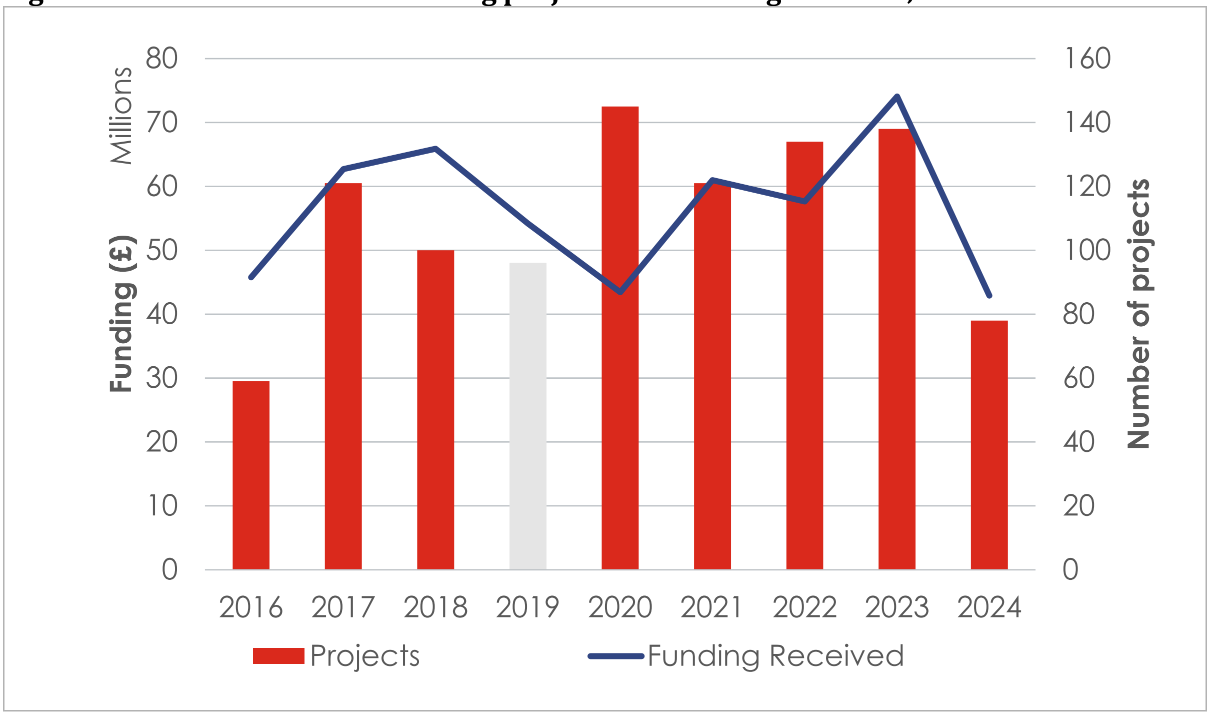
Source: SQW Analysis of GtR data
Note: Funding in current Prices

Figure H-9: Artificial Intelligence (including Machine Learning and Data Analytics) projects and funding awarded, 2016 to 2024



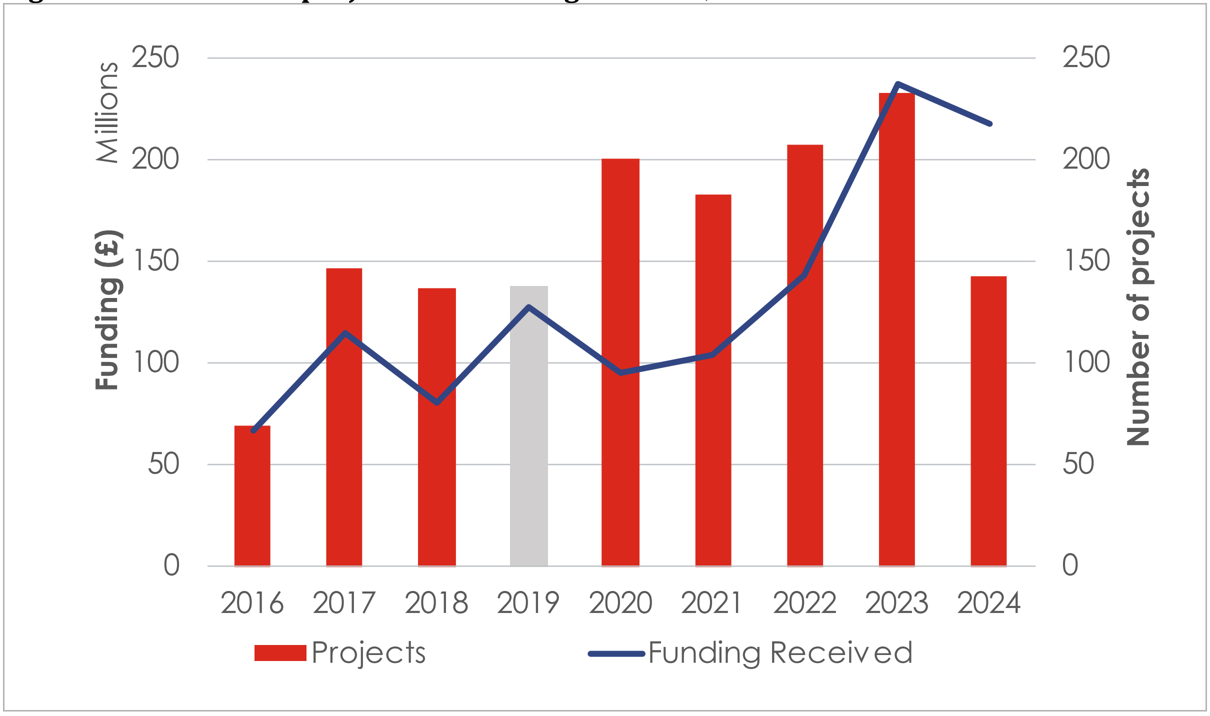
Source: SQW Analysis of GtR data
Note: Funding in current prices

Figure H-10: Additive Manufacturing projects and funding awarded, 2016 to 2024



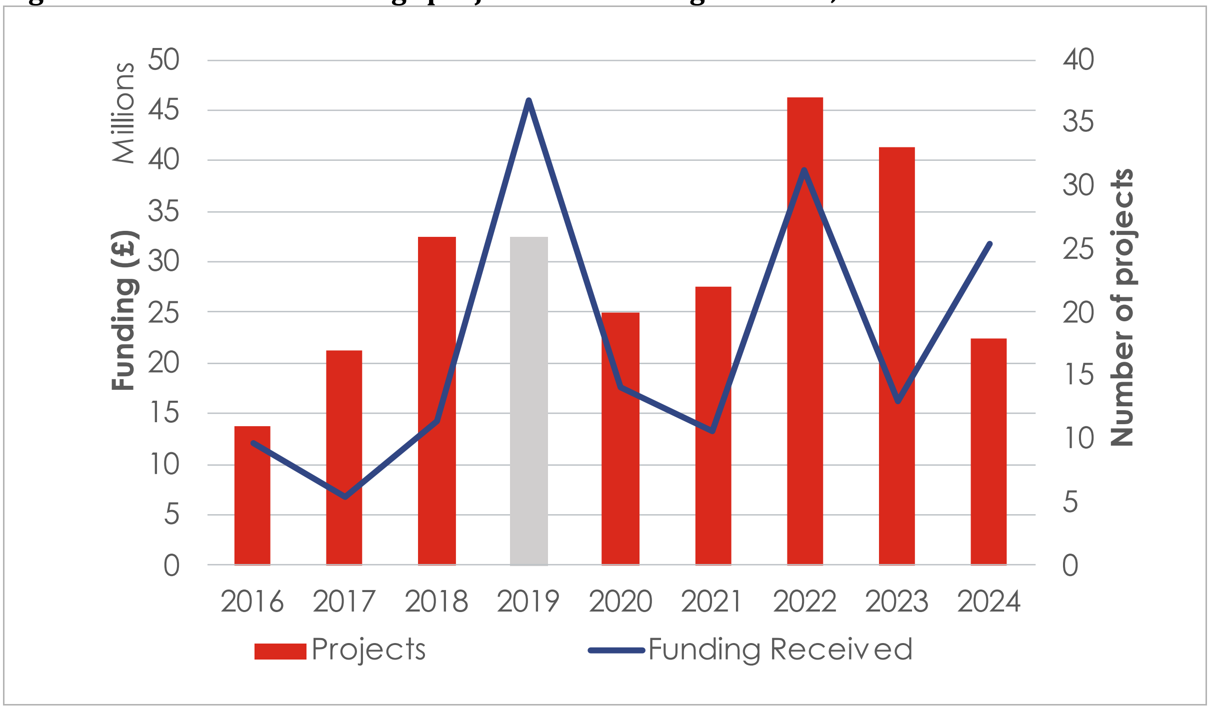
Source: SQW Analysis of GtR data
Note: Funding in current prices

Figure H-11: Robotics projects and funding awarded, 2016 to 2024



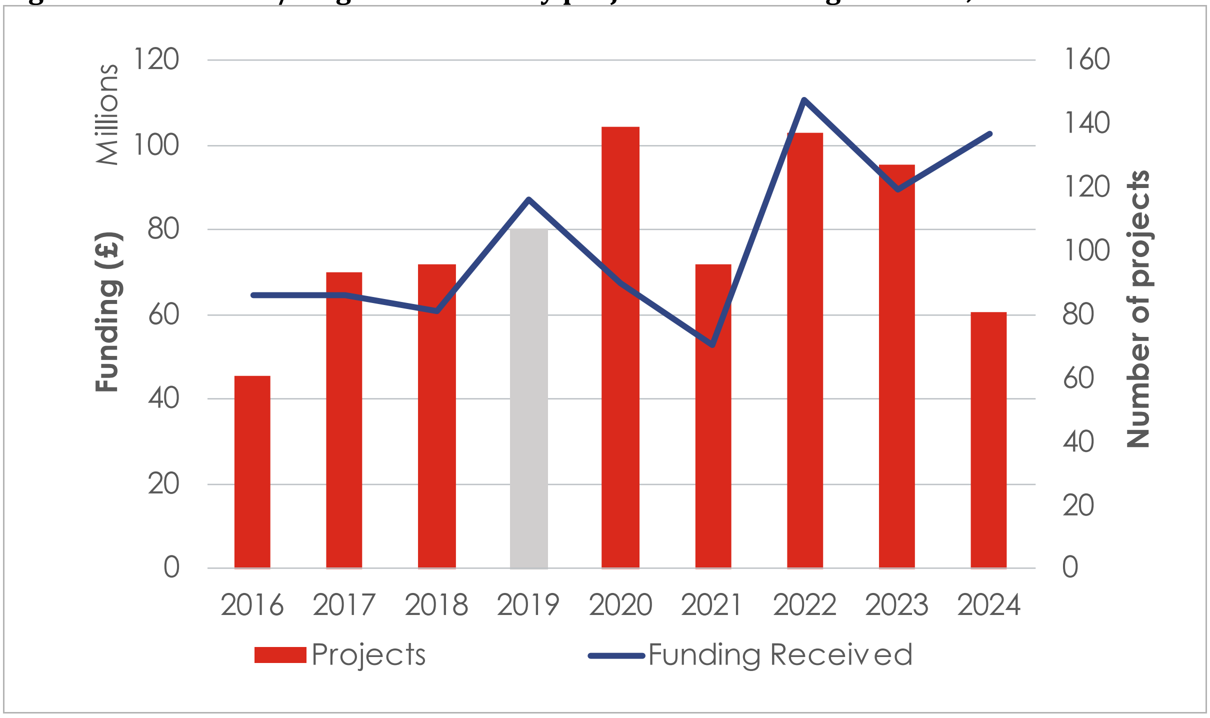
Source: SQW Analysis of GtR data
Note: Funding in current prices

Figure H-12: Internet of Things projects and funding awarded, 2016 to 2024



Source: SQW Analysis of GtR data
Note: Funding in current prices

Figure H-13: Virtual / Augmented Reality projects and funding awarded, 2016 to 2024



Source: SQW Analysis of GtR data
Note: Funding in current prices

Annex I: Econometric analysis

I.1 This annex provides further detail on the statistical analysis described in the main report. Specifically, it includes information on how firms in the matched comparison group were selected, including the graphical representations of balance tests that show the reduction in differences between the beneficiaries and comparison companies before and after Propensity Score Matching (PSM). It also includes summary profiles of the two comparison groups: matched comparators and unsuccessful applicants. Finally, the annex also outlines the specification of DiD models used to estimate impacts and shows the estimation results omitted from the main report for conciseness.

Selecting the matched comparators

I.2 We used PSM to select our matched comparison group which served as our main benchmark for the beneficiaries. Firms in the matched group were selected from c. 3,000 of potential companies identified on Beauhurst using a set of criteria around companies' sector, age and innovation profile detailed in Table I-1. The matching specification then included a wide range of characteristics available on Beauhurst, including proxies for innovation activity.

Table I-1: Criteria for potential comparator firms

Criteria	Restriction	Comment
Industry (primary SIC 2007 code)	5 sector groups that were most common for beneficiaries C - Manufacturing J - Information and communication M - Professional, scientific and technical activities G - Wholesale and retail trade / repair of motor vehicles and motorcycles N - Administrative and support service activities S - Other service activities	These five sector groups cover 91% of beneficiaries
Beauhurst Tracking status	46% of the sample were tracked (currently or at some point)	43% of beneficiaries are or were tracked by Beauhurst
Beauhurst Buzzwords	38% of the sample associated with at least one of the following buzzwords:	34% of beneficiaries are linked to a buzzword. These buzzwords cover 75% of beneficiaries' buzzwords

Criteria	Restriction	Comment
	➢ Software-as-a-Service (SaaS) ➢ Artificial Intelligence ➢ 3D printing ➢ CleanTech ➢ Internet of Things ➢ Blockchain ➢ Robotics ➢ Cloud computing ➢ Subscription ➢ Mobile apps	
Date of incorporation	Jan 2000 – Jan 2023	This range covers over 78% of beneficiaries. Focusing on younger firms

Source: SQW

I.3 For each beneficiary, we selected two non-beneficiaries with the closest propensity scores, yielding the 1:2 matched comparison group. In any statistical analysis there is a chance to miss the effect when it is present (i.e. to declare there are no statistically significant differences between the beneficiaries and comparison groups).[16] The larger the sample, the smaller the difference between the groups that we can confidently identify. We decided to create a 1:2 comparison group (as opposed to 1:1) which would give us a slightly larger statistical power and allow us to be more confident about any borderline results.[17]

I.4 To assess the quality of the comparison groups we carried out the descriptive analysis of key characteristics (presented in Annex J). For the matched group we also considered the reduction in the average differences between groups after the matching and the similarity of the profiles of propensity scores (detailed below). We also undertook a graphical analysis of pre-treatment trends. Overall, our view was that PSM had successfully reduced imbalances between the beneficiaries and potential comparators across the matching characteristics and provided us with a high quality comparison group.

I.5 The matching model did not match on pre-treatment size, as measured by employment, turnover or total assets. There were not enough turnover observations on Beauhurst to even consider

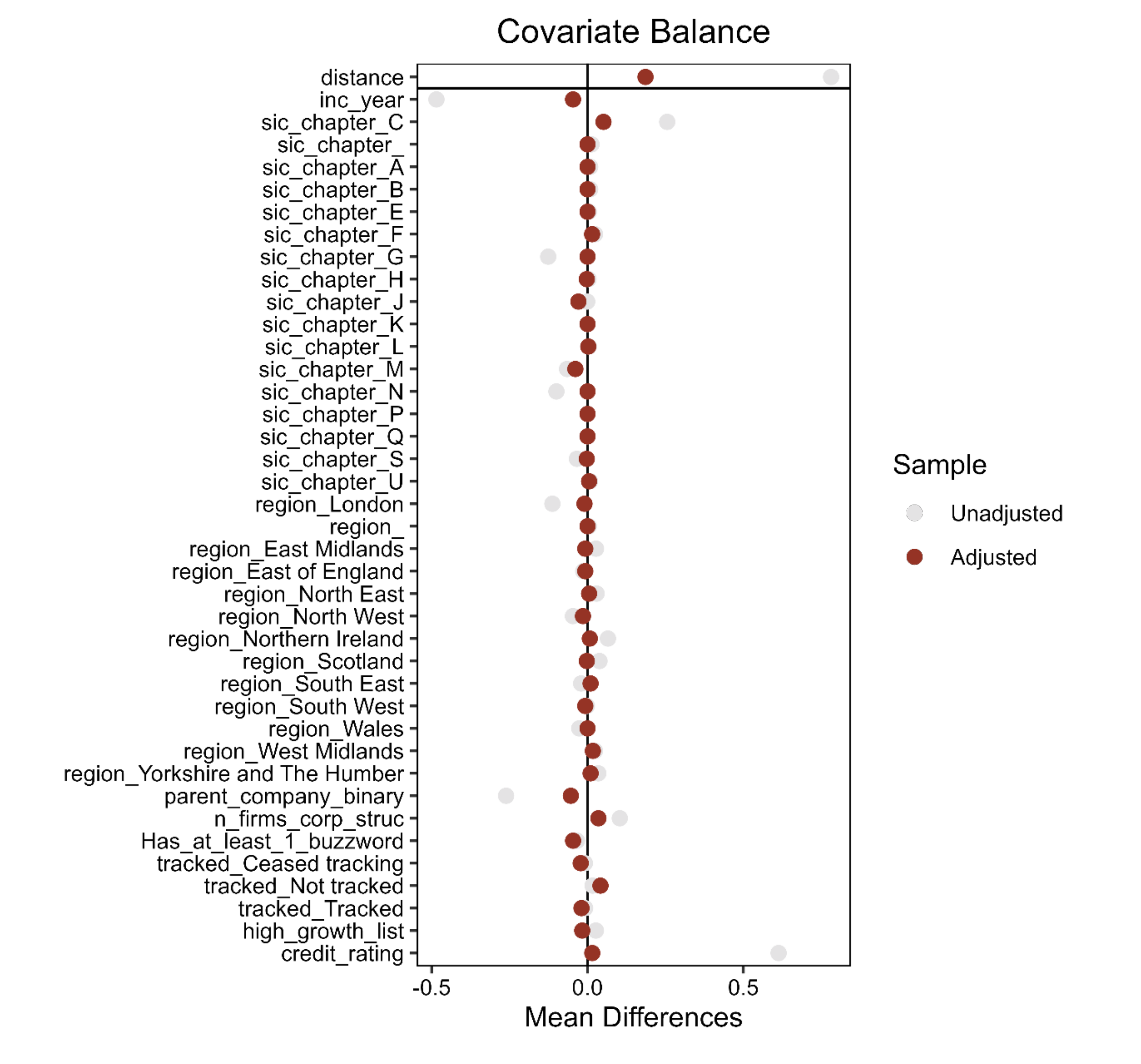
[16] Effects are statistically significant when they are unlikely to be observed by chance. The common thresholds for statistical significance are 10%, 5% and 1% indicating the probability of concluding the effect is present when in fact it is not.
[17] Statistical power is the probability to correctly identify the effect when it is indeed present. We checked that using a 1:2 group did not have any negative impacts on the quality of the comparison.

matching on it. Using employment would result in c. 30% loss in the number of analysed beneficiaries. There was a slightly lower loss when matching on pre-treatment total assets. We tested these specifications and found the resulting comparison groups very similar. Therefore, the decision was not to consider measures of pre-treatment size for matching.

I.6 Figures below show the reduction in imbalances after PSM. Figure I-1 shows the mean differences between the groups by individual characteristic (averaged across all companies in the sample). The closer the dots are to the vertical line, the more similar the averages in the samples are.

I.7 Figure I-2 demonstrates the distributions of propensity scores ("distance") before and after matching. The more similar the shape is below and above the middle line, the more like-for-like the groups are when we consider the samples through the prism of the combinations of characteristics of each business (rather than looking at the averages of one variable at a time across all businesses). Note that comparison group 2 consists of unsuccessful applicants – they were not selected through PSM, therefore there are no PSM balance graphs for that group.

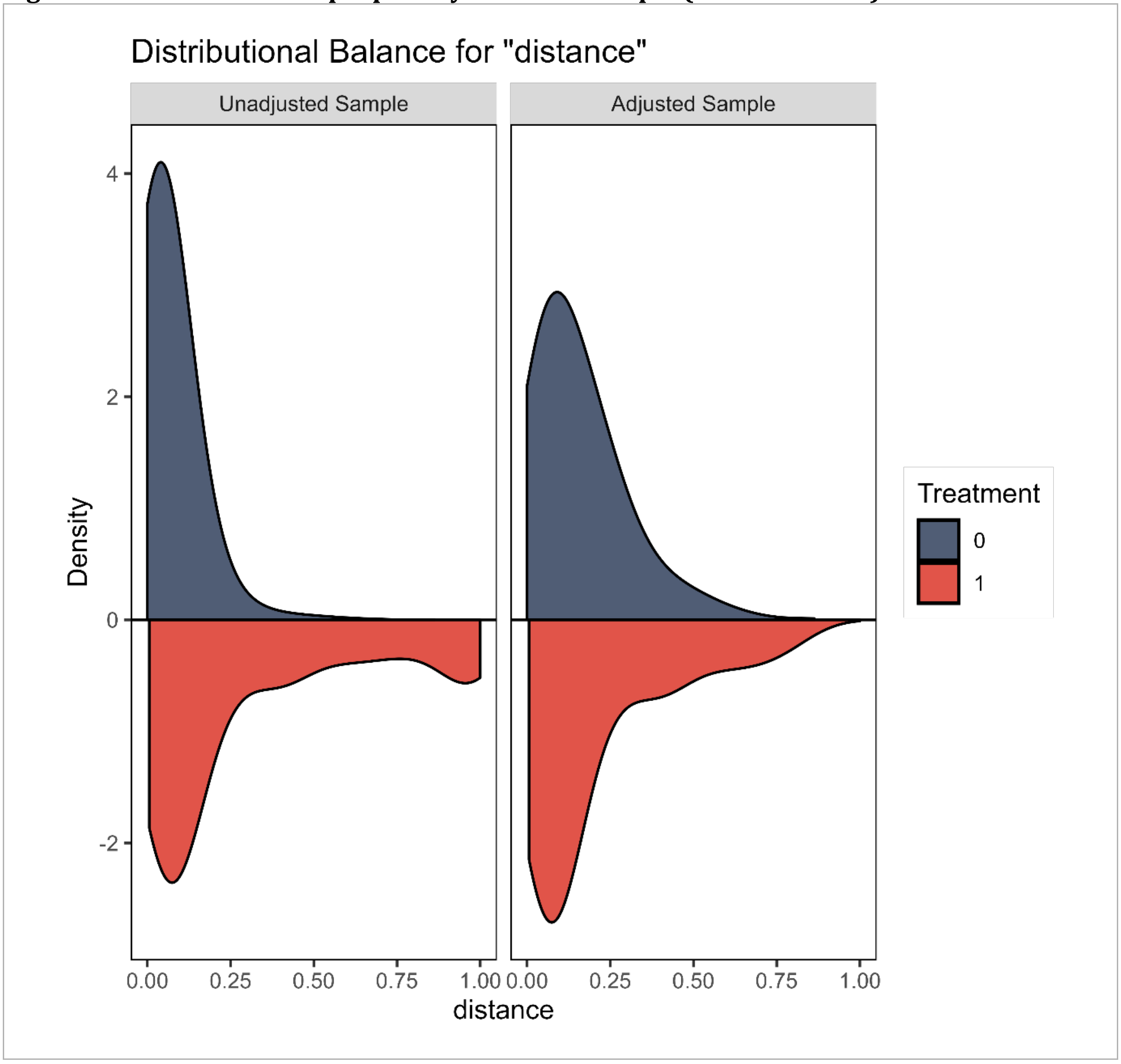
Figure I-1: Balance by characteristic – Group 1 (1:2 Beauhurst)



Note: distance is the propensity score.

Source: SQW

Figure I-2: Distribution of propensity scores – Group 1 (1:2 Beauhurst)



Note: distance is the propensity score.

Source: SQW

I.8 There is a lack of overlap between the distributions of propensity scores at the very right edge of Figure I-2. That is due to the pre-filtering used to select c. 3,000 potential comparators. Since several beneficiaries were founded before 2000, their age perfectly predicted the treatment status. We investigated those companies for any other systematic differences with the rest of the beneficiaries and did not find any. Therefore, we excluded them from the matching exercise but decided to keep them in the sample for analysis despite them having propensity scores that are higher than the scores estimated for any potential comparator.

Profiles of comparison groups

I.9 This section provides headline profiles of the two comparison groups: unsuccessful applicants and the matched comparators, and compares their characteristics to the MSI beneficiaries.

Unsuccessful applicants

I.10 Just over three quarters of unsuccessful applicants represent the same three most popular sectors as the beneficiaries: manufacturing (Section C), information and communication (Section J), and professional, scientific, and technical activities (Section M). However, unlike among the beneficiaries, manufacturing was the least represented sector of the three (12%) with the ICT being at the top (39%). This is likely a direct result of screening of applicants by MSI.

I.11 Approximately 40% of UAs were registered in London or the South East, which mirrors the geographic distribution of beneficiaries, and the regional distribution more broadly is also in line with that of the beneficiaries. The UAs also tended to be slightly younger companies – the median age at the time of application for them was six years vs eight years for the beneficiaries.

I.12 As could be expected, data indicates slightly lower levels of growth potential and innovation activity among UAs compared to the beneficiaries. Only 33% of unsuccessful applicants are tracked, compared to 43% of beneficiaries; 6% were classified as high growth (compared to 14%o of the beneficiaries). Furthermore, the proportion of unsuccessful applicants linked with at least one buzzword was also slightly lower (approximately 28% vs 34%). The selection of buzzwords was, however, similar to that of the beneficiaries, with Software-as-a-Service (SaaS), Artificial Intelligence, Internet of Things, Blockchain, and CleanTech being the most common).

I.13 Table I-2 summarises the data on unsuccessful applicants size in the year before they applied to the MSI. Overall, consistent with being on average slightly younger, applicants were also smaller than MSI's beneficiaries, both in terms of employees (median of 5 and 12 respectively), and in terms of turnover (median of £0.23m and £0.96m respectively).[18]

Table I-2: Average pre-application size of unsuccessful applicants

	Beauhurst	BSD
Turnover (median)	Data insufficient	£0.23m (n=125)
Employees (median)	6 (n=122)	5 (n=125)

Source: SQW analysis of Beauhurst and BSD data

Matched comparison group

I.14 The matching worked well to mirror the geographical, sectoral and age profiles of the beneficiaries. Just like the beneficiaries, a vast majority (87%) of the comparison firms belongs to

[18] Using Beauhurst data, mean employment of the unsuccessful applicants was 238 employees. Using BSD data, mean turnover was £166m and mean employment was 290 employees.

the following three SIC 2007 sectors: Manufacturing (section C), Information and communication (section J) and Professional, scientific, and technical activities (section M). Around 40% of companies are registered in London or the South East, in line with the geographic distribution of beneficiaries. The median age of firms in the matched comparison group (eight years) was very close to that of beneficiaries. Just over half of them were less than a decade old.

I.15 Similar to the beneficiaries, the matched comparison firms have characteristics that signal a high degree of innovation activity and presence in emerging, high-tech sectors. The share of firms that have a buzzword attached to them by Beauhurst is slightly higher than among the beneficiaries (44% vs 34%), and the selection of buzzwords was strongly aligned with those of beneficiaries (including Software-as-a-Service, Artificial Intelligence and CleanTech). Furthermore, the comparison group matched the beneficiaries on indicators of their potential: the proportion of firms that were tracked by Beauhurst was approximately the same as among the beneficiaries (42% vs 43%), while 14% of them were featured on the high growth list.

I.16 Table I-3 summarises the pre-support size of firms in the matched comparison group in terms of employment and turnover.[19] In the year before the start of the matching year, the matched comparator firms were smaller in terms of median turnover (£0.31m vs £0.96m). This highlights that statistical matching cannot perfectly match every average statistic of the sample. Rather it reduces the average differences between the groups along as many dimensions as possible and selects companies that, on balance of metrics, would have been as likely to receive support as the beneficiaries.

I.17 For a DiD approach to work properly, it is much more important to find companies with ex-ante similar trends than with the same 'absolute size' of operations. This is because differences in size are easy to control for at the analysis stage. Since the direction of the development of the beneficiaries is likely to be determined by their innovation activity, and the comparators appeared to be at least on par with the beneficiaries on the innovation proxies, the statistical matching approach provided us with a solid foundation for the DiD analysis.

Table I-3: Average pre-support size of matched comparators

	Beauhurst	BSD
Turnover (median)	Data insufficient	£0.31m (n=250)
Employees (median)	5 (n=273)	4 (n=250)

Source: SQW analysis of Beauhurst and BSD data

[19] Using Beauhurst data mean employment of the matched comparators was 116 employees. Using BSD data, mean turnover was £268m and mean employment was 93 employees.

Regression analyses

Model specifications

I.18 Our main DiD estimates came from a two-way fixed effects specification applied to the 'natural' timeline. On other words, the treatment 'switched on' for each business at the relevant point in time. As discussed in a great detail in Goodman-Bacon (2021), in such a model, the treatment coefficient (the effect of support) is estimated using both the variation in beneficiaries' outcomes relative to the comparison group as well as relative to other beneficiaries that engaged with the MSI earlier or later (sometimes these comparisons are referred to as the 'pipeline design'). This is particularly useful for the analysis of relatively small samples. The models also included a linear group-specific trend which captured pre-existing differences between the beneficiaries and comparators that could not be attributed to support. The following equation describes the general model:

$$Y_{it} = \alpha_i + \gamma_\tau + \beta_1 D_{it} + \beta_2 X_{it} + \beta_3 Ct + \varepsilon_{it},$$

where:

- Y_{it} – is the outcome measure of interest for company i in time t: natural logarithm of employment or turnover.
- α_i – is a company 'fixed-effect' capturing potentially unobserved time-invariant characteristics of each particular company (e.g., their management style, risk attitudes etc.)
- γ_t – is the time 'fixed effect' capturing the influence of general macro-economic conditions in the economy and tracing out the growth over time that is common for beneficiaries and comparators
- D_{it} – takes the value of one for the beneficiaries when $t \geq \tau_i$ (τ_i is the year in which the firm first engaged with the MSI programme) and zero otherwise. β_1 is the coefficient of interest (the DiD estimate). It represents the average uplift in the outcome of interest observed in the years after the start of the support
- $X_{i\tau}$ – is a vector of additional variables that could be included to control for specific business characteristics[20]
- $C \cdot t$ is the pre-existing linear group trend. C takes the value of one for all beneficiaries and t is linear trend[21]

[20] Our models did not include any additional controls, since the approach is mimicking a randomised control trial with the allocation performed by PSM and fairly equal balance on observable characteristics across the groups.
[21] We tested an alternative non-linear specification for the trend that does not assume monotonicity (i.e. that the beneficiaries are on a constantly increasing trajectory relative to the comparison companies), however we found this approximation to be a better fit for the data.

- ε_{it} – is the error term.

I.19 All outcome variables were log-transformed (using the natural logarithms). This data transformation improved the properties of the models, including the distributions of the error terms and allowed us to interpret small coefficients (in terms of their magnitude) as percentage effects. However, the percentage approximation is inaccurate for estimates larger than c. 0.2. In those cases, to interpret the findings as percentages, we exponentiated the coefficients. The model was estimated using OLS. The standard errors were clustered at both the business and the year level, reflecting that observations for each company over time are not independent of each other and that outcomes of companies that were supported in the same year may also be related (controlling for cross-sectional dependence, given that some supported projects involved multiple beneficiary firms, engaging in collaborative R&D).

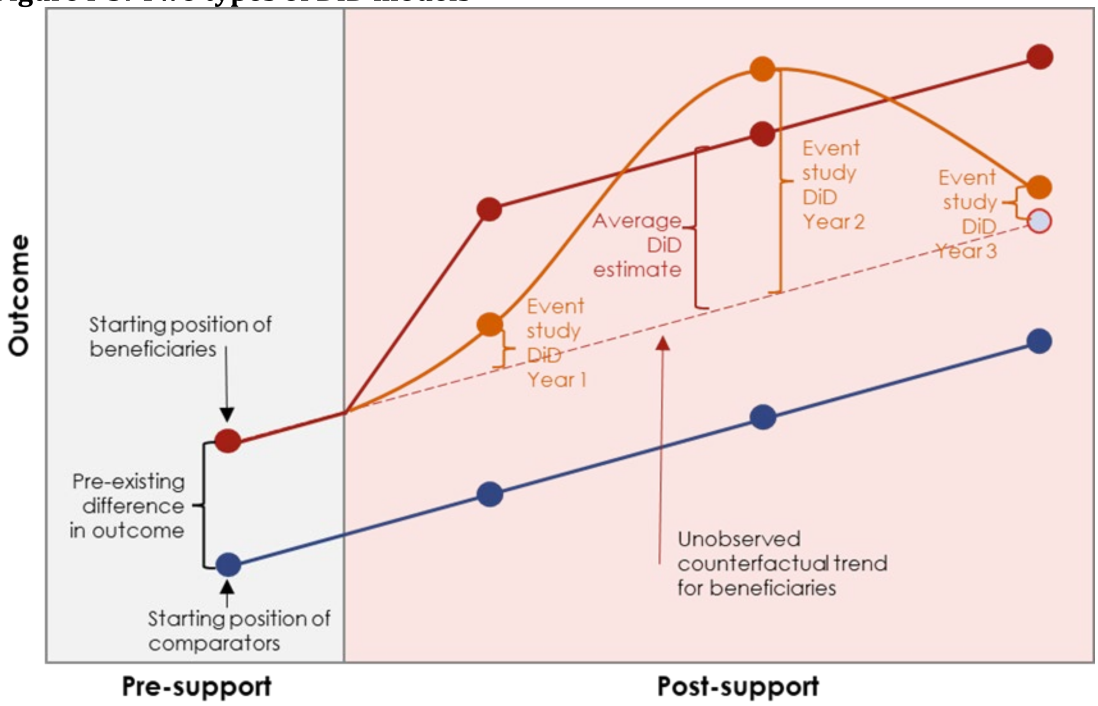
I.20 We also estimated an events study specification of the models. These variants differed in that instead of a single treatment indicator for all years following the start of the support they included separate variables for the first, second and third years following the support:

$$Y_{it} = \alpha_i + \gamma_\tau + \sum_{\tau=t_i}^{t_i+3} \beta_{1_\tau} D_{i\tau} + X_{it} + \beta_3 Ct + \varepsilon_{it}.$$

I.21 The two types of DiD are summarised on Figure I-3. The first DiD type (estimating average effect of the support) ignores the effect dynamics (the fact that it may build up and decay over time). The event study approach fleshes out the dynamics and often can provide additional insights into time additionality of support. However, it relies on smaller sub-samples to estimate the effect in each year and assumes that the effects of support are the same irrespective of the year in which support was provided. The latter assumption cannot be tested directly, however to the best of our knowledge the support model has been fairly constant making this assumption plausible.

I.22 The sample sizes that can be leveraged to estimate year-specific effects, however, were small (Table I-4). The time profile of the support does severely limit the usefulness of an event-study DiD design. With the first beneficiaries receiving support in the 2019/20 financial year and the BSD data on firm outcomes being only available up to 2022/23, we observe firms for a maximum of three 'post-support' periods (financial years after the year in which they engaged with the programme). In general, since about half of companies were supported from 2021/22 onwards, the samples underpinning estimates were too small to rely on results from the event study as main evidence of impacts. We used these models to sense-check the findings from the main models.

Figure I-3: Two types of DiD models



Source: SQW

Table I-4: Coverage of beneficiaries relative to the year of support (t)

Year relative to support	Turnover (BSD)	Employment (BSD)
t (year of support)	66%	66%
$t+1$	54%	54%
$t+2$	52%	52%
$t+3$	18%	18%

Note: the percentages in the table are relative to the total number of beneficiaries in scope (232)

Source: SQW analysis of BSD data

Estimation outputs

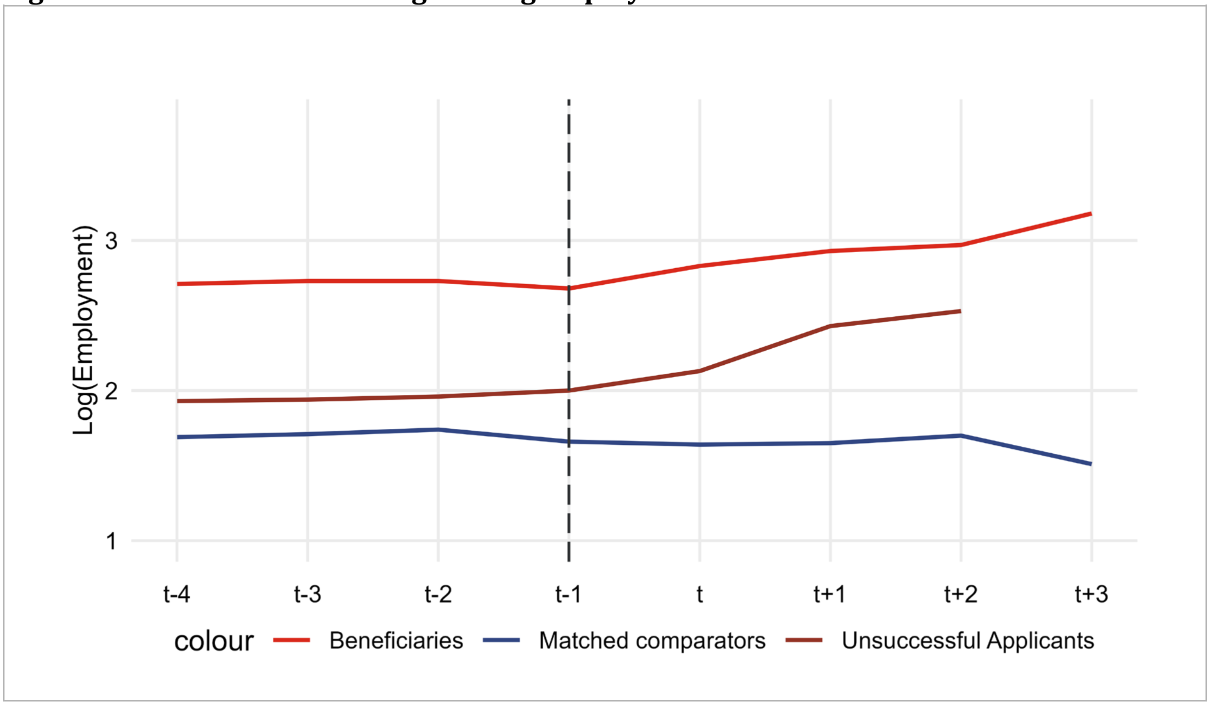
I.23 Below we present descriptive figures and estimation outputs that informed our conclusion on the effects of the MSI support on SME beneficiaries but were not included in the main body of the report. Specifically, these include figures showing trends in the averages of log employment and log turnover, the estimates from the event study specification of DiD, as well as calculation of aggregate GVA impacts for the Value-for-money assessment.

I.24 Figure I-4 shows the trends in the average log-employment by companies in each group. Data on these graphs was stacked relative to the support (t). Such graphs are useful tools for visually assessing the parallel trend assumption of DiD and gathering first indications of potential impacts. However, these graphical illustrations have a serious limitation that can obscure the true picture – they do not reflect the year of support. As a result, the sample composition behind each year on the graph is different. We had fewer observations for the years that are further away from the date of the beneficiaries' first interaction with the programme potentially making the line beyond 't+2' very sensitive to outliers or outcomes observed in a handful of companies. At the same time, the samples that underpin the line towards the edge of the graph are more homogeneous in terms of the macroeconomic effects and other external factors which companies were experiencing before, during and after the support. Because of these nuances, the graphs can play only a supporting, descriptive role in the analysis.

I.25 The graphical analysis suggests similar trends in the average employment before the support across the beneficiaries and the comparison groups (justifying the parallel trend assumption of DiD methodology), and divergence between the groups after the support. Prior to receiving the support, the MSI beneficiaries are already larger on average than either unsuccessful applicants or the matched comparators, but the gap grows larger after the support, especially compared to the matched comparators.

I.26 Figure I-5 shows the trends in the average log-turnover of beneficiaries and the two comparison groups. The graphical analysis suggests that the matched comparison group and beneficiaries were likely on similar trajectories in terms of turnover growth before the beneficiaries received the support. On the other hand, the average in the unsuccessful applicants group seemed to accelerate before the support and be closing the gap with the beneficiaries. However, this pattern was not confirmed by regression analysis and could be driven by a few faster growing UAs.

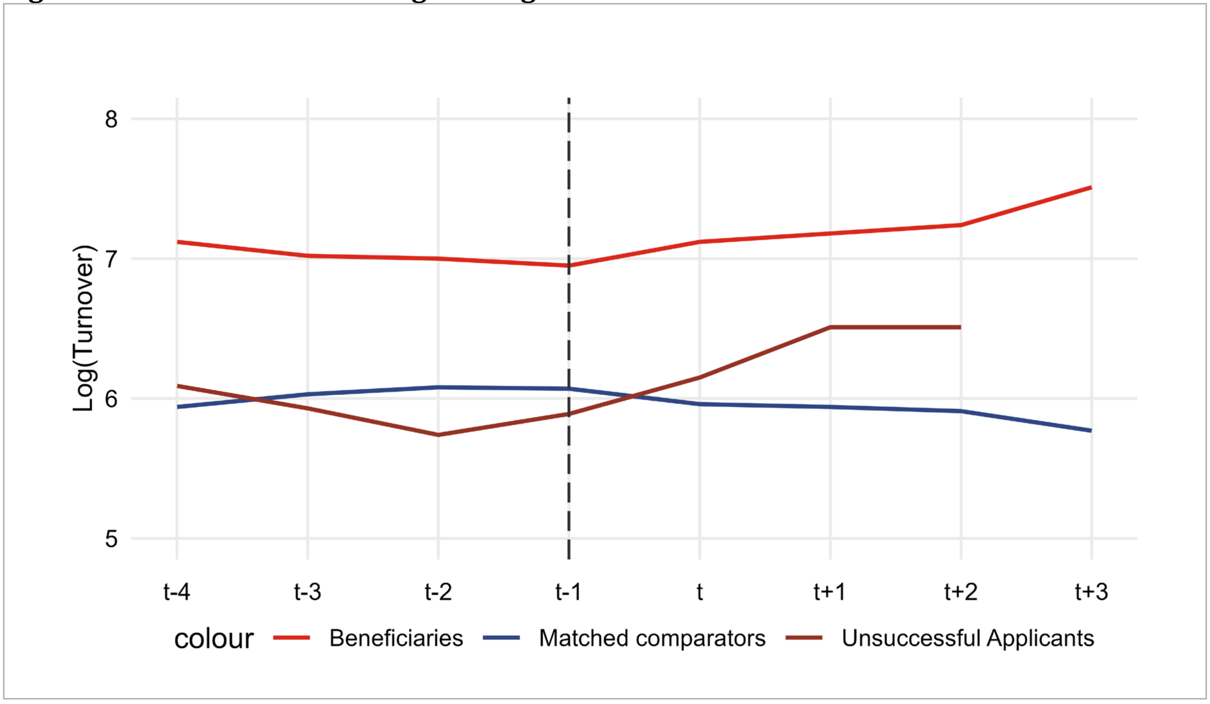
Figure I-4: Trends in the averages of log employment



Note: Data stacked relative to the first interaction of companies with the MSI programme. For the matched comparison group we used the quasi-treatment years we assigned them during the statistical matching process. Fewer than 10 unsuccessful applicant firms had observations in t+3, the average was suppressed to meet the requirements of statistical disclosure control.

Source: SQW analysis of BSD data

Figure I-5: Trends in the averages of log turnover



Note: Data stacked relative to the first interaction of companies with the MSI programme. For the matched comparison group we used the quasi-treatment years we assigned them during the statistical matching process. Fewer than 10 unsuccessful applicant firms had observations in t+3, the average was suppressed to meet the requirements of statistical disclosure control.

Source: SQW analysis of BSD data

Table I-5: DiD event study results – employment effects

	Group 1: Matched comparators	Group 2: Unsuccessful Applicants
DiD coefficient: t	0.137 ** (0.061)	0.156 ** (0.071)
DiD coefficient: $t+1$	0.160 (0.112)	0.192 (0.119)
DiD coefficient: $t+2$	0.085 (0.115)	0.010 (0.115)
DiD coefficient: $t+3$	-0.062 (0.111)	-0.052 (0.108)
Pre-existing group trend	0.032 ** (0.015)	Insignificant (excluded)

*Note: two-way cluster robust standard errors in parentheses, asterisk represent statistical significance * p<0.1, ** p<0.05, *** p<0.01*

Source: SQW analysis of BSD data

Table I-6: DiD event study results – turnover effects

	Group 1: Matched comparators	Group 2: Unsuccessful Applicants
DiD coefficient: t	0.103 (0.077)	0.220** (0.086)
DiD coefficient: t+1	0.077 (0.095)	0.214 ** (0.103)
DiD coefficient: t+2	0.062 (0.112)	0.202 (0.130)
DiD coefficient: $t + 3$	-0.071 (0.142)	0.085 (0.163)
Pre-existing group trend	Insignificant (excluded)	Insignificant (excluded)

*Note: two-way cluster robust standard errors in parentheses, asterisk represent statistical significance * p<0.1, ** p<0.05, *** p<0.01*

Source: SQW analysis of BSD data

Table I-7: Total GVA generated by the programme, adjusting for discounting of impacts after 2024/25 financial year

Financial year of support	GVA in t	GVA in t+1	GVA in t+2	GVA in t+3	GVA per firm	Number of beneficiaries	Total GVA
2019/20	598,580	43,996	32,205	17,680	692,461	45	31,160,760
2020/21	598,580	43,996	32,205	17,680	692,461	81	56,089,369
2021/22	598,580	43,996	32,205	17,680	692,461	5	3,462,307
2022/23	598,580	43,996	32,205	17,083	691,863	39	26,982,675
2023/24	598,580	43,996	31,116	16,505	690,197	37	25,537,279
2024/25	598,580	42,508	30,064	15,947	687,099	36	24,735,549
Total						**243**	**167,967,939**

Note: t refers to the year of receiving support from the MSI programme.

Source: SQW calculations

Annex J: Technology trends

J.1 The analysis on technology developments relating to the IDTs was prepared by the Policy Links Unit, Institute for Manufacturing (IfM) Engage, University of Cambridge.

Table J-1: Summary of developments in IDTs

Industrial Digital Technology	
Artificial intelligence, machine learning and data analytics	• In 2022, OpenAI launched ChatGPT, a groundbreaking conversational AI software based on a large language model (LLM).[22] Since then, LLM-based AI software has rocketed in the development of AI. • LLMs could pave the way for more intuitive and efficient industrial systems.[23] • The applications of complex AI to manufacturing are fairly new, so few countries have seen widespread adoption so far. • The UK has a very strong research base for AI in general and is in a strong position to increase the applications of AI in the manufacturing industry in the future. • Overall, the global AI market in manufacturing is valued at USD 3.2 billion in 2023 and is likely to reach USD 20.8 billion by 2028:[24] it is expected to grow at a compound annual growth rate (CAGR) of 45.4% during this forecast period. • The UK is considered a leading country in AI research and innovation globally, ranking 3rd in the world.[25] • In 2024, the UK was beyond the G7 average for readiness to use AI in business in general. • Specific strengths include:[26]companies' adoption of emerging technologies knowledge and technology outputs.

[22] LLM is a type of AI specialising in language processing, learning from a significant amount of text data including books, articles and webpages to uncover patterns and rules of language. Microsoft AI Tour, "Large Language Model (LLM)", available at https://microsoft.github.io/Workshop-Interact-with-OpenAI-models/llms/

[23] World Economic Forum, "Why Large Language Models are the future of manufacturing", available at https://www.weforum.org/stories/2024/04/why-large-language-models-are-so-important-for-the-future-of-the-manufacturing-industry/#:~:text=LLMs%3A%20The%20gateway%20between%20humans%20and%20machines&text=By%20interpreting%20vast%20amounts%20of,language%20in%20production%20and%20management.

[24] World Economic Forum, "6 ways to unleash the power of AI in manufacturing", available at https://www.weforum.org/stories/2024/01/how-we-can-unleash-the-power-of-ai-in-manufacturing/.

[25] UKRI, "How we work in artificial intelligence", available at https://www.ukri.org/who-we-are/our-vision-and-strategy/tomorrows-technologies/how-we-work-in-ai/moving-forward/#:~:text=We%20rank%20third%20in%20the,of%20Europe's%20AI%20start%2Dups.

[26] Salesforce, "Salesforce UK AI Readiness Index", available at https://www.salesforce.com/uk/news/wp-content/uploads/sites/5/2024/12/Salesforce-UK-AI-Readiness-Index.pdf

Industrial Digital Technology	
	• The Department for Science, Innovation & Technology (DSIT) has identified AI as one of five critical technologies to the UK's prosperity and global influence in the 21st century.[27] • Overall uptake of AI in UK companies is considered to be low. According to Make UK (2024) survey, only 7% of the UK manufacturers have successfully introduced ChatGPT-like software into their businesses, while 34% are considering it and 28% are using it. For AI and machine learning in general, only 8% of the manufacturers successfully adopted this technology in their businesses. • Cost and systems integration are the biggest barriers to AI adoption. In the Make UK survey (2024), 44% of respondents cited the two challenges to widely adopting AI into their business.[28] • In general, AI adoption in the US is concentrated among larger companies and clustered in sectors such as manufacturing, information services, and healthcare.[29] • In September 2024, the Chinese central government published the action plans for AI Capacity-Building for Good and for All, in which China pledges to empower AI applications in manufacturing and other sectors through international cooperation.[30]
Additive manufacturing	• Between January 2013 and July 2023, UKRI spent over £550 million on 811 AM-related projects.[31] • In general, 51% of the UK manufacturers have introduced AM in their business, according to a survey done by Make UK in 2024.[32] • **UK manufacturing in general has experienced challenges in recent years**, which dropped from being the 9th largest global manufacturer by value added in 2013 to 11th in 2023.[33,34] In particular, aerospace which is an important sector for AM was impacted and a step change is unlikely until a

[27] DSIT, "The UK Science and Technology Framework", available at https://www.gov.uk/government/publications/uk-science-and-technology-framework/the-uk-science-and-technology-framework#foreword-from-the-secretary-of-state
[28] Make UK (2024) "Future Factories Powered by AI", available at https://www.makeuk.org/insights/reports/future-factories-powered-ai
[28] World Economic Forum, "6 ways to unleash the power of AI in manufacturing", available at https://www.weforum.org/stories/2024/01/how-we-can-unleash-the-power-of-ai-in-manufacturing/
[29] McElheran, K., Li, J. F., Brynjolfsson, E., Kroff, Z., Dinlersoz, E., Foster, L., & Zolas, N. (2024). AI adoption in America: Who, what, and where. Journal of Economics & Management Strategy, 33(2), 375-415.
[30] Ministry of Foreign Affairs, the People's Republic of China, "AI Capacity-Building Action Plan for Good and for All," available at https://www.mfa.gov.cn/eng/wjbzhd/202409/t20240927_11498465.html
[31] Additive Manufacturing UK, "AMUK Annual Action Plan 2024," available at https://additivemanufacturinguk.org.uk/wp-content/uploads/2024/01/AMUK-2024-Annual-Action-Plan.pdf
[32] Ibid 28.
[33] ITA, "United Kingdom Industry 2021 Additive Manufacturing," available at https://www.trade.gov/market-intelligence/united-kingdom-industry-2021-additive-manufacturing
[34] CIIP UK Manufacturing Dashboard, available at https://www.ciip.group.cam.ac.uk/manufacturing-report/uk-in-global-manufacturing-value-added/

Industrial Digital Technology	
	new airframe is designed and enters operation, which is unlikely this decade in either defence or civil aviation. • **The lack of awareness in supply chains is a main challenge for AM technology adoption.** Many manufacturers still need clear evidence of the benefits of additive manufacturing, while AM companies are struggling to connect with potential clients in sector supply chains.[35] • The standards landscape for AM technology is complex. Since AM introduces a new way of producing parts and components, there are numerous new standards that companies must comply with. This creates a challenge for companies to navigate among relevant standards when applying AM technology.[36] • Most major manufacturing countries have recognised AM as important and are striving to improve their capability in this area. Examples include: ➢ In October 2022, the US government published a national strategy for advanced manufacturing, in which additive manufacturing is a key focus across various recommendations.[37] ➢ AM was highlighted in Made in China 2025,[38] a plan to develop their manufacturing sector. Among others, there is a focus on aerospace and medical applications and the development of AM materials. Similarly, AM was also addressed in the Smart Manufacturing Development Plan for the "14th Five-Year Plan" Period, an action plan for smart manufacturing published in December 2021.[39] ➢ In 2021, the French government promoted the 3D printing of parts and components for waste management.[40] ➢ In 2023, Korea's Ministry of Science and ICT allocated $70 million to the development of AM technology. Currently, there are around 400 companies in the Korean AM market.[41]
Robotics and automation	• The UK has a strong robotics and automation research base but has comparatively low levels of uptake of industrial robots. Only one-third of UK

[35] Ibid **Error! Bookmark not defined.**.
[36] Ibid **Error! Bookmark not defined.**.
[37] The White House, "National Strategy For Advanced Manufacturing," available at https://www.whitehouse.gov/wp-content/uploads/2022/10/National-Strategy-for-Advanced-Manufacturing-10072022.pdf
[38] State Council for People's Republic of China, "Made In China 2025 plan issued," available at http://english.www.gov.cn/policies/latest_releases/2015/05/19/content_281475110703534.htm
[39] State Council for People's Republic of China, "Notice by the Ministry of Industry and Information Technology, the National Development and Reform Commission, the Ministry of Education and Other Departments of Issuing the Smart Manufacturing Development Plan for the "14th Five-Year Plan" Period," available at https://www.gov.cn/zhengce/zhengceku/2021-12/28/content_5664996.htm
[40] ITA, "France - Country Commercial Guide Additive Manufacturing," available at https://www.trade.gov/country-commercial-guides/france-additive-manufacturing-am#:~:text=In%202017%2C%20the%20French%20government,spare%20parts%20to%20combat%20waste.
[41] ITA, "South Korea Additive Manufacturing," available at https://www.trade.gov/market-intelligence/south-korea-additive-manufacturing.

Industrial Digital Technology	
	manufacturers have adopted robotics and automation in their operations, in terms of a survey conducted by Make UK in 2024.[42] With just 119 robots per 10,000 manufacturing employees, the UK has the lowest robotics adoption rate among G7 countries.[43] • Embodied AI, also known as embodied intelligence, has emerged as a key development direction in robotics and automation, fuelled by recent breakthroughs in AI. Unlike digital AI, embodied AI operates through agent-based systems, such as robots, that can physically interact with objects and people in the real world. More advanced than pre-programmed robotics, embodied AI systems feature self-learning capabilities, allowing them to adapt to their surroundings using diverse sensors. [44] • Countries with strong robotics research bases and/or high levels of industrial robot uptake include Germany, Sweden, China, Japan, South Korea, Singapore, and the USA. Total industrial robots installation in the US reached 44,303 units in 2023, increase of 12% compared to 2022.[45] Automotive industry remains a leading sector for automation and robotics usage. Meanwhile, the industry of electrical and electronics is becoming another sector driving the robotics adoption in the US. Research and implementation is spearheaded by the National Robotics Initiative.[46] The US national strategy for advanced manufacturing highlights the critical role of robotics in driving manufacturing productivity.[47]
Virtual reality and augmented reality	• A 2024 survey by Make UK revealed that only 22% of UK manufacturers had introduced 'virtual and augmented reality' into their business.[48] The top three application scenarios of VR/AR technology in the UK manufacturing

[42] Make UK, "Future Factories Powered by AI", available at https://www.makeuk.org/insights/reports/future-factories-powered-ai
[43] The National Robotarium, "Why 2025's Industrial Strategy must close Britain's manufacturing robotics gap", available at https://thenationalrobotarium.com/why-2025s-industrial-strategy-must-close-britains-manufacturing-robotics-gap/#:~:text=With%20just%20119%20robots%20per,economies%20like%20Mexico%20and%20Turkey.
[44] High Value Manufacturing Catapult, "2050 vision for automation and robotics in UK manufacturing," available at https://hvm.catapult.org.uk/wp-content/uploads/2024/07/2050-vision-for-automation-and-robotics-in-UK-manufacturing.pdf
[45] The Robot Report, "U.S. manufacturers invested heavily in robotics in 2023, finds IFR", available at https://www.therobotreport.com/us-manufacturers-invested-heavily-robotics-2023-finds-ifr/#:~:text=U.S.%20manufacturers%20have%20increasingly%20adopted,Robotics%2C%20or%20IFR%2C%20today. (last accessed 07/01/2025)
[46] National Robotics Initiative summary, available at https://www.manufacturing.gov/programs/national-robotics-initiative (last accessed 15/03/2022)
[47] The White House, "National Strategy For Advanced Manufacturing," available at https://www.whitehouse.gov/wp-content/uploads/2022/10/National-Strategy-for-Advanced-Manufacturing-10072022.pdf (last accessed 06/01/2025)
[48] Make UK, "Future Factories Powered by AI", available at https://www.makeuk.org/insights/reports/future-factories-powered-ai (last accessed 03/01/2025)

Industrial Digital Technology	
	sector are consumer engagement, product & service development, and learning & development.[49] • A 2024 survey by Make UK that found that, among UK manufacturers, only 5% of those were successfully adopted the technology in their business.[50]
The Industrial Internet of Things (IIoT) and connectivity	• 'IIoT' is a subset of IoT. However, IIoT and the consumer IoT focusing on individuals are more different than they are similar.[51] In an IIoT network, collecting data is only the first step in a more complex system, emphasising automation and efficiency across an interconnected organisation ecosystem. The technology needed to implement the IIoT is available, sufficient and at the adoption stage. Advances in IIoT technologies, such as fast computing, storage, improvement of battery, and developments in advanced analytics, AI and machine learning enable more granular insights from data provided by sensors. • The UK has a network of centres, Catapults, and initiatives that support the adoption of IIoT technologies. The IoTUK is an ambitious fully-integrated IoT acceleration programme. The UK also leads the research on IoT systems cybersecurity. It supports the commercialisation and adoption of new technologies with PETRAS, the National Centre of Excellence for IoT Systems Cybersecurity, funded by UKRI. • The UK has both technology adopters and providers. Some of the companies that lead the IIoT technologies are ARM, a global market player, Secure Thingz, Analog Devices, Arkessa, GeoSpock, Sensat, Intellisense.io, Kx, Worcester Bosch. However, many IoT components and devices are manufactured outside the UK, with implications for the UK's global competitiveness and its role in international regulation. • Connectivity is the backbone of industrial IoT. 3G/4G networks are currently deployed in the UK, and the 5G rollout is undergoing. Other network protocols are available such as LPWAN (low-power, wide-area networks). In this context, future telecommunication is identified as one of the five critical technologies in the UK Science and Technology Framework.[52] A survey by Eseye highlights that cellular IoT deployments have still not reached critical mass, as out of 500 respondents, only 10% had deployed between c. 10,000 and 100,000 devices in the field.[53]

[49] PwC, "How UK organisations are using XR", available at https://www.pwc.co.uk/issues/technology/immersive-technologies/how-uk-organisations-use-vr-ar.html (last accessed 07/01/2025)
[50] Make UK, "Future Factories Powered by AI", available at https://www.makeuk.org/insights/reports/future-factories-powered-ai (last accessed 03/01/2025)
[51] Stan Schneider, "THE INDUSTRIAL INTERNET OF THINGS (IIoT)," in Internet of Things and Data Analytics Handbook, Wiley, 2017, pp.41-81, doi: 10.1002/9781119173601.ch3.
[52] DSIT, "The UK Science and Technology Framework", available at https://www.gov.uk/government/publications/uk-science-and-technology-framework/the-uk-science-and-technology-framework#foreword-from-the-secretary-of-state (last accessed 06/01/2025)
[53] Eseye, "Eseye 2021 State of IoT Adoption Report; Unlocking the untapped potential of loT," 2021.

Industrial Digital Technology	
	• The development of 6G telecommunication standards is on the horizon.[54] Compared to 5G, 6G is expected to be more responsive, reliable, faster and capable of transferring a higher volume of data simultaneously. In 2023, the UK Government released the 6G Strategy that committed an initial £100 million for 6G research.[55] • Industrial digitalisation and the internet of things has been the focus of policy for the US, China, South Korea, Germany, France. • **China:** Industrial digitalisation has been one of the focuses of the "Made in China 2025" plan. In 2021, China released its Industrial Internet 2021 Work Plan, highlighting the objectives that aim at improving 5G and IIoT infrastructure and expanding China's expertise in areas such as edge computing[56]. In 2023, the State Council issued the Plan for the Overall Layout of Building a Digital China, which highlights the large-scale deployment and application of IPv6 and supports the development of IIoT.[57] • **Germany:** In 2019, Germany launched the 2030 vision for Industrie 4.0, focusing on autonomy, interoperability, and sustainability. • **France**: IoT is one of the nine objective areas of "Industrie du Futur".[58] France has been supporting manufacturing industries to adopt IoT technologies. One of the "Connected Industries" pillars is manufacturing robotics, emphasising standardization, cybersecurity, and IoT tools for SMEs. • **South Korea:** is among the 5G leading countries, with long support for SMEs to adopt digitalization and automation through the "Smart Factory" initiative. In 2020, the South Korean government injected $414.4 million into R&D projects to help SMEs utilize AI and real-time monitoring with IIoT[59]. In Korea's Digital Strategy, the government pledges to launch a Pre-6G service demonstration in 2026 for the world's first time. The strategy also targets achieving dominance in 6G telecommunication standards and patents.[60] • **US:** IoT has been identified as a strategically important area by many US federal agencies; the US government invests in R&D and commercialisation of such technologies as part of its "Lab to Market" process.[61] In the US

[54] Ericsson, "6G standardization – an overview of timeline and high-level technology principles", available at https://www.ericsson.com/en/blog/2024/3/6g-standardization-timeline-and-technology-principles (last accessed 07/01/2025)
[55] DSIT, "UK Wireless Infrastructure Strategy", available at https://www.gov.uk/government/publications/uk-wireless-infrastructure-strategy/uk-wireless-infrastructure-strategy (last accessed 07/01/2025)
[56] Chinese Ministry of Industry and Information Technology, "Industrial Internet 2021 Work Plan," 2021.
[57] State Council for People's Republic of China, "The CPC Central Committee and the State Council issued the "Overall Layout Plan for the Construction of Digital China", available at https://www.gov.cn/zhengce/2023-02/27/content_5743484.htm (last accessed 07/01/2025)
[58] Alliance Industrie du Futur, "Alliance Industrie du Futur," *http://www.industrie-dufutur.org/aif/*, 2021.
[59] IntraLink, "Internet of Things South Korea Market Intelligence Report Department for International Trade Report," 2018.
[60] Ministry of Science and ICT, "Korea to Come up with the Roadmap of Digital ROK, Realizing the New York Initiative", available at https://www.msit.go.kr/eng/bbs/view.do?sCode=eng&mId=4&mPid=2&bbsSeqNo=42&nttSeqNo=742 (last accessed 07/01/2025)
[61] NIST, "Lab-to-Market (L2M)," https://www.nist.gov/tpo/lab-market, 2021.

Industrial Digital Technology	
	National Strategy for Advanced Manufacturing, IIoT is addressed as a critical technology to achieve digital transformation of supply chains.[62]

Source: IfM, University of Cambridge

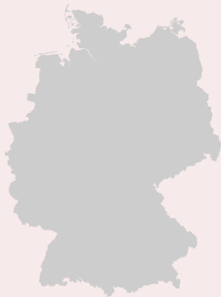
[62] The White House, “National Strategy For Advanced Manufacturing,” available at https://www.whitehouse.gov/wp-content/uploads/2022/10/National-Strategy-for-Advanced-Manufacturing-10072022.pdf (last accessed 07/01/2025)

Annex K: International comparison

K.1 This annex provides an overview of Industry 4.0 in selected countries: Germany, United States, Singapore, Korea, and Taiwan. This overview was prepared by the Policy Links Unit, Institute for Manufacturing (IfM) Engage, University of Cambridge.

Overview of selected national Industry 4.0 initatives

Germany



Overview

- **Industrie 4.0** was conceived of as a 10-15 year project, which started in 2011.
- The strategic goal is maintaining Germany's traditionally strong position in manufacturing and mechanical engineering. The Germany 2030 Industrial Strategy (2020) provides principles which outline the case for state interventions in industries, and acknowledges that Germany's continued strong industrial position is not guaranteed.
- The high-profile "**Plattform Industrie 4.0**" initiative is steered by Germany's Federal Ministry for Economic Affairs and Energy (BMWi) and Federal Ministry of Education and Research (BMBF) as well as high-ranking representatives from industry, science, and trade unions.
- The **Mittelstand-Digital** funding priority offers comprehensive support with digitisation via the Mittelstand 4.0 Centres of Excellence, the IT Security in Commerce Initiative (€5m/year), and the Digital Now (40-70% of costs, up to €50k) investment grant programme for SMEs.
- 26 regional '**Mittelstand 4.0 centres of excellence'** receive funding from the Federal Ministry for Economic Affairs and Climate Action, and the Centre of Excellence for the 'Digitalisation of Skilled Crafts' to help German SMEs become more aware of Industrie 4.0.
- The Digital Hub Initiative fosters collaboration between start-ups, established companies, and researchers. Twelve hubs are funded to facilitate networking, services, and international marketing.

Funding

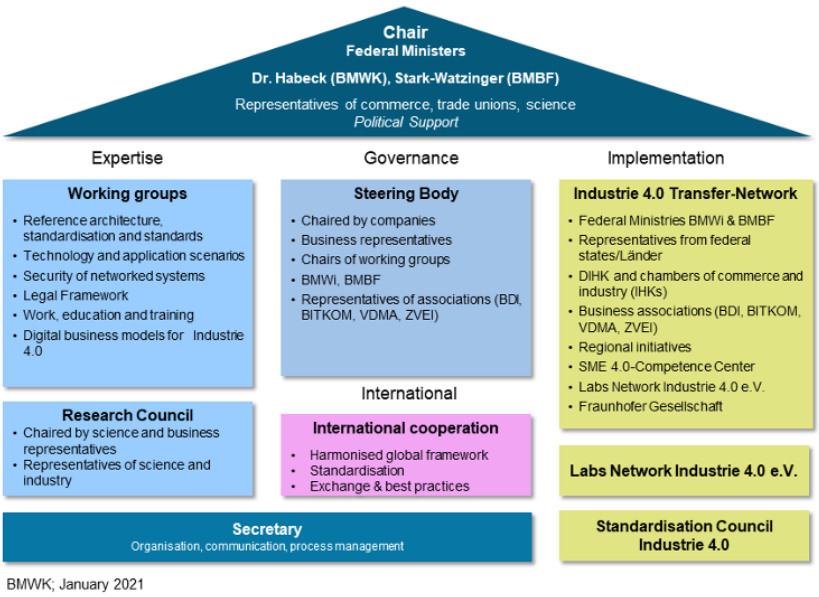
- The Ministry of Education and Research (BMBF) and the Ministry for Economic Affairs and Energy (BMWI) jointly allocated €200m funding for the Plattform Industrie 4.0.

- In two funding programmes entitled 'Autonomics for Industrie 4.0' and 'Smart Service World', the Ministry for Economic Affairs and Climate Action is already providing close to €100 million to foster research and innovation in the field of Industrie 4.0.
- SME's can get up to 50-60% in public funding, and larger companies can receive <50% public funding (in accordance with EU funding rules).
- The €250 million funding initiative for SMEs, '**Digital Jetzt**', supports SMEs in Germany to develop digital technologies and skills, up to €50k.
- The "Digital Innovations" competition for business start-ups provides up to six prizes of €32k each.
- The Federal Ministry for Economic Affairs and Energy work on "developing digital technologies" covers the promotion of research and development projects in the field of digitalisation. At precompetitive stages, companies can bid for 25-50% and researchers for 100% of costs, up to tens of millions of euros.
- The ERP Digitalisation and Innovation Loan finances digitalisation and innovative projects in SMEs, from €25k to €25m per bid.

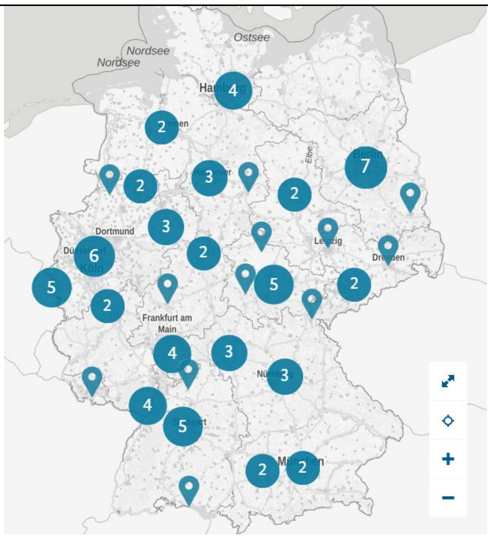
Germany (continued)

Key efforts and institutions supporting technology transfer / diffusion

The Industry 4.0 Platform works together with the Chambers of Industry and Commerce locally, developing professional practice and workshops on knowledge transfer, aimed at addressing specific company needs Information is exchanged in an existing network, consisting of contacts in the Federal States and the regional initiatives, as well as in the local trade associations specific to particular business sectors.



Map of testbeds in R&D institutions where Industrie 4.0 applications can be tested



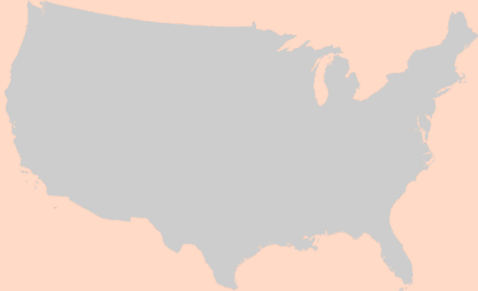
Germany (post-2021 developments)

- **GAIA-X** (European Association for Data and Cloud AISBL). The goal of this initiative is to establish an ecosystem, whereby data is shared and made available in a trustworthy environment. The intended outcome is not a cloud, but a federated system linking many cloud service providers and users together in a transparent environment to drive the European data economy of tomorrow. By participating, users gain access to a trusted ecosystem and a community that fosters innovation, collaboration, and scalability across industries, all while ensuring compliance with European and local regulations. Participants benefit from driving data privacy innovation, interoperability, and the ability to shape digital transformation.
- **Digital Now investment grant programme**. The Digital Now investment grant programme offers SME and Small Midcaps (3 – 499 employees) financial support for investments in digital technology and applications as well as digital skills among their workforce. The funding rate varies between 30 – 60 % in line with company size. Up to €50,000 in funding can be provided per company. Investments of companies in value chains or networks can receive grants of up to €100,000. Companies which invest in internal or external network-building (value chain), IT-security or which are located in structurally weak regions receive higher rates of support. The programme offers direct, individual and easily accessible support for SMEs and Small Midcaps. Investments addressing such diverse topics as Cloud, big data and AI can receive support.
- **German Agency for Transfer and Innovation (DATI)**. With its open-stakeholder approach, DATI offers people from universities, research institutions, companies and society from all over Germany the opportunity to implement their innovative ideas. In this way, DATI strengthens regional and supra-regional innovation ecosystems. DATI supports innovation actors through needs -based, tailored funding and other support services, for example through information, advice and coaching as well as networking and activation of transfer partners. The concept for the establishment of the DATI has already been approved by the Federal Government, but the establishment of the DATI is still pending.
- **Competence Centre eStandards for SMEs**. The "Mittelstand-4.0 Kompetenzzentrum eStandards" is a competence centre that brings digitalisation and standardisation to German SMEs. With the CSCP as part of the consortium, the Competence Centre specifically looks into how digitalisation can be used to enable more sustainable business

models and production processes. The CSCP will conduct pilot projects, develop hands-on tools and provide comprehensive curricula to SMEs on creating future-proof companies through digitalisation.

- **DataSpace Industrie 4.0**: The German government is creating a DataSpace Industrie 4.0 to develop data-based business models in industry (e.g. for greater resilience and sustainability) and to increase efficiency and flexibility in production. To this end, they are evolving the Industry 4.0 platform and supporting the cross-sectoral 'Manufacturing-X' initiative as a key measure for digitalising supply chains. We are developing a concept to promote research and development projects as well as the broad transfer of technologies and applications to small and medium-sized enterprises.
- **Robotics Research Action Plan**: The Robotics Research Action Plan is designed to enhance Germany's innovative strength as well as safeguarding Europe's technological sovereignty. The aim of the Action Plan is to strengthen the national robotics ecosystem in the fields of research and skilled labour as well as to pool and strategically align sources of robotics research funding. The Robotics Research Action Plan presents the funding provided by the Federal Ministry of Education and Research (BMBF) for robotics research in four fields of action: Utilizing innovations in basic technologies for robotics; Concentrating and interlinking cutting-edge robotics research; Supporting skilled workers for the robotics of the future; and developing practical applications for intelligent robotics. Robotics research benefits from close cooperation between government ministries, which is why the measures of the Action Plan have been designed as part of an overarching course of action between the BMBF and the Federal Government.
- **Robotics Institute Germany.** The Robotics Institute Germany (RIG) forms the backbone of the Robotics Research Action Plan. It brings together the top locations for robotics research in Germany to form a decentralized institution that represents cutting-edge German robotics research at an international level. The RIG aims to: Prominently represent cutting-edge German research internationally; Jointly offer novel initial and further training measures for talent recruitment; Encourage cooperation with relevant stakeholders in the robotics ecosystem; Develop a national roadmap for excellent and transfer-relevant robotics research; and serve as a first point of contact internationally.
- **AI Action Plan.** Germany launched its national Artificial Intelligence Strategy in 2018 and has considerably increased its spending on AI as a consequence of this. The updated AI Strategy was launched on 2 December 2020 and focuses on new developments and needs. The AI Action Plan is the BMBF's update to the AI Strategy. The BMBF alone plans to invest more than 1.6 billion euros in AI in the current legislative period.

United States



Overview

- Advisory support on Industry 4.0 delivered through existing manufacturing-centred institutions with presence in every State of the country.
- In 2018, the **Strategy for American Leadership in Advanced Manufacturing** was published, which highlighted three key areas: developing and transitioning to new manufacturing technologies; educate, train and connect the manufacturing workforce; and expand the capabilities of the domestic manufacturing supply chain.
- Created in 2014, the **'Manufacturing USA'** initiative coordinates and catalyses public and private investment in precompetitive advanced manufacturing technology infrastructure. There were over 14 Manufacturing USA institutes 2019, with MxD (Manufacturing times Digital) and CESMII (Clean Energy Smart Manufacturing Innovation Institute) focussing most directly in Industry 4.0. activities.
- A number of other methods have been utilised to support manufacturer more broadly over the past five years, including significant business tax breaks and increases in requirements for domestic components within government-procured products.

Funding

- Through 2018, Manufacturing USA institutes attracted more than US$2 billion in private investment leveraging US$1 billion in Federal funds (from the Departments of Defense, Energy, and Commerce).
- In 2020, the budget assigned to **Manufacturing Extension Partnership Centres** is of US$126.7 million. For every dollar of federal investment in FY 2019, the MEP Centres as part of the MEP National Network generated $33.80 in new sales growth and $32.20 in new client investment.

United States (continued)

Key efforts and institutions supporting technology transfer / diffusion

The Strategy for American Leadership in Advanced Manufacturing (2018) identifies clear ownership of tasks within government departments across three key areas.

Goals	Objectives	DoD	DOE	DOC	HHS	NSF	NASA	DOL	USDA	DOEd
Develop and Transition New Manufacturing Technologies	Capture the Future of Intelligent Manufacturing Systems	●	●	●		●	●			
	Develop World-Leading Materials and Processing Technologies	●	●	●		●	●			
	Assure Access to Medical Products through Domestic Manufacturing	●		●	●	●				
	Maintain Leadership in Electronics Design and Fabrication	●	●	●		●	●			
	Strengthen Opportunities for Food and Agricultural Manufacturing	●				●			●	
Educate, Train, and Connect the Manufacturing Workforce	Attract and Grow Tomorrow's Manufacturing Workforce	●	●	●		●	●	●		●
	Update and Expand Career and Technical Education Pathways	●	●	●		●	●	●		●
	Promote Apprenticeship and Access to Industry-Recognized Credentials	●	●	●		●	●	●	●	●
	Match Skilled Workers with the Industries that Need Them	●			●			●	●	
Expand the Capabilities of the Domestic Manufacturing Supply Chain	Increase the Role of Small and Medium-Sized Manufacturers in Advanced Manufacturing	●	●	●	●	●	●		●	
	Encourage Ecosystems for Manufacturing Innovation	●	●	●	●		●			
	Strengthen the Defense Manufacturing Base	●	●	●	●		●			
	Strengthen Advanced Manufacturing for Rural Communities								●	

United States (continued)

There are an extensive number of federal programmes across these departments that have contributed to the implementation of Industry 4.0 in the US context.

Below is a list of Federal programs that have contributed to progress in advanced manufacturing R&D.

Agency	Manufacturing and Related Programs	
DOC (NIST & ITA)	• Manufacturing USA • Manufacturing Extension Partnership • Additive Manufacturing • Smart Manufacturing Systems • Robotics for Smart Manufacturing • Advanced Materials Measurements • Standard Reference Materials	• Materials Genome Initiatives • Physical Measurements • Biomanufacturing • ITA Global Markets • ITA Industry & Analysis • ITA Enforcement and Compliance
DoD	• Manufacturing Technology Programs • Manufacturing USA institutes • Defense Industrial Base Modernization	• Industrial Base Analysis and Sustainment Program • Defense industrial base scale-up • Defense Production Act Title III
DOE	• Clean Energy Manufacturing Institutes • High Performance Computing for Manufacturing • Lab-Embedded Entrepreneurship	• Energy Innovation Hubs • Manufacturing Demonstration Facility at Oak Ridge National Laboratory • Critical Materials Hub
HHS/FDA	• Advanced Research and Development of Regulatory Science for Continuous Manufacturing • Centers for Innovation in Advanced Development and Manufacturing	• Bio-Medical Advanced Research and Development Authority • Medical Countermeasures Advanced Development and Manufacturing
NASA	• Game Changing Technology Program • Advanced Exploration Systems Program, In-Space Manufacturing Project	• Advanced Manufacturing Technology Project • National Center for Advanced Manufacturing
NSF	• Engineering Research Centers • Industry/University Cooperative Research Centers • Advanced Manufacturing • National Robotics Initiative 2.0	• Secure and Trustworthy Cyberspace • Cyber Physical Systems • Cellular and Biochemical Engineering • Designing Materials to Revolutionize and Engineer our Future
USDA	• Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program • Business and Industry Guaranteed Loan Program • Biofuel Infrastructure Partnership • Rural Utility Service	• Rural Business-Cooperative Service • Research grants • Small Business Innovation Research • Support for export-related activities and marketing, including USDA BioPreferred Program

Of these, a number of key activities are worth highlighting.

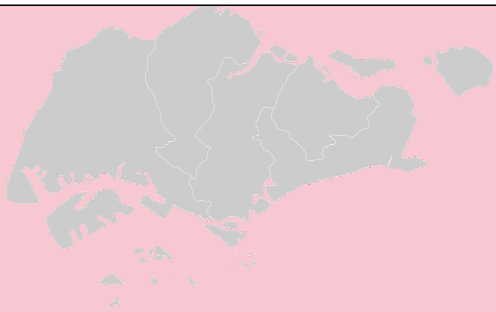
NIST Manufacturing Extension Partnership (MEP): The MEP is a public-private partnership with centres in all 50 states, supporting SMEs. While its scope extends beyond Industry 4.0, all centres have adopted digital manufacturing as a key theme. For example, the National Institute of Standards and Technology (NIST)'s Smart Manufacturing Systems (SMS) Test Bed enables smart manufacturing research and development across the product lifecycle.

Manufacturing USA: A network of 14 manufacturing institutes each with a distinct technology focus. Four institutes (America Makes, ARM, MxD and CESMII) provide digital manufacturing support. Examples of services include: technology roadmaps; test beds; open platform and marketplace for secure, real-time data analytics, industrial applications, and manufacturing solutions; Future Factory - a physical and digital manufacturing shop leveraging data and cutting-edge manufacturing tools; and education and workforce training.

United States (post-2021 developments)
National Strategy for Advanced Manufacturing. The 2022 National Strategy for Advanced Manufacturing, developed following extensive public outreach, is based on a vision for United States leadership in advanced manufacturing that will grow the economy, create quality jobs, enhance environmental sustainability, address climate change, strengthen supply chains, ensure national security, and improve healthcare. This vision will be achieved by developing and implementing advanced manufacturing technologies, growing the advanced manufacturing workforce, and building resilience into manufacturing supply chains. Strategic objectives are identified for each goal, along with national technical and program priorities and recommendations for the following four years. **Making the Minority Business Development Agency permanent**. In 2021, MBDA was made a permanent Agency and was expanded and elevated with the passage of the Infrastructure Investment and Jobs Act signed by President Joe Biden on November 15, 2021. Congress and the Biden Administration mandated the elevation of the MBDA as the leader for America's MBEs. The Act grants MBDA a bold new mission to evolve and to both strengthen our efforts serving individual businesses and break down the systemic barriers holding back minority business enterprises. MBDA has Specialty Centres that helps companies upgrade their activities, including some specifically focused on advanced manufacturing. **CHIPS for America**. Following the CHIPS and Science Act of 2022, the CHIPS for America initiative encompasses two offices responsible for implementing the law: The CHIPS Research and Development Office is investing $11 billion into developing a robust domestic R&D ecosystem, while the CHIPS Program Office is dedicating $39 billion to provide incentives for investment in facilities and equipment in the United States. While not directly an Industry 4.0 policy, it will likely have strong effects on the digitalisation efforts of US companies. **Renewal of MxD as a National Manufacturing Institute.** MxD is a Manufacturing USA institute focused on manufacturing digitalisation. It has over 300 members within its ecosystem across industry, academia, non-profit and government, with 650 members over its 10-year history. As the US's only dual-mission institute focusing on digital and cybersecurity, MxD leads a portfolio representing over $415 million of public-private investment supporting 194 projects in R&D, cybersecurity and workforce development, generating more than 540 IP assets focused on technology innovation and adoption. In December 2024, it was awarded a renewal of its core agreement with the Department of Defense. The contract is a five-year commitment of $40 million. It will enable continued investment in digital manufacturing, cybersecurity, and workforce development solutions. The total government value will be matched dollar for dollar by MxD and its members over the period of performance. Through this renewal, MxD will continue to work on projects, programs and partnerships with the goal of helping U.S. manufacturing, including the Department of Defense industrial base, digitalize operations and empower the manufacturing workforce. **MxD partnership with the Manufacturing Extension Partnership (MEP)**. In 2023, MxD, the digital manufacturing and cybersecurity institute, announced a new partnership with the National Institute of Standards and Technology's (NIST) Hollings Manufacturing Extension Partnership (MEP) to advance digital adoption by small and

medium-sized manufacturers (SMMs). The five-year collaboration will help strengthen America's manufacturing base and increase competitiveness by delivering tailored support to SMMs to accelerate digital adoption initiatives, including cybersecurity preparedness, and securing funding opportunities that directly benefit SMMs.

Singapore



Overview

- The Singaporean government focuses more heavily on additive and advanced manufacturing than Industry 4.0 specifically. There are a number of activities which support Industry 4.0, but grant funding is not leveraged to the same extent as in the US and UK.
- Multi-agency approach involves the Agency for Science, Technology & Research (**A*STAR**), **Ministry of Trade and Industry** (MTI), Economic Development Board (**EDB**), and SME Agency (**Enterprise Singapore**).
- The **Singapore Smart Industry Readiness Index**: designed as a comprehensive self-assessment tool for companies to evaluate their digitalisation level, and Singapore has partnered with the World Economic Forum to launch the Index as an internationally recognized standard for Industry 4.0 transformation.
- **Industry Transformation Maps** (ITMs) were enabled via a project worth of S$4.5bn to roadmap the advancement of 20+ industries in Singapore representing 80% of GDP.
- Through the **Tech Access** scheme, 149 unique companies have utilised A*STAR's research infrastructure and expertise.
- The **Tech Depot** provides companies with plug and play technologies and has enabled more than 800 digital adoptions by 635 companies.
- Emphasis is on digital skills formation through their **FutureSkills** programme, which has reached around 10% of all the population above 25%.
- Singapore consistently promotes its ICT infrastructure as a key enabler of competitive advantage in this area.

Funding

- Typically, grant funding is not earmarked for Industry 4.0 initiatives, with most publicised government support taking the form of private-public partnerships, particularly with A*STAR and EDB (Economic Development Board, Singapore).
- **Productivity Solutions Grants** help businesses automate existing processes.
- **Partnership for Capability Transformation** scheme supports 70% of qualifying costs for partnerships in capability development.

Singapore (continued)
Key efforts and institutions supporting technology transfer / diffusion • The **Advanced Remanufacturing and Technology Centre (ARTC)** is a public-private partnership, led by the Agency for Science, Technology and Research (A*STAR), in partnership with the Nanyang Technological University. ARTC has a membership consortium with over 80 members, and focuses on advanced manufacturing and remanufacturing, and aims to delivery R&D solutions to industry needs. Programmes include model factories, smart manufacturing labs, software open-source projects, product personalisation manufacturing, and a Supply Chain 4.0 program to develop digital and automation tech to support supply chains. • **Advanced Manufacturing Training Academy** will collaborate with schools and training providers to help ensure the manufacturing workforce has emerging skills and knowledge. • The **Centre for Innovation for Electronics & Internet of Things (COI-EIoT)**, within Nanyang Polytechnic, supports local enterprises with developing capabilities, networking opportunities, and funding access. • **Model Factories**: allow SMEs to test new technologies with help of public sector researchers before adopting into their factories, by A*STAR (SIMTech, ARTC). The A*STAR Model Factory Initiative has supported over 100 companies and deployed close to 2,600 technologies. • The 600ha space of the **Jurong Innovation District** (JID) aims to capture advanced manufacturing capabilities. The first phase will be completed in 2022 but had already attracted more than US$300 million in investments in 2020. • The **National Additive Manufacturing Innovation Cluster (NAMIC)** established in 2015, has engaged over 1,800 organisations, orchestrated 23 international partnerships, curated over 230 projects, and supported 68 start-ups that have collectively raised more than US$140 million.

Singapore (post-2021 developments)
Currently available incentives for Industry 4.0 businesses in Singapore. Singapore offers a variety of fiscal and non-fiscal incentives that have been tailored to assist the development of high-value economic activities, as well as encourage businesses to upgrade their capabilities and expand their scope of operations in the era of industry 4.0. Applicants must fulfil rigorous requirements, which include committing to certain levels of investments, introducing leading-edge skills, technology, as well as contributing to the growth of research and development and innovation capabilities. Most of these incentives have local ownership requirements. Businesses involved in industry 4.0 activities in Singapore can make use of the following benefits: **Industry-specific tax incentives:** government agencies such as the EDB, the IRAS, Enterprise Singapore, and the MAS have industry-specific incentives **Pioneer tax incentive or development and expansion incentive:** If the business engages in the manufacture of high-value-added products or services, they can apply for a pioneer certificate to enjoy tax exemption or applicable concessionary tax rate. **100 percent investment allowance scheme**. Administered by the EDB, the program offers tax relief that can be used to offset taxable income for approved automation projects by the EDG and ESG. **Land intensification allowance scheme.** This program provides a targeted allowance on qualifying capital expenditure incurred for the construction or renovation of an approved LIA building structure. The LIA is available to businesses in the manufacturing and logistic sectors that have large land takes and low Gross Plot Ratios (GPR). **Incentives for innovation and R&D.** The Tech@SG program helps Singapore-based technology companies recruit highly skilled foreign talent and expand in the region. Other incentives are available for research and development, such as the Research, Innovation, and Enterprise (RIE) 2025 plan and the Intellectual Property (IP) Competency Framework.

Korea

Overview

- Korea's strategies seek to maintain its competitive advantage in Industry 4.0, evidenced through high standing within key indices such as first in the 2021 Bloomberg Innovation Index, second in the 2020 UN E-Government survey, and second in the 2017 Global ICT Development Index.
- The Korean government conceptualises the arrival of Industry 4.0 as the Fourth Industrial Revolution.
- The "**Manufacturing Industry Innovation 3.0**" strategy, launched in 2014, invested $376 million in developing smart manufacturing technologies, while **'I-Korea 4.0',** which is the 'People Centred Plan for the 4th Industrial Revolution to Promote Innovative Growth', was launched in 2017.
- The Korean government established the '**Presidential Committee on the Fourth Industrial Revolution**' (PCFIR) in 2017, an advisory body.
- The Ministry of Trade, Industry and Energy and the Ministry of Employment and Labor promote industrial complexes as the base of smart manufacturing innovation and aims to **create 10 smart industrial zones by 2022** by forming "smart industrial zone task force."
- Targets are often pitched around the number of '**Smart Factories**' within the country, with a current target of 30,000 Smart Factories by 2022.
- **Industrial Digital-Transformation Alliance** announced on 28 October 2020 to support digital transformation projects in various industrial sectors including: automotive, electronics, healthcare and shipbuilding. Measures include support to knowledge generation, diffusion and deployment.

Funding

- The **US$133bn Korean New Deal** announced in 2020 has three pillars (digital, green, and social welfare), and 44.8 trillion won ($40 billion) was allocated to the "**Digital New Deal**" pillar, which would boost the integration of data (5G), network, and AI into the Korean economy, and fund digitalization of public infrastructure over five years. The digital new deal has three layers – technology development citizen-centred applications, and ecosystem innovation, involving 76 research institutes.
- Korea's government has committed to investing $189.3 million through 2020 into R&D projects developing technologies related to **smart factories**, with research and testbed projects sponsored with federal funds
- In 2020, the Korean government injected $414.4 million into R&D projects to incentivize **SME companies to advance and upscale automated technologies**.

- In 2020, the budget of the **Department of Smart Manufacturing Innovation** is of ~US$4.1 billion.

Korea (continued)
Key efforts and institutions supporting technology transfer / diffusion • The **Ministry of Trade, Industry and Energy** (MOTIE) is leading main government efforts. • The **Ministry for SMEs and Startups,** through its **Department of Smart Manufacturing Innovation**, provides smart manufacturing-related services. • The **Smart Manufacturing Innovation Center (SMIC)** provides support on building proof of concept production lines, interoperability testbeds, technical verification and consulting, and training. • The **Smart Factory Standard Research Council** was formed within the private sector to standardise regulations. • **Korea Industry 4.0 Association**, established in 2015, has over 1000 members from companies, universities, R&D institutions and government organisations. It is linked to the Ministry of Trade Industry and Energy, and shares insights through education programmes, annual conferences, and working groups. • The **Korea Policy Center for the Fourth Industrial Revolution** (KPC4IR) are a team of researchers funded by the Ministry of Science and IT to investigate the socioeconomic impacts of the fourth industrial revolution.

Korea (post-2021 developments)
New growth strategy 4.0. In 2023, the Korean Ministry of Economy and Finance published the new growth strategy 4.0. The focus is on: 1. AI semiconductor industries; 2. Urban Air Mobility; 3. Hydrogen; 4. Autonomous driving; 5. Used Batteries; 6. Private sector MyData based services; 7. R&D equipment ordering processes. While not directly Industry 4.0 policies, they may have impact in industries engaging with Industry 4.0 technologies. **Strategy to Foster the National High-tech Industry**. The government will make all-out efforts to promote 6 key tasks including 1. Securing an unmatchable level of technological capacities, 2. Nurturing innovative talents, 3. Building regionally specialized industrial clusters, 4. Establishing a sound ecosystem, 5. Emerging as the world's best investment destination, 6. Strengthening trade capacity with the goal of securing a dominant position in high-tech industries. **Development Plan for National High-tech Cluster**. High-tech industrial complexes will be constructed across the nation in a balanced manner by fostering regionally specialized industries to develop future and high-tech industries. Proposals for demands for technologies and locations of industrial complexes were made by each region after they had analyzed their comparative advantages, before the central government selected potential industrial-complex sites after accounting for their relevance to the national strategic industries and balanced growth throughout the nation. A total of 15 national industrial complexes will be constructed on sites spanning 40.76 million square meters, which will come with a significant support by the government to induce corporate investment in an attempt to nurture future and high-tech industries, such as semiconductors, future vehicles, aerospace, and nuclear power.

Taiwan

Overview

- Like Korea, Taiwan seeks to maintain a dominant position in manufacturing, particularly in areas of laptops and semiconductors. Industry 4.0 is called Productivity 4.0 in Taiwan.
- The **Smart Machinery Development Programme** is one of Taiwan's main industrial innovation policies (under the 5+2 Innovative Industries[63] initiative, which includes 'intelligent machinery'). Its main purpose is to upgrade Taiwan from precision machinery to smart machinery and to promote the adoption of smart machines.
  - In 2016, the Digital Nation and Innovative Economic Development Program (**DIGI+),** was launched. This initiative aims to make Taiwan a smart digital region by 2025.
  - In 2015, Taiwan released the development plan of **Productivity 4.0** to promote the development of intelligent industries, which mainly focused on intelligent machinery.
- The Smart Machinery Promotion Program was introduced in 2017. It aims to develop smart-machinery applications by combining manufacturing expertise with that from information and communications technologies. The **Smart Machinery Promotion Office** was established to help create a new ecosystem for Taiwan's smart machinery industry.
- **Taiwan's Smart Manufacturing Strategy** involves three main pillars:
  - Digitalised production management, from Industry 2.0 to 3.0 (Manufacturing Enterprise Solutions, MES and Enterprise Resource Planning, ERP)
  - Develop Network Service Platform (PaaS) and testbed for SMEs.
  - Develop industry's software model (SaaS)
- In 2019, Taiwan announced a 4-year, $658-million spending plan for 5G technology to increase the region's digital competitiveness.

Funding

- The government invested NT$15 billion (US$508.5 million) between 2016-2020 to upgrade Taiwan's machinery industry from precision machinery to smart machinery.
- In 2019, the budget of the Industrial Technology Research Institute (ITRI) was NT$25 billion (US$ 276 million).
- In 2017, the Ministry of Science and Technology invested US$33m over 5 years for three facilities developing AI technologies, including the Artificial Intelligence for Intelligent Manufacturing Systems research centre.

[63] Includes "intelligent machinery", "Asian Silicon Valley", "Green Energy Technology", "Biomedical Industry", "National Defense Industry", "New Agriculture", and "Circular Economy".

• In 2017, the Ministry of Science and Technology announced a 4-year, $132-million semiconductor programme to speed up the development of AI processor chips, and a 5-year, $517.5-million strategy to cultivate AI talent and research (2017 to 2021). •
Taiwan (continued)
Key institutions supporting technology transfer / diffusion • The Smart Machinery Development Programme is led by the **Ministry of Economic Affairs (MOEA)** and the **Ministry of Science and Technology (MOST)**. • The **Smart Machinery Promotion Office** assists companies in achieving smart manufacturing through: (i) a smart manufacturing consultant team that makes on-site visits and provides consulting, diagnosis, and technical services; (ii) establishing test sites for plumbing hardware and hand tools, aerospace machine tools, auto parts and components, and semiconductor equipment; and (iii) linking together domestic and overseas platforms to help companies build partnerships. • The **Smart Manufacturing Pilot Production Site,** established by **ITRI,** serves as the domestic smart manufacturing planning center, and shows the Industry 4.0 applications of domestic equipment to the industry. • The Ministry of Economy, the Ministry of Sciences and Technology, the Ministry of Education have established a number of initatives in partnership including the Intelligent Manufacturing Experimental Plant and Smart Machine Box Plan of Industrial Development Bureau.

Taiwan (post-2021 developments)
The current strategic service offering of the Ministry of Economic Affairs of Taiwan for companies includes: • **Forward-looking technology research and development plan.** According to the "Ministry of Economic Affairs' Subsidy and Guidance Measures for Assisting Industrial Innovation Activities", this programme seeks to promote forward-looking technology research and development plans, induce enterprises to invest in high-end advanced technology development, and promote the production of leading technologies in the country, which may significantly enhance the added value of Taiwan's industries and compete in the international market. • **Global R&D innovation partnership program.** This programme seeks to connect multinational companies that are complementary and mutually beneficial to the country's industries to come to Taiwan to engage in innovative R&D activities and enhance their competitiveness through cooperation with Taiwan's industries. • **Leading enterprise research and development plan.** This programme seeks to attract major international manufacturers (domestic and foreign leading manufacturers) to take root in Taiwan by using forward-looking technologies, coordinate with China's industrial chain cooperative research and development, accelerate the development of new industrial layouts, strengthen the research and development of China's industry-leading technologies, and lead Taiwan to become a global high-tech R&D centre, In accordance with the "Ministry of Economic Affairs' Subsidy and Guidance Measures for Assisting Industrial Innovation Activities", the "Leading Enterprise R&D Deepening Plan" is promoted through subsidies. • **Forward-looking technology venture investment program (A+STEP).** Through familiar fund-raising procedures for new ventures, this programme guides corporate venture capital to conduct professional investment evaluations and determine investment targets through commercial mechanisms. Through this program, corporate venture capital and new ventures that receive investment are encouraged to invest in forward-looking technology development, and the energy of corporate venture capital is supplemented to accelerate the implementation of commercial applications. • **International innovation R&D cooperation subsidy program.** This programme seeks to encourage Taiwan's industry to think globally, build international strategic partner innovation cooperation relationships, participate in international (such as the European Union, etc.) R&D projects, leverage international innovation energy, carry out internationalisation of technology R&D, enhance the country's industrial R&D level and core competitiveness, and drive the development of the overall industrial chain, create industrial value, and expand international market opportunities. • **IC design capture subsidy program.** This programme focuses on promoting the country's IC design industry to invest in the development of "internationally leading" chips and systems. One of the subsidy goals is to leverage Taiwan's semiconductor hard power to promote the application of AI technology in various industries. • **Subsidy program for independent development of key chips and modules for drones.** This programme seeks to promote domestic chip factories or system manufacturers to invest in the drone industry and assist manufacturers in developing "drone AI imaging chip modules" and "drone low-cost flight control boards" to enhance industrial technology capabilities, reduce costs and expand global market share. More closely aligned with Industry 4.0, recent policy programmes include: • **Smart Machinery Industry Promotion Program.** In response to the massive changes brought by IoT, 3D printing, AI, and robot technologies to life and industries, Taiwan

implemented the "Smart Machinery Industry Promotion Program" in July 2016, in hopes of upgrading the precision machinery industry into the smart machinery industry.

- **Smart Machinery Park.** In central Taiwan, Taichung City is the largest city with the most business activity going on, as well as known for the machinery industry and is the main hub for it. Taichung City Government has expanded the hinterland of Fengzhou Technology Science-based Industrial Park in Taichung during Phase 2 development of the Park to build the Smart Machinery Park, which supports the transformation of traditional industries and the development of industries that support the Central Taiwan Science Park. Sales of Phase 1 of the Park have been completed. Applications for Phase 2 began in April 2021 and the area of development is 81 hectares.
  Smart Manufacturing Technology Test Site. The Smart Manufacturing Technology Test Site is equipped with 100% high-end machinery processing equipment produced in Taiwan. The site links digital product systems that are domestically developed and produced, develops machinery processing application service modules, and has 9 mixed-model smart manufacturing production lines for parts and components. As a domestic test site for smart manufacturing, this planning centre demonstrates to industry the capabilities of domestic equipment in Industry 4.0 applications.
- **Smart Machinery Promotion Office.** The Smart Machinery Promotion Office was established in February 2017 and it has taken steps such as the "digitalization of production management, from Industry 2.0 to Industry 3.0," "establishment of a public platform as a service (PaaS)," and "development of software as a service (SaaS) modules for different industries" to help key industries adopt smart manufacturing. The Smart Machinery Promotion Office can help foreign companies participate in testing facilities or exchange platforms and establish supply chain and partner networks in Taiwan.
- **Several Tax Incentives**
- **Joint R&D Programs (subsidies)**
  - **Global R&D Innovation Partner Program** (part of the A+ Industrial Innovation R&D Program): In line with the global trend of innovation, ITRI (Industrial Technology Research Institute; a technology research and development institution founded by the Taiwanese government and headquartered in Hsinchu, it has branch offices in the U.S., Europe, and Japan) guides the industry to invest in forward-looking technology development and promotes cross-cutting integration to complete the industrial ecosystem development of Taiwan. Since 2014, the Department of Industrial Technology (DOIT) has encouraged subsidized enterprises to invest in innovation R&D through the A+ Industrial Innovation R&D Program. Initiatives such as Global R&D Innovation Partnership Program, and International Innovation R&D Collaboration Subsidy Program aim for promoting international collaboration. The subsidy scheme includes Funding for Participants in the EU Research and Innovation Program, Program for Taiwan-Germany Collaboration on Innovation R&D, Program for Taiwan-Spain Collaboration on Innovation R&D, and Program for Taiwan-Israel Collaboration on Innovation R&D.

  - **Program for the Development of Pioneering Companies** (part of the A+ Industrial Innovation R&D Program): Also known as the Pioneers for Innovation Leadership On Technology Program, its aim is to strengthen Taiwan industry’s ability to research and develop leading technologies, and enable Taiwan to become a global high-tech research and development (R&D) centre, by galvanizing foreign and domestic international leading enterprises to develop advanced technologies in Taiwan, collaborate with the local industrial ecosystem on R&D, and accelerate the deployment of blue ocean strategies. The R&D content has to be one of the following technology domains: 1. Advanced Semiconductors: e.g. next generation memories, high frequency, and high power semiconductors; 2. Next-Generation Communication: e.g. new open 5G network architecture; 3. Low earth orbit satellite communication systems; 4. Artificial Intelligence: e.g. new AI models and platform technologies

- **Taiwan Industry Innovation Platform Program.** To help promote industrial upgrading and transformation, the Industrial Development Bureau of the Ministry of Economic Affairs launched the "Industrial Upgrading Innovation Platform Guidance Program," through the subsidy mechanism to guide the industry in developing products or services with market competitiveness, to encourage independent research and development, and to assist in fostering Taiwan's innovation ecosystem, in hopes of enhancing the added value of Taiwan's industries, optimizing the industrial structure, and connecting to the international market.

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Annex L: Case studies

Table L-1: List of case studies

Case study name
SmartPSC (Smart Pharma Supply Chain)
Prime 3D
Singular Intelligence (SI)
Mallaghan Engineering
Adey Steel
Human Robot Collaboration
Omnifactory®
Platform 2 'Self-Driving Tableting DataFactory'
Hot Strip Mill
The use of legitimacy to inform decision-making in digitalisation
Artificial intelligence for visual inspection
Batch.Works AI 3D Printing Factory Network
"Business in a Box" Sensor Monitoring Solution
Certified AM Parts Finished with Intelligence Robotics Engine (CAMPFIRE)
DM2 - Platform Five (Network and Skills), Extended Reality

Case study: SmartPSC (Smart Pharma Supply Chain)

Overview

This case study focuses on the Smart Pharma Supply Chain (SmartPSC), a CR&D project that ran between 2021 and 2023. The project was led by the pharmaceutical firm GlaxoSmithKline (GSK) and had four participating partners: AstraZeneca, Centre for Process Innovation (CPI), Wyoming interactive (an SME) and the University of Cambridge. In total, the project was awarded £1.4m by MSI and received the same in match funding from the industry partners. The case study draws on evidence from three consultations, one with GSK, one with Wyoming, and one with the University of Cambridge, as well as data and documents provided by the partners.

The consortium identified an opportunity to solve a key problem at the front-end of the supply chain, where the quality of materials is assessed prior to formal approval for use in manufacturing. Modern pharma supply chains are a collaboration of multiple suppliers and partners. Each time material moves between parties, Certificates of Analysis (CoAs) move with them to certify its required quality. Current processes to review CoA data are very laborious. Typically, the material is tested by the supplier and the results end up in paper copy or as a scanned PDF version of the CoA. Then, highly qualified scientists at the receiving company evaluate these printed paper documents manually without recourse to digital tools. These processes increase the costs companies need to charge. Digitally enabled processes in a highly competitive environment would allow firms to reduce costs. Additionally, managing the delay and uncertainty associated with CoA evaluation often requires manufacturers to hold additional stock that can be used in case of an issue with a particular batch. This results in high levels of inventory tied up in this review-to-approval stage which may impact ultimate product expiry dates. Therefore, there is an attendant risk of waste.

SmartPSC aimed to automate the evaluation of in-bound material quality certification using digital technologies. This was a complex endeavour given the multiple relationships within the supply chain of both consumers and suppliers of data, with different stakeholders having different levels of digital maturity. The consortium aimed to create a new digital structured data application that accommodates alternative partner capabilities and practices. SmartPSC primarily focused on suppliers of incoming materials such as raw materials, packaging materials, and device components.

Aims and objectives

The SmartPSC project aimed to create a standardised method for ingesting CoA data from multiple suppliers and sending it digitally to the next manufacturer in the supply chain. The intention was to speed up the approval process by 'approving by exception', with CoAs automatically verified against reference data and only those with outstanding data queries being verified manually. This required development of software to determine whether a product meets the CoA criteria and what additional oversight is required if the product does not fall within specified parameters.

Delivery

The project began with a discovery phase to understand the state of the industry and current technologies followed by proof-of-concept work, where they considered different technologies (Optical Character Recognition and Intelligent Character Recognition) that could extract data and turn it into a structured format for further processing. The proof of concept benefitted from working with real pharmaceutical data from GSK's suppliers. Critical to the PoC was a 'many to many' connector, developed by Wyoming, that allowed suppliers to feed in their current CoA format and have it converted to the format the manufacturer requires.

Multiple vendors were invited to build rapid prototypes for the software applications that would manage the extracted data. The prototypes had to include four 'modules':

- Module 1 – accepting data input from suppliers, in whichever format it was provided.
- Module 2 – loading that data into the central system
- Module 3 – processing the data in the system
- Module 4 – reporting the results

Subsequently, the Minimum Viable Product (MVP) was built with the support of an industry leading rapid business process development application and the best-in-class OCR/ICR tool identified at PoC. It underwent a 10-week Proof of Value trial, involving four GSK suppliers. The trial allowed the consortium to assess critical metrics such as cycle times for CoA verification, batch matching, and usage decisions, identify potential opportunities to optimise these processes, and perform micro-testing for raw materials.

The strength of the consortium's relationships played a key role in the project's success. Initially, these relationships were more siloed and disjointed, mainly due to pandemic restrictions in 2021. The first two to three quarters of the project were completed remotely, without in-person interaction. This caused delays and, as a result, the project was granted an extension. Active effort was then put in to build these relationships, including informal meetings over dinner and coffee. Building trust among partners facilitated the sharing of data, which was crucial for the project's success.

"A critical internal factor was that we didn't just assume that these relationships would be good; we actively built on them. And the result was that the majority of our partners were eager to continue working together and build on what we achieved."

GSK member

The **range of experience, expertise and assets among the project partners** added value to the project. For example:

- Access to GSK's data and CPI's quality management system helped to show the technology could be applied to real quality management processes.

- Wyoming provided the agility to quickly spin-out prototypes and brought their knowledge of ontologies and data-sharing methods.
- The CPI leveraged their extensive experience in similar projects and acted as the programme coordinator, helping the consortium design their conceptual approach and facilitating workshops.
- The University of Cambridge brought a whole supply chain view to the project.

"One of the challenges with technology interventions, especially digital ones, is understanding their impact on the supply chain. Often, improving one part of the process doesn't necessarily shorten production time or reduce inventory unless you apply end-to-end, system-wide thinking."

UoC member

- Having two major pharmaceutical partners, AstraZeneca and GSK, ensured that the project did not become an "echo-chamber" of either of their own experience.

Senior level buy-in was also identified as an important factor in project progress. By keeping engagement and momentum with senior staff members, the project became more adaptable, and able to deal with roadblocks or changes in the project course. This senior level buy-in was created by discussing the overall picture of the project and potential benefits for the organisations, instead of focussing on the narrow scope of this specific project.

Beyond internal support, having **open conversations with IUK** at both a Monitoring Officer and more senior level about the project goals and strategies was seen as key to the project's success. The regularity of meetings in maintaining discipline amongst the partners was also welcomed.

Key benefits

Although different partners had varying perspectives on the project's TRL progress, the product made significant overall progress from exploratory investigation to PoC and testing with real-world suppliers and CoA data.

The outputs from the trial showed potential reduction in cycle time for review to approval for incoming material by 30-40% on average (CoA Verification in less than 10 secs). It reduced manual effort between 25 and 50%, and demonstrated potential to reduce both rework and inventory of incoming materials by 25%. Moreover, it will increase the visibility of CoA related issues, and the speed of their resolution.

The project demonstrated the potential for a generic hub where suppliers can upload CoA and automatically receive structured data for sharing with sponsors. This solution could significantly reduce the burden on smaller suppliers.

Another output of the project was the development of standalone algorithmic approaches for supply chain optimisation, developed by the University of Cambridge. These approaches were distinct from the MVP but could be incorporated to allow for better supply chain management. The University did this partly by leveraging techniques learned in other work unrelated to SmartPSC.

For the SME partner, involvement in this project has helped them raise their profile, build connections and increase their credibility. They have been involved in further work due to this project.

The project was not successful in obtaining follow-on funding from IUK. Some partners felt that with more advice and support, they could have been awarded funding. Currently there are no other funding options and further development is uncertain although potential productivity benefits are significant and applicable to other sectors.

Role of MSI

In the absence of MSI funding, all project partners agreed that the project would not have gone ahead, and none of the benefits would have been realised. Both the collaborative element of MSI programme and the funding were cited as being important to the benefits being realised. The funding provided a *"shot in the arm"* for a good idea to take off and be progressed. Without the funding the consortium would have lost their competitive edge. One partner also mentioned that, since this technology is novel, it could help the UK to make its pharmaceutical sector more competitive relative to other countries.

"What I can say is that I'm actively involved in industry forums where similar conversations are happening, and I see many companies having the same discussions they were having three years ago. We're really leading the way on this topic, and the reason we're in this position is because of the MSI funding, which gave us the push to get the project off the ground."

GSK member

The collaborative element brought together the diversity of stakeholders needed for this project to be successful. The varied experiences and perspectives ensured the solution was industry-relevant but also technically sophisticated. All partners agreed that MSI funding was the critical contributory factor, in part because it catalysed the creation of the consortium.

Learning

Collaborating with major pharmaceutical firms gave the SME partner an insight into the nature of the quality control and approval processes.

Key learning for IUK includes:

- Ensuring effective signposting and support to follow-on funding where private investment is unlikely to be forthcoming and there is a clear rationale for public funding, such as maintaining a competitive edge in an innovative and important sector

- Reducing administrative burden or the perception of it.

Future Prospects

While the technology developed by this project has significant potential in supporting the competitiveness of UK pharmaceutical companies, the future development of the technology is contingent on securing further funding to undertake ‘validation’, a protracted and resource intensive process where the software is proven to work in an a highly regulated environment like pharmaceuticals.

Case study: Prime 3D

Overview

PRIME-3D was a CR&D project to develop the technology for the application of circuit boards on to 3D surfaces composed of a standard substrate. The project received £245k grant funding from Innovate UK, which was matched with £245k of private finance. The project had two funded partners: Q5D Technologies - the lead - and the Manufacturing Technology Centre (MTC) a research technology organisation which is part of the High Value Manufacturing Catapult. Additionally, the project had one unfunded partner – AWAN, a developer and manufacturer specializing in wireless communication products, with their funding support provided by the Department of Industrial Technology, Ministry of Economic Affairs of Taiwan. ITRI, a leading research and technology organization in Taiwan and regarded as the Taiwanese equivalent of Innovate UK, was commissioned by AWAN to jointly develop the protective ink used in this project.

Aims and objectives

As standard, circuits are printed onto a flat circuit board (PCB) and then integrated into technology. Printing a circuit onto a 3D surface has a number of benefits including a reduction in weight, a saving of copper, a reduction in manufacturing time, and the ability to create more complex electronics. The currently favoured method for 3D printing circuits – developed by the German company LPKF – requires an expensive specialist substrate that has been seeded with nanomaterials.

The PRIME-3D project aimed to demonstrate an alternative method of forming 3D electronic components onto a standard substrate, as a proof of principle, developing the technology and creating an operational laser system for this method. This method involves spraying an uncoated mould with a protective ink, stripping away this ink into the correct pattern using a laser, immersing the mould into a catalyst, washing the ink off with a solvent and then electroless plating this piece with copper.

Delivery

The three project partners had specific roles within the project:

- Q5D developed a machine that integrated the laser technology
- MTC refined the laser processing techniques by coating materials in the ink before exposing them to commercially available lasers with differing parameters (such as intensity) to ascertain which were most effective
- AWAN completed the design of the 'Intelligent MIMO Antenna Module' and the 'High-Speed 3D Die Bonder', and jointly developed the protective ink with ITRI.

Q5D had intended to integrate both the spraying head and the laser head into the same machine but discovered it was easier and more cost effective to coat the parts outside of the machine. Likewise, initially the project plan involved the use of specialist lasers but commercially available lasers were found to be just as effective. Both of these project alterations resulted in a more flexible, lower cost and more convenient process.

Factors that were cited as helping the progress of the project included:

- The engagement between project partners, and their willingness to trust each other and share information. This was mediated by frequent project meetings via video conference and email conversations as well as two in-person visits with ITRI in Taiwan. Due to the project extension (see below) ITRI's funding from the Taiwanese Government expired before the end of the project (as planned) but they continued to engage with the project, providing assistance and reviewing demo parts even without funding.
- The differing Taiwanese perspective towards innovation and how to approach problems brought new ideas to the project.
- Additional staff taken on by the lead organisation as a result of the project, including a new project manager and a laser engineer, provided in-house skills and expertise that were critical to the success of the project.

Factors that were cited as hindering the project included:

- A major commercial success for the lead organisation (unrelated to the project) led to a lack of research capacity. As a result, they were required to seek an extension to the project as well as take on additional staff to increase their capacity.
- The delay in waiting for a new batch of ink, which has a relatively short shelf life, to be delivered from Taiwan, which usually took around two weeks.
- The UK no longer has a plating industry, so there was no ability to access expertise or assistance during this stage of the process.

Key benefits

The project was ultimately successful in achieving its aims. The MTC successfully demonstrated laser ablation to create a highly precise and controlled mask for electroless plating, which was demonstrated on a 3D component with three faces. The lead organisation successfully integrated this into a baseline machine that demonstrated an ability to create 3D circuits on a non-specialist substrate, and can be used to further explore 3D electronics in the future.

Technology readiness level (TRL) estimates of where the project was at the beginning and at the end of the project differed because partners were involved in different technologies. The lead estimated that the 3D circuit technology had progressed from TRL3 (Experimental proof of concept) to TRL4-5 (Technology validated in a lab), whilst the machine they had developed was TRL5-6 (Technology validated in relevant environment). The laser component within the machine, however, was thought to be TRL9 (Actual system proven in operational environment) because it has been demonstrated to work reliably and consistently.

The project lead and the MTC reported that there had been widespread interest within industry at this technology, particularly within the key sectors for the MTC: Aerospace, Defence and Automotive. Lockheed Martin, a major international defence manufacturer, has invested $3m in Q5D Technologies, partly as a result of this technology. The ability to 3D print electronics is particularly important in defence and aerospace applications because it has potential to reduce the weight of aeroplanes by stripping out copper wiring, meaning they require less fuel and produce fewer emissions. The technology also has potential applications in filtering or directing of radio frequency signals, which can improve the accuracy of radar sensors.

Beyond the direct technology advancement benefits, partners reported increases in their skills and capabilities. The project lead reported that, as a result of bringing in additional staff, their capabilities in both lasers and project management had improved, whilst the MTC reported improved skills in this technology area (particularly electroless plating) and the upskilling of technicians – one technician likely secured their position at the MTC as a result of their work on this project.

The connections and collaborations established through this project were thought to be an important outcome too. Beyond the end of the project, the MTC is now working on separate projects with both Q5D and ITRI, both entirely separate from this project but kickstarted through their collaboration on this project.

The project lead reported, as a result of this project, that they have developed a network of industry expertise within printed electronics that they can engage with to further progress the technology, and understand how it should be presented to a commercial audience.

The MTC reported that involvement in this project had helped them achieve their mission statement because they have successfully supported a British manufacturing SME to develop a high-value product.

This project demonstrated this technology in the UK for the first time. Retaining these capabilities within the UK is important to national competitiveness and resilience, as well as being important to national security, given the implications of this technology in the defence sector.

Role of MSI

In the absence of the MSI programme, all project partners agreed that none of the benefits would have been realised. The project lead cited that the funding allowed for collaboration with partners that otherwise would not have been possible - in particular ITRI on whose 'ink' technology the entire project depends. The MTC reported that they would not have been able to fund their involvement in the project in the absence of grant funding, and thus the MSI programme unlocked their participation.

Relative to the other factors detailed above, including the close collaboration between partners, the MSI programme was seen as the critical contributory factor, because only through MSI were the close collaborations created and maintained.

Learning

Key learnings from this project included technical learnings in areas that were new to the lead and the partners, but also greater knowledge of the potential market for this technology and what value it would bring to customers.

The lead learned about the importance of including an RTO (Research and Technical Organisation) – the MTC – in CR&D projects, because they have access to technologies, techniques and capabilities that would conventionally be out of reach for a UK SME.

Future prospects

It is hoped that, within 2025, a launch event can be held at which potential customers can be shown the technology, with the event acting as a platform upon which to launch pre-sales. The lead aims to further develop the technology and the capabilities in-house before commercialising the machines. The lead anticipates developing the technology as a pilot in 2026 before reaching full commercial production in 2027. ITRI reported that, if made available for purchase, they would consider buying the technology and installing it in Taiwan.

Beyond the end of this programme, the technology will continue to be developed by the project lead, supported by strong venture capital finance, to push the technology up to TRL7 and beyond. However, government finance for more research into the potential applications of this technology, with a strong focus on the end-user, was thought to be helpful.

Case study: Singular Intelligence (SI)

This case study focuses on the Singular Intelligence project delivered by the Digital Supply Chain Hub (DSCH – 'The Hub'), as part of the Made Smarter Innovation programme. The purpose of the case study is to provide an illustrative example of the work undertaken by the DSCH and the benefits achieved. It draws on evidence from two consultations, with the hub director and one of the three partners on the project, as well as data and documents provided by the partners.

Overview

The project aimed to develop an AI-driven data analytics solution to reduce supply and demand imbalances in the fast-moving consumer good (FMCG) Retail and Supply Chain sector. It was delivered by Singular Intelligence, an AI start-up, in partnership with Sainsbury's supermarket and the UK's largest meat producer, Cranswick. Cranswick produces a variety of pork & poultry products for customers in the UK, including Sainsbury's 'Taste the Difference' range. In recent years, Cranswick has faced fluctuations in demand caused by changing consumer trends, alongside supply side issues possibly related to labour shortages at farms and slaughterhouses. This resulted in over and under supply in pigs for Cranswick at different times, and excessive food waste and revenue loss for Sainsbury's.

Aims and objectives

The purpose of this project was therefore to investigate how AI and digital technologies could be used to improve planning and reduce supply and demand imbalances, by improving forecasting decisions at different levels of the supply chain. These imbalances occur in many supply chains (with higher consequences for perishable goods) and so the solution developed would have the potential to scale across different supply chains in the FMCG sector, in line with the DSCH's objectives to improve supply chain operations. To support this, DSCH provided funding to the value of £80k, which was matched by partners, for an initial period of six months from April to October 2022.

Delivery

The key activities related to developing and testing an AI solution to interpret market signals and mitigate the risk of supply-demand imbalances. Singular Intelligence had earlier developed an AI solution for Unilever and done a shelf-life optimisation project for Sainsbury's in the fresh supply chain (Spinach Category) and so the project started at TRL 4. With support from the Hub, Singular Intelligence progressed three key functions of the technology:

- **Demand sensing technology,** which is used to track and forecast demand signals such as sales, product availability and weather
- **Supply sensing technology,** which analyses cost and production risks, and supply shocks
- **Intelligent planning technology,** which proposes planning actions to mitigate any foreseeable gaps.

Support from the DSCH included expert input to solution development, project management, and commercialisation planning, in addition to the funding outlined above. Each of these elements were important in enabling the successful delivery of the project, particularly the weekly project review meetings involving the Hub, input from data scientists, and 'go-to-market' strategy sessions. Crucially, the Hub also brought together two partners from different ends of the supply chain. Their inclusion gave Singular Intelligence access to supply side data (from Cranswick) and demand side store-level data (from Sainsbury's) and two different customer perspectives on the solution.

Whilst project activities were broadly delivered as planned, there were a small number of factors which hindered delivery. First, the Hub reported some difficulty in onboarding Sainsbury's and Cranswick to the project. This was due to the way the flexible funding call was designed: rather than getting industry 'sponsors' to set their own challenges, the Hub opted to identify industry wide challenges and then find partners interested in participating. Second, there were some issues at the outset around Cranswick and Sainsbury's sharing their data. This was overcome through meetings to discuss and agree compliance requirements. The third challenge was around the quality and completeness of the data provided, which required extensive cleaning. Finally, there was a challenge associated with the complexity of the pork supply chain. Singular Intelligence dedicated significant resource to undertaking research including interviews with representatives from different parts of the supply chain and factory visits, in order to understand the decision processes at each stage.

Key benefits

One of the key outcomes for the project was the progression of the solution from TRL 4 to TRL 7. The prototype was tested in an operational environment and the pilot resulted in a 70% reduction in the supply-demand imbalance overall. The following benefits were reported by partners:

- On the supply side, Cranswick **reduced the over-slaughtering of pigs** by 11%, which resulted in a 14% **increase in revenue** per pig
- There was a **reduction in food waste** for Sainsbury's of between 50%-70% in its Taste the Difference pork range
- There was a 18-28% **reduction in quality downgrades** of pork products made by Sainsbury's due to better inventory management
- Sainsbury's was able to improve **product availability** by 2-5%
- The above outcomes are expected to result in long-term impacts in relation to **reduced GHG emissions** and **improved productivity.**

From an industry perspective, the project was an example of successful collaboration between partners, including different components of the supply chain, and Singular Intelligence has sustained engagement with Cranswick and the Hub since the project completed. Furthermore, Singular Intelligence has expanded its team to explore opportunities to apply the technology more widely. This includes other applications within the pork supply chain and in other segments of the FMCG sector with perishable products, such as fruit, meat, leafy greens, herbs, and seafood.

Role of MSI

The flexible funding pot through which this project was backed had two key elements. First, the Hub played an important role in project set up. Unlike a typical CR&D call, the Hub set the specific challenge (based on extensive industry consultation), brought together the supply chain partners, and sought out the innovative technology companies to provide a solution. As outlined above, the Hub then played an active role in project delivery through technical input and project management.

Without the support from the Hub (one of the MSI workstreams), Singular Intelligence would have continued to develop the technology, but more slowly. The Hub *"acted as a catalyst"* by providing investment and expertise, and, importantly, bringing together the project partners. The Hub was important alongside a number of other factors in achieving the benefits outlined above, including Singular Intelligence's previous experience of delivering large scale projects focused on the supply chain. As a result they were able to foresee and mitigate potential risks. Furthermore, the level of collaboration between partners was "*excellent*". Although there was an early issue in relation to data sharing, this was overcome through close collaboration to come up with a solution.

Learning

In terms of key learning, consultees mentioned the following points:

- The **processes around the flexible funding open call generally worked well**. In particular, monitoring arrangements were appropriate and helped to keep the project on track.
- **Establishing buy-in** from all of the project partners at the outset is time consuming but essential. The Hub considered it important to engage the right partners in terms of competence, and willingness to collaborate.
- **Data sharing** processes are a common issue in this type of project. Sufficient resource needs to be allocated to develop appropriate data sharing agreements. Relatedly, the quality of the data that partners can provide may not be ideal, and projects should expect to dedicate substantial resource to cleaning the available data. Singular Intelligence has submitted a proposal to Innovate UK for additional funding for a federated learning model which will resolve some of the data privacy issues.

Future prospects

At the time of fieldwork it was unclear if Cranswick would formally adopt the technology more widely. This was dependent on a board level decision to fund a wider product roll out following the trial. Singular Intelligence was simultaneously considering options for investment to progress the solution to TRL 9 and develop it for other markets. The US was a market of particular interest as the food supply chain there is perceived to be "*more open to innovation".* Singular Intelligence was therefore in the process of reaching out to large food companies in the US for follow-on investment. Other potential markets include Europe and South East Asia. The largest barrier to expanding into these markets related to securing funding to adapt the solution for different supply chains.

Case study: Mallaghan Engineering

This case study focuses on a Digital Innovation Fund National Lighthouse Project funded by the Smart Manufacturing Data Hub (SMDH – the Hub) and delivered by Mallaghan. The purpose of the case study is to provide an illustrative example of an SMDH Lighthouse project and the types of benefits achieved. It draws on evidence from two consultations, one with the SMDH lead on the project and another with Mallaghan's Continuous Improvement Manager.

Overview

In line with the wider objectives for SMDH Lighthouse projects, the purpose of this project was to enable Mallaghan to embark on a smart manufacturing journey by de-risking major investment. Mallaghan is a leading manufacturer of ground support equipment for the aviation industry, based in Northern Ireland. Managers within the firm saw significant potential to improve efficiencies, reduce costs, and become more environmentally sustainable through the use of IDTs. However, there had been some challenges around gaining buy-in at company board level to secure the significant capital expenditure that was required. Mallaghan therefore applied to the Digital Innovation Fund to de-risk this investment. The company was successful in securing a grant of £159k, which it matched with £489k of internal investment.[64] The grant funding, alongside the comprehensive plan that was drawn up to inform the application, was sufficient to secure board-level buy in to the project and start Mallaghan's smart manufacturing journey.

Aims and objectives

The overarching aims of the project were to improve data collection to inform decision making and to introduce a digital system for process management. These changes, in turn, were expected to drive efficiency, reduce costs/improve profitability, and increase the environmental sustainability of the company. Importantly, Mallaghan was then expected to act as a 'demonstrator' for other manufacturing companies to show the types of activity undertaken and the benefits achieved through the adoption of IDTs.

Delivery

The key activities related to installing sensors and software to improve data collection and interpretation throughout the manufacturing process. The project was delivered in three parts:

- **Digitising the shop floor:** Prior to embarking on this project, Mallaghan ran a paper-based shop floor system to trace the movement of components and products through different stages of the manufacturing process. The first element of the project was to invest in a new digital system for the storage of this information. This required significant upfront investment

[64] Figures as of end of December 2024

for the hardware (PC or tablet) required by each end user alongside the software package itself ('Pulse').

- **Power tracking:** The second part of the project focused on improving data collection about energy and gas use. This involved installing sensors to consistently gather usage data in order to see when there were surges in use and how much electricity or gas was used by specific processes or equipment.
- **Metal cutting resource usage:** A significant part of Mallaghan's manufacturing processes involves cutting different types of metal for a variety of requirements (e.g. different thicknesses etc). There are multiple methods for doing this, including using lasers. However, the company did not have a strong evidence base on the cost of using lasers for this process versus other techniques. With funding from SMDH, Mallaghan invested in new sensors and software to provide data on the costs of different methods.

The primary source of support from SMDH was the grant funding. The Hub also provided introductions to other companies that had embarked on a similar journey as well as technology providers who might have been able to supply the necessary equipment. Furthermore, the Hub provided support from data scientists who helped develop dashboards to interpret the data.

Delivery of the project activities went broadly as planned. There were some initial delays associated with sourcing the equipment which meant the project timelines (as detailed in the application) had to be shifted back slightly. There were also challenges with Mallaghan's resourcing for the project due to recruitment taking longer than anticipated. Despite these minor setbacks, the project delivered all of the intended activities, enabled in part through the close relationship and frequent communication between Mallaghan's project manager and the Hub. The project lead from SMDH supported Mallaghan through the application process and provided an effective 'sounding board' during project delivery.

Key benefits

Mallaghan reported three key company-level benefits achieved through this project:

- **Data driven decision making to improve efficiency and cost management:** The activities delivered through the project provided detailed insights into production costs and processes**,** particularly on electricity and gas usage and the time required for particular processes. This enabled data-driven decisions that have resulted in cost savings and more efficient operations.
- **Improved environmental sustainability:** By reducing electricity and gas usage, the firm has been able to achieve enhanced environmental sustainability. The company is currently working towards achieving the ISO 1401 environmental standard, and this project is a key part of the process. However, the firm was not able to provide quantitative estimates of the energy or CO_2 savings to date.

- **Enhanced traceability:** The implementation of a digital shop floor system has improved the traceability of components and reduced manual data entry errors.

These benefits are expected to improve the productivity and resilience of the company as well as potentially support future growth.

There have also been benefits for the wider manufacturing sector, particularly in terms of improved awareness of the opportunities for, and benefits from, IDT adoption. Mallaghan has acted as a demonstrator for industrial digitisation, seeking to be "*an open door for all companies".* The firm has worked with MEGA, an industry-led collaborative local network, to promote the project. This includes scheduled on-site visits with members of the network. Moreover, Mallaghan is working closely with its supply chain to encourage adoption of IDTs. For example, Mallaghan is seeking to integrate suppliers into its digital system for data collection and storage at different stages of the manufacturing process. Finally, the project also contributed to SMDH's database. Using the dataset from Mallaghan, and combined with data from other companies, SMDH has started looking at benchmarking of different processes. This data can be used to inform decision making at other businesses engaged with SMDH.

For Mallaghan, the benefits achieved are considered to be partially additional. Without the funding and support from SMDH, Mallaghan would have progressed with smaller versions of each strand of activity at a slower pace. Overall, it would have taken 3-4 years longer to achieve a similar scale of benefits. SMDH was the critical factor required to achieve benefits because the funding was essential for securing board-level buy in. Other factors that were also important included apprentice resource at Mallaghan, the availability of sensor technology from a supplier, and the strong communication between the firm and SMDH.

Learning

In terms of key learning, from the Hub's perspective getting businesses interested in a grant with a 3:1 funding ratio was challenging: "*it is not conducive to businesses buying into this".* However, this worked with Mallaghan since there was prior interest in the planned changes and because they had successfully engaged with similar programmes in the past. It is therefore important for the Hub to engage with businesses that are open to change, as well as working to promote the potential benefits to a wider group of businesses.

From the firm's perspective the key learning was around ensuring projects are adequately resourced internally. As mentioned above, Mallaghan had some issues around recruiting resource to deliver the project. It was able to absorb the additional workload without this resource but flagged that other SMEs may not be able to.

Future prospects

At the time of fieldwork, only two months had passed since the project had completed. As a result, the firm had not yet been able to capture sufficient data to make significant changes or investments. It was expected that most of the benefits in terms of improving productivity, profitability, and environmental sustainability are yet to be achieved. A greater impact is expected once the company has at least six months of data on which to base business decisions. The extent of these benefits will depend on wider market conditions including demand for air travel, as well as the local labour market, since obtaining the right skills has been a significant issue for Mallaghan in the past.

In the meantime, Mallaghan will continue to engage with businesses in the MEGA network, its supply chain, and more widely, generating further benefits by raising awareness which in turn may lead to greater adoption of IDTs.

Case study: Adey Steel

This case study focuses on a project delivered by InterAct in partnership with Adey Steel, as part of the Made Smarter Innovation programme. InterAct has funded over 50 activities and this case study provides one illustrative example of the type of project supported. It draws on evidence from two consultations, one with InterAct's co-director and another with a representative from the partner company.

Overview

The aim of the project was to explore options for future business models and the role of enabling industrial digital technologies (IDT) for Adey Steel, one of the UK's leading specialist steel fabricators. The project originated from several other strands of work that InterAct had been involved in including: the Future of Digital Manufacturing Ecosystem (FODME) project, which was about developing a methodology for scenario analysis to inform business planning using an approach called back-casting; sharing the knowledge from FODME to SMEs through a Made Smarter Adoption training programme; and a series of 'case studies' exploring the capabilities SMEs need to adopt different technologies. Following Adey Steel's participation in one of these 'case studies', InterAct, in collaboration with Circular Metals, and Adey Steel worked together on a project (which is the focus of this case study) to develop a business model based on circular economy principles, drawing on methods developed in the FODME project.

Delivery

The project started in April 2024 and was delivered in several phases:

- **Scoping:** The initial activity was a scoping meeting between Adey Steel, InterAct and Circular Metals. The purpose of this was three-fold: to improve understanding of Adey Steel's business processes and context; to identify and map the firm's current supply chain; to identify products which might be suitable for transition to a circular model; and to explore options for IDTs which could support a future business model.
- **Phase 1 - Envisaging long-term circular business model:** The next stage involved an in-person workshop with representatives from Adey Steel (including the operations director, procurement representatives etc), InterAct and Circular Metals. The project partners decided to focus the work on smart motorway gantries, one of Adey Steel's products. The workshop used tools developed through InterAct and Circular Metal's previous research to explore options for a future business model for gantries, and how IDTs could be adopted to support this.
- **Phase 2 – Explore implications:** This stage involved InterAct and Circular Metals conducting a series of interviews with Adey Steel to explore the implications of the proposed changes to the business model for the supply chain and product design.
- **Phase 3 – Review:** The final stage involved a workshop to validate the findings and summarise the lessons learned.

The project activities were all delivered as planned. The successful delivery of the project was enabled by the academic expertise brought by InterAct and Circular Metals and the senior input from Adey Steel.

Key benefits

Adey Steel confirmed that they are not likely to adopt the circular business model for gantry production at this stage primarily because it would involve a significant diversification from their current model and require substantial upfront investment. However, the plan may be adopted within the next 5-10 years, depending on a number of factors including: government policy on transport infrastructure; Adey Steel's ability to secure investment to expand the site; and whether National Highways would be supportive of the model (which would involve leasing rather than buying gantries). Productivity and environmental sustainability benefits would be expected to follow adoption.

There have been important benefits for Adey Steel even in the absence of implementation of the business model, such as strengthening the relationship with both Loughborough and Brunel universities. Since the project completed, Adey Steel has sustained engagement with the universities (e.g. it has been in contact with Loughborough to take on a placement student). The project has also generated positive publicity for Adey Steel through demonstrating that they are actively thinking about ways to become more sustainable. One of Adey Steel's key clients, National Highways, which is increasing its focus on sustainability through procurement, took part in the Phase 1 workshop.

One of the key outputs from the project, building on prior research, has been the development of resources by InterAct for businesses. This includes a six-step guide on how businesses can develop alternative business models. The plan is to develop the guide further into an executive education programme at Loughborough. InterAct has also developed an online tool about supply chain design principles and product design principles for companies. To develop these tools, InterAct has drawn on its 'Actionable Insight Fund', which allows it to take project findings and translate them into formats that are useful for industry.

The benefits outlined above would not have been achieved without InterAct. This is in part because InterAct delivered the prior work that this project built on and had the connections to bring together the necessary partners and expertise. Adey Steel also reported that this kind of 'blue sky thinking' would not have occurred without the academic input. As a result, MSI was considered to be the critical contributory factor to the benefits achieved.

Learning

In terms of key learning, consultees mentioned the following points:

- The nature of InterAct, as a Network+, allowed for **successful connections between different programmes and partners**. This ensured that work undertaken by different organisations (e.g. InterAct and Circular Metals) did not happen in a silo and different outputs could be fed into this project.

- Ensuring **senior level buy-in** to the project was essential from an Adey Steel perspective, along with dedicating sufficient resource internally.
- The project highlighted that **supply chain design is an important component of transitioning to more circular business models.** This needs to be a consideration at the start of the process of designing alternative models.

Future prospects

As highlighted above, Adey Steel may consider transitioning to the new business model for smart motorway gantries in the future (5-10 years). However, the likelihood of this is dependent on a number of external factors such as the government's transport infrastructure policy (particularly in relation to smart motorways) and National Highway's willingness to transition to a lease system. If implemented, the new business model would improve Adey Steel's environmental sustainability and may contribute to business growth. More widely, the tools developed by InterAct (including the six-step guide) will help other businesses to consider and plan alternative business models and improve understanding of manufacturing processes/challenges to consider in relation to sustainable business models.

Case study: Human Robot Collaboration

Overview

The 'Collaborative human robot crop collection' project researched Human-Robot collaboration in the collection of grapes in a vineyard. The project was led by Professor Anja Maier (PI) and Professor Jörn Mehnen (Co-I), both at the University of Strathclyde, involved researchers at seven universities and the 'UK-Agritech Centre' ('Agri-EPI' at the time of the project). The project was part of a wider body of research undertaken by the Smart Cobotics Research Centre on the rapid design, validation and deployment of a smart Human-Robot collaboration (HRC) system.

Typically, engineered systems are not designed with humans in mind – the technology is designed first, and the issue of how to fit a human around the technology is considered later. This project instead aimed to reverse the order - starting with the human and developing technology around that.

Aims and objectives

The project focused on grapes because the degree of collaboration between humans and robots would be higher on a vineyard than other types of farms and, compared to other soft fruits, there has been comparatively little research into grapes. The project was conducted at a vineyard in Oxfordshire for which a large amount of data was already available, due to previous research.

The development of this IDT is early stage (low TRL). As such, the project focussed on the fundamental research behind the IDT, instead of developing or deploying a previously developed technology.

Delivery

Using previously collected data, a digital twin of the vineyard was built in the Nvidia's Omniverse platform. The rules for the robots operating at the vineyard were built based on this digital twin, in particular, a rule was made that vines were barriers and the robot was prohibited from crashing into them. Human detection was included in the model, so robots can sense and be directed by humans, i.e. by a human pointing.

Related research was undertaken by the same team on:

- Understanding 'Opto-tactile sensing' for the harvesting of soft fruit, where camera detection of deformation in the fruit indicates whether too much force is being applied.
- Using cameras to understand the mood and mental workload of employees through their behaviour. This information could then be fed into a robot which can respond appropriately.
- Creation of a digital twin of a factory to simulate drone flight in an enclosed environment, such that drones can ultimately be used to identify defects in manufactured goods.

The main hindrance to the project was slow engagement from Agri-EPI, which was likely a consequence of the consolidation into the UK Agritech Centre. However, Agri-EPI were not very involved because the Technology Readiness Level (TRL) of this IDT was lower than they are able to support.

Key benefits

This project generated a digital twin that can be used on this vineyard. In the long-term, the digital twin can be used in conjunction with robots to improve the productivity of harvesting the grapes. More significantly, the learning about how the digital twin was developed can be rolled out to other vineyards, both at an industrial scale and a small farmer scale. Where harvesting of soft fruit is labour-intensive, in conjunction with robots, there is potential to improve productivity, and reduce waste.

The demonstration of the digital twin is a key step to realising the potential productivity and labour benefits of this IDT. As a result of this project, the team secured further funding to work with a group of Scottish tea farms to trial the use of a robot to test the soil quality, and to remove loose leaves on the ground. There is a possibility of further work with the vineyard via a Knowledge Transfer Partnership or similar scheme. Through both the secured project, and the potential future project, the IDT will continue to be developed, pushing it up the TRLs towards commercialisation.

A key outcome for this project was the production of academic papers: each of the projects referenced have produced, or plan to produce, a journal article or conference paper. This will strengthen the credibility of the work. Other outcomes have included the dissemination of skills developed through this project through researchers on this project securing new positions at academic institutions. Externally the value of this research for industry has been validated through the shortlisting of the DMEM (Design, Manufacturing and Engineering Management) team for the CeeD (Centre for Engineering, Education and Development) 'Knowledge Exchange Excellence Finalists' award, alongside BAE systems.

The impact upon the agricultural sector at this stage is limited given the low TRL of this IDT. Ultimately, adoption of this or similar technologies within farming would support upskilling of agricultural staff, raising their wages, and a reduction in labour requirements. Potential additional benefits included better yield estimation through analysis of soil quality, and increased disease protection of crops, through automated detection of diseased plants.

Role of MSI

Given the low TRL of this technology, it is likely that the additionality of this project was high. In the absence of this project and the associated funding, it is unlikely research relating to this IDT would have been undertaken because industry partners tend to fund industrial research of higher TRL technologies, where a ROI can more easily be demonstrated.

Case study: Omnifactory®

Overview

Omnifactory® is a key part of the Made Smarter Innovation Research Centre for Connected Factories (MSIRCCF), which was led by the University of Nottingham, and jointly delivered with the University of Sheffield, the Advanced Manufacturing Research Centre (AMRC) and the University of Cambridge. The overarching focus of the Research Centre was on factories of the future and the technologies to enable manufacturers to respond to changing market requirements by being resilient, adaptable and reconfigurable. Each partner utilised its expertise on a range of different research themes and application studies. The University of Nottingham's application studies focused on the Automated Assembly of Aerostructures, and Industrial Cyber Security and Multi-Site Connectivity using the Omnifactory® as a demonstrator and testbed.

Omnifactory® is a facility with a footprint of 444m^2 containing commercially available hardware e.g. robots, automation equipment, sensors, etc., and software with underpinning connected digital architecture, located on site at the University of Nottingham. It is a national demonstrator and testbed. The architecture and hardware of the Omnifactory® built on a previous government supported project, FA3D2 (Future Automated Aircraft Assembly Demonstrator Phase 2) which was initially funded in 2018. The project was supported by Airbus, BAE Systems, FANUC, Siemens and others, who provided industrial needs, hardware, software and training. The facility has been operating as Omnifactory® since March 2023.

Aims and objectives

The low volume, high complexity, unique nature of the products being manufactured (e.g. fighter jets) in the aerospace sector means that they are unsuitable for conventional manufacturing production lines where the same process is repeated many times. Some aerospace items need to be manufactured using certain industrial machinery whilst others do not. As a result, significant capital expenditure is wasted on machines that are not in operation and on the large manufacturing footprint is needed to store them all, even if they are infrequently used. By adopting adaptable manufacturing techniques, space and time can be used more efficiently, saving expenditure.

Through undertaking research and engaging with industry partners, the objective of the Connected Factories Research Centre was to share best practice on digitally enabled manufacturing with industry, thereby improving the uptake of techniques and systems to improve efficiencies and resource utilisation within the aerospace manufacturing sector. The rationale for the role of Omnifactory® in the Connected Factories Research Centre was that, as a national test-bed for digitally enabled manufacturing, Omnifactory® had the infrastructure available for research projects and demonstrations.

Delivery

The MSIRCCF project oversaw the completion of research and demonstration both in the physical space of the Omnifactory®, as well as theoretically and digitally. The main activities undertaken as part of the MSIRCCF project included a range of projects, such as:

- Understanding how to integrate metrology (measurement) systems into a flexible factory environment, including which systems should be used and where should they be utilised for the greatest impact. There was a particular focus on low-cost, off-the-shelf solutions such as imaging cameras to achieve the accuracy desired by industrial use cases, when compared to higher cost metrology systems. Better use of metrology systems and their digital integration with manufacturing systems reduce the time required for employees to make measurements manually and maintains data integrity when stored and used digitally.
- The 'High Fidelity Digital Twin', which explored how to use metrology systems within a factory environment to improve the accuracy of a digital twin (i.e. how close the digital twin is to its physical counterpart), thus improving the reliability of simulations within that digital twin. As part of this, researchers walked around the Omnifactory® with a smartphone camera, taking measurements that were fed into the digital twin to refine the model. A more accurate digital twin will reduce the amount of real-world experimentation required, and hence reduce the time and materials involved in testing.
- Research into the automatic generation of PLC (programmable logic controller) code. In a flexible factory, the PLC integrates all technologies and is responsible for orchestrating the manufacturing processes. The project examined how to use AI and Machine Learning to generate PLC code more quickly with the potential for greater reconfigurability of the factory space.
- Research into smart factory layout optimisation to improve business competitiveness by being better able to scale dynamically to mitigate demand or product variation compared to traditional fixed production layouts. Although a flexible factory can help with this, additional challenges emerge when trying to optimise for assembly zone areas, production assets and time. Quantifying the trade-offs inherent in build philosophy and choice of process technology is also a significant challenge to modern industry.

Research was also undertaken to understand the skills that would be required for businesses to adopt the outputs generated and demonstrated by the MSIRCCF project. Businesses that possess these skills will be better placed to take advantage of the opportunities offered by flexible factory systems and thus gain potential productivity benefits. The MSIRCCF project created solutions for industry which removed barriers to technology adoption and addressed the skills gap in the manufacturing sector.

The MSIRCCF project was supported through industry engagement. The 'research themes' and 'application studies' were informed by potential use cases detailed by an Industrial Advisory Board (IAB) comprising major manufacturing firms, including Airbus, BAE systems, Rolls Royce and others. The IAB had wide representation, including OEMs, SMEs, businesses in the supply chain and stakeholders.

A key factor that helped the delivery of the MSIRCCF project was the open and engaged nature of the team, with regular meetings between the team and the project board to share ideas and strategic direction for the project. The project team listened to the board's feedback and actioned related changes. This kept the project grounded in the needs of industry and the challenges where they need solutions. The project also sought feedback from wider businesses of a range of sizes and types. The academics involved were adept at understanding the value propositions for both industry and academia, allowing for better conversations and for the project to maintain grounded in the realities of both industry and academia.

A major delivery challenge was developing the data infrastructure for the different manufacturing robots to communicate with one another. For example, integrating a number of AGVs (Automated Guided Vehicles) with industrial machinery required a high level of precision and accuracy: the connection between machines had to be seamless. It was also challenging to upskill the staff to use Omnifactory® facility effectively. It took time to understand what skills were needed, what training was needed and whether each piece of training would deliver value.

Key benefits

The MSIRCCF project has created 33 'technology solutions' (against a target of 15). These are physical and/or digital demonstrations of the technologies, some of which are outlined above (3D digital twin layout, automatic PLC code generation). Most of these systems are around TRL 2-5, and one is at TRL 6.

One of the most important outcomes of MSIRCCF project is its ability to inspire further projects through knowledge exchange. The focus on engagement has meant that a number of businesses have taken ideas from the MSIRCCF project and advanced them in their own business, either with the support of the MSIRCCF project team or on their own. Examples of such projects include:

- Working with an aerospace company to optimise the flow of manufactured goods in the most cost-effective manner.
- Working with an aerospace/defence company to develop and deploy a flexible manufacturing system to create low cost, multiproduct manufacturing (with links to an ATI (Aerospace Technology Institute) project, ELCAT).

Beyond these examples, all of the companies on Industrial Advisory Board of the MSIRCCF project have used the project as a reference point for their own activities. Whilst the University of Nottingham's elements of the project focussed on aerospace manufacturing, the lessons learnt through the project (e.g. increasing the accuracy of digital twins) have applications in all manufacturing sub-sectors.

MSIRCCF has produced, in effect, a menu from which businesses can pick and choose the relevant technology solutions for themselves, with most manufacturers likely to find a relevant application within their organisation.

This open innovation model means potential productivity benefits are open to everyone. In closed innovation, businesses run the risk of duplicating research undertaken elsewhere. Open innovation therefore creates the opportunity to raise the aggregate productivity level of manufacturing in the UK, increasing international competitiveness.

Role of MSI

In the absence of MSI, it is likely that none of the benefits would have been achieved. First, funding would not have been available to undertake this research and thus none of the learning would have been generated. Second, as a publicly funded project with a deliberate focus on knowledge exchange, the knowledge developed has been shared more widely than if a business or other organisation had undertaken this research themselves. It is this knowledge sharing that has led to most of the current and anticipated future benefits.

Learning

Key learning from the project related to the benefits of undertaking an industrial research scheme on this scale with close involvement from industry. The willingness of industry to invest sufficient resources and time into the project was crucial to generating the achieved success.

Future prospects

It is anticipated that the activities of the MSIRCCF project will continue to grow through alternative EPSRC and private industrial funding, which has not yet been secured. One industry partner consulted was keen to see further investment into the Omnifactory® by their business, as well as an expansion of the MSIRCCF project to consider industries beyond aerospace (for example automotive) and more of a focus on engagement with SMEs.

Case study: Platform 2 'Self-Driving Tableting DataFactory'

Overview

The Digital Medicines Manufacturing ('DM^2') Research Centre received £5m funding from the MSI programme. It was led by the University of Strathclyde, specifically CMAC, a medicines manufacturing research centre. DM^2 also involved close collaboration with the Universities of Cambridge and Loughborough, and industry partners. DM^2 delivered activities under five platforms aimed at developing and accelerating the adoption of industrial digital technologies (IDTs) in the pharmaceutical sector.

This case study focuses on Platform 2 of DM^2 which delivered the 'Self-Driving Tableting DataFactory'. The Tableting DataFactory is an autonomous microscale development, manufacturing and testing facility to make and test individual pharmaceutical tablets. The case study also highlights the linkages between Platform 2 and activity delivered by the other DM^2 Platforms.

This case study has been informed by interviews with two individuals at Strathclyde University - the academic lead for Platform 2 who is an Associate Director of CMAC and a Senior Research Fellow in Modelling and Simulation.

Aims and objectives

The overall aim of the Self-Driving Tableting DataFactory was to accelerate the development of pharmaceutical products using industrial digital technologies (IDTs).

Bringing new pharmaceutical products to market as quickly and efficiently as possible is a core focus for pharmaceutical companies. Currently, the development of pharmaceutical products relies on a 'trial and error' approach to design the formulation of a drug and achieve the required criteria (e.g. dissolution, stability, shelf-life etc.). This approach is experimentally driven, which is time and resource intensive. Also, the process is completed sequentially, so the formulation is developed first (i.e. combination of the active pharmaceutical ingredient(s) and other materials), then its performance is tested, and so on. If an issue arises during the process, these steps must be repeated.

Delivery

The delivery of the Tableting DataFactory was led by the Associate Director of CMAC and supported by two post-docs who were each responsible for a specific element of the work (modelling and automation/robotics). The process also involved engagement with a range of industry partners – from equipment suppliers to global pharmaceutical companies - who contributed through providing materials, devices and scientific contributions.

Development of the Tableting DataFactory included two main strands of activity:

- **Modelling** – the creation of various data-driven models that can select and optimise tablet formulations.
- **Robotics** – utilisation of two robotic arms to automate manual tasks, focusing on transport of powder and tablets between various powder preparation, tablet compaction, testing and storage stations. The entire Tableting DataFactory including the robotic arm, dosing, NIR spectrometer, balance, compaction, hardness tester, sessile drop testing, storage. The AI-aspect makes the automated Tableting DataFactory a self-driving Tableting DataFactory.

Throughout project delivery, the team have also delivered a suite of other demonstrators[65], which have attracted the attention from representatives from industry, regulatory bodies, and political parties. Furthermore, it is important to acknowledge the activities delivered under Platform 2 align with, and complement, other Platforms delivered by the Research Centre. For example, Platform 4 provides information from the supply chain to develop a new product, and the formulation of this product is then developed under Platform 2. Similarly, activity under Platform 1 has focused on building trusted and structured datasets, which Platform 2 can draw on and vice versa.

The skillsets of the individuals at DM² were key in the effective delivery of Platform 2. The Platform 2 lead is very experienced in the pharma sector, but the two post-docs came from different backgrounds bringing transferrable skills and knowledge from other sectors such as petroleum and electric engineering. The focus on demonstrators supported strong industry engagement by providing regular opportunities to show industry partners the outputs being delivered. It also ensured the team remained focused on delivering Platform 2 activities.

There were several challenges although these did not have a material impact on the progress or outputs of the project:

- First, at the start of the project, the existing literature provided limited information on models for predicting the properties of a tablet based on raw materials. Only two of the eight models developed were included in the existing literature.
- Second, integrating the digital equipment was challenging. Most of the devices that constitute the Tableting DataFactory already existed. However, because there were supplied by different companies, compatibility had not been considered, so the process of integrating the devices was complex and time consuming.

Key benefits

Platform 2 has delivered against its original objectives. As set out above, the main output is the table-sized Tableting DataFactory which rapidly generates large, structured data, turning it into actionable insights for pharmaceutical manufacturing that allows rapid tablet development.

[65] Demonstrators are showcases of the technology under development.

The following outcomes have been realised:

- **Technology progression**: the Tableting DataFactory allows rapid tablet development, reducing manufacturing times from months to less than a day and using minimal materials, reducing waste by 60% and costs by 50%.
- **Increased understanding and awareness of IDT use, application and benefits**: from an academic perspective, the project has supported increased understanding of the integration and standardisation of data and the effective deployment of IDTs (including the skills required to do this).
- **Additional investment in IDT solutions**:
  - A PhD will undertake further research into the Tableting DataFactory, specifically focused on dissolution and stability as a property of tablets (which has not previously been explored).
  - Since investing in the first robotic arm, CMAC has invested in an additional 11 robotic arms.
  - Whilst not directly attributable to this project, CMAC has secured additional research funding which will be used to advance some aspects of the Tableting DataFactory (see below).

The Tableting DataFactory has not led to any wider outcomes or impacts on the UK manufacturing sector to date. However, the concepts and technologies applied to the Tableting DataFactory could be transferred to other sectors such as food and battery manufacturing.

Role of MSI

In the absence of the funding from MSI, the benefits may have been achieved but would have taken longer to achieve, been on a smaller scale, and been of lower quality. From an academic perspective, there were no other funding calls at the time the MSI funding was secured which could have funded this project. It may have been possible to progress the Tableting DataFactory through smaller, more targeted funding calls. However, progress would have been considerably slower so the benefits would not have been delivered in the same timescale. If this project had been led by a pharmaceuticals company, it would have been very challenging to engage all the technology developers and manufacturers as effectively as DM², which has been key to the success of the project.

The MSI programme was seen as an important contributory factor alongside other in delivering the benefits set out above. Other factors deemed important were:

- The infrastructure/equipment for the Tableting DataFactory was not funded by MSI, therefore partner contributions and other funding sources have been crucial. This included a £2.5m grant from Research England for net zero technologies, which contributed to purchasing the robotics/sensors.

- DM² is part of CMAC so has been able to leverage CMAC's existing relationships with industry and its administrative/support teams (e.g. finance, industry, and national facility teams).

Learning

There are two key learnings from this project. First, the importance of early engagement with industry. From the outset, DM² involved industry partners in Platform 2 and the focus and scope of the project was co-created with industry. For example, industry demand informed the decision to focus on oral solid dosage forms. Having sufficient time and resource to engage industry effectively was important here. Second, the value of a multi-disciplinary research team. The Platform 2 team came from a range of backgrounds – many not from pharmaceuticals – bringing transferable and complementary skills that contributed to the effective delivery of the project.

Future prospects

There is the potential to develop the Tableting DataFactory further in future. For example, the conversion of the manufacturing facility for capsule use (rather than a tablet) could be progressed. Whilst the first phase of the work focused on the manufacturability of a tablet, there are other aspects to consider such as performance and stability, so the team hope to secure additional funding to conduct this research. CMAC secured EPSRC funding for the MediForge Hub (commencing in October 2024) to integrate the Tableting DataFactory with other CMAC DataFactory to create a cyber-physical research infrastructure capable of tackling key challenges in the development of new drug products. The Tableting DataFactory will be integrated within this Hub, and some aspects advanced, albeit there will be less focus on this area of work.

In terms of commercialisation there has been strong interest in the Tableting DataFactory from industry. CMAC is exploring commercialisation routes, for example through industry paying a fee for service projects or license fee or the creation of a spin-out.

Case study: Hot Strip Mill

Overview

The Materials Made Smarter ('MMSC') Research Centre received £5m funding from the MSI programme. It was led by the University of Sheffield, in collaboration with the Universities of Cambridge, Brunel, Nottingham, Swansea and UCL. The MMSC Research Centre delivered a range of activities focused on making digital technologies accessible to the UK's materials intensive manufacturing industries.

This case study reports on work carried out under pilot line 1 – digital metallurgy – which was led by Swansea University. In particular, it focuses on a collaborative research project between MMSC, the SUSTAIN Future Manufacturing Hub[66] and Tata Steel that sought to deliver greater insights into the cooling profile and transition point of the steel strips in the Hot Strip Mill to inform improvements to the physical control system (via improvements to the existing simulation model).

This case study has been informed by interviews with the co-Director of the MMSC Research Centre and a representative from Tata Steel.

Aims and objectives

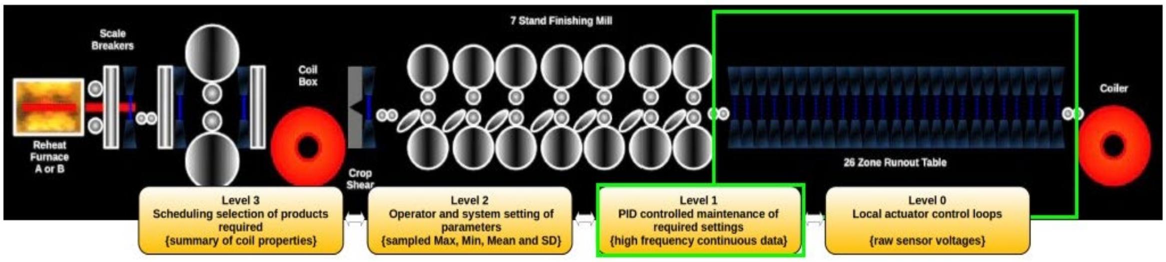
The focus of the project was on the Hot Strip Mill – a steel strip rolling mill - at Tata Steel, Port Talbot. This is where a steel slab is taken and reheated to 1,200 degrees Celsius, rolled to the required thickness, and then rolled into a coil. Before coiling, the strip is cooled on the run-out table to a product-specific profile. The profile and final coiling temperature were the focus of the project. Achieving the correct temperature is crucial in achieving the desired mechanical properties of the finished steel strip and avoiding rejections or re-working strips.

Tata Steel has a simulation process control model (rather than the physical model which controls the mill) that is used to simulate the inputs in the plant (e.g. temperatures, speeds, water flows) and calculate the resultant temperature and phase transformation of the strip. This offline model is used to tune the settings for the online process control model. There was scope to improve the tuning of the model, which was quite manual in nature. Prior to the project, Tata Steel had committed to investing in a set of electromagnetic sensors for the mill to detect the degree of phase transformation at four places, with the intention of utilising the sensors to refine their process control model.

In this context, the overall aim of the project was to explore the use of Artificial Intelligence (AI) to improve the existing online model at predicting transformation and temperature in order to reduce rejections and reworks in Tata Steel's Hot Strip Mill.

[66] For more information see here: SUSTAIN Steel - EPSRC Future Steel Manufacturing Research Hub

Figure L-1: Diagram of a Hot Strip Mill



Source: Swansea University

Delivery

The project involved inputs from Swansea University as part of the MMSC Research Centre – including the co-Director of the Research Centre and a PhD student sponsored by Tata Steel – and Tata Steel. There were two aspects to the project. The first was to develop a data-driven machine learning prediction of the two-phase cooling to final coiling temperature to inform understanding of the cooling process. While the second was to design and build an AI-driven optimisation of the existing control system, specifically a 'Particle Swarm Optimisation' algorithm was deployed.[67] The algorithm was informed by actual data from Tata's Hot Strip Mill, including data from four new electromagnetic sensors. The algorithm was tested first on the University's system before sharing with Tata Steel to test it on their own system.

Effective partnership working between Swansea University and Tata Steel was key in enabling the successful delivery of the project. The project built on a well-established relationship between the University and Tata Steel, which was important in enabling effective project delivery and ensuring that outputs were aligned with industry needs.

There were a number of challenges although these did not have a material impact on the progress or outputs of the project. The main challenges related to data, notably the time required to quality assure the data from industry to ensure it was robust. There were also some delays obtaining data from the sensors in the Hot Strip Mill because the sensors took longer to install then anticipated due to supplier related issues.

Key benefits

The project delivered against its original objective. The main output was an algorithm which has helped Tata Steel to identify the optimum parameters for their simulation model allowing them to more accurately predict cooling and final coiling temperatures.

The following key outcomes have been realised:

[67] Particle Swarm Optimization (PSO) is a computational method used to find the optimal solution to a problem. It is based on the idea of simulating the social behaviour of a group of birds or insects, known as a swarm, searching for food.

- **Increased understanding and awareness of Industrial Digital Technologies (IDT) use, application and benefits**: from an academic perspective, the project has supported increased understanding of the considerations when deploying technologies such as machine learning in industry, particularly the need to take a people-centred approach to support adoption.
- **Efficiency benefits:** by using the optimisation algorithm, the time taken to determine the optimised parameters for the process model has reduced from six months to a week per product type.
- **Adoption of IDT solutions:** transferring the results from the simulation model to the physical model takes time. However, some product types are already being produced using the optimised parameters from the machine learning algorithm. As a result, Tata Steel has already seen a reduction in the level of rejections and reworks on these product types, including a reduction in Non-Right First Time of 86% for a particular product type.

Role of MSI

In the absence of the support from MSI, the benefits would still have been achieved but would have taken longer to achieve. Prior to the project, Tata Steel had some sensor data and a simulation model. However, optimising the parameters for each product type took six months (based on the iterative process of tweaking the model and then trialling on a few bars of metal). This has been reduced to one week per product by using the model created by the MMSC Research Centre.

MSI was seen as an important contributory factor alongside others in delivering the benefits set out above. Other factors which were also important were:

- Prior to the project commencing, Tata Steel committed to investing in state-of-the-art electromagnetic sensors with the aim of optimising processes to recoup the investment.
- The simulation model was created prior to the project and required the expertise of Tata Steel staff. It also required substantial modifications by Tata Steel to enable the project to go ahead.
- The project built on existing collaborations between Swansea University and Tata Steel. Leveraging these established collaborations enabled project resources to be utilised effectively to deliver the intended outputs.
- Complementary activities including the data driven innovation theme of the Future Manufacturing Research Hub supported cross-fertilisation of ideas and knowledge sharing.[68]

Future prospects

Tata Steel intend to use the model to support with the optimisation of every product type produced in their Hot Strip Mill. There is also scope to develop the approach further: this project

[68] For more information see here: SUSTAIN Steel - EPSRC Future Steel Manufacturing Research Hub

focused on determining how best to 'turn the dials' on the model but the model itself could be improved to more accurately reflect each product type.

There is potential to apply a similar approach to other models within the business. Tata Steel have process control models to control all of their processes so the concept of building a simulation model and using an AI-driven algorithm to optimise process parameters is transferable to other processes.

More broadly, the project demonstrates how AI can be used to achieve process improvements in the steel industry and therefore could stimulate interest in and/or adoption of these technologies in other industries/sectors.

Case study: The use of legitimacy to inform decision-making in digitalisation

Overview

The Centre for People-Led Digitalisation (P-LD) received £5m funding from the MSI programme. It was led by the University of Bath, in collaboration with the Universities of Loughborough and Nottingham. The overall aim of the Research Centre was to create a person-led approach to make manufacturing more efficient, resilient, and robust in the uptake of digital technologies.

This case study examines the 'Use of legitimacy to inform decision-making in digitalisation' project delivered by P-LD in collaboration with Rolls-Royce. The project involved Rolls-Royce trialling a deck of legitimacy cards designed to be used in a workshop setting to support decision-making regarding technology adoption.

The case study has been informed by interviews with a Knowledge Transfer Officer at the University of Bath and a representative from Rolls-Royce, plus a review of online material on the P-LD website.

Aims and objectives

Legitimacy can be defined as "*a generalised perception or assumption that the actions of an entity are desirable, proper, or appropriate within some socially constructed system of norms, values, beliefs, and definitions*"[69]. Analysis by Mark Suchman, identifies there are three 'primary forms' of legitimacy:

- pragmatic, based on audience self-interest
- moral, based on normative approval
- cognitive, based on comprehensibility and taken-for-grantedness[70].

The purpose of the project was to explore the concept of legitimacy in relation to the implementation of (novel) digital technologies in industry settings, with the aim of supporting organisations' decisions on which technologies to adopt and how to implement them effectively.

Rolls-Royce is a large company so there are lots of different ideas and opportunities regarding digitalisation to pursue at any given time. Choosing which to pursue therefore requires effective decision-making processes. Therefore, the primary rationale for Rolls-Royce's involvement in the project was to explore the potential role of the legitimacy cards in decision-making processes.

[69] Suchman, M.C., 1995. Managing legitimacy: Strategic and institutional approaches. Academy of management review, 20(3), pp.571–610.
[70] Ibid

Delivery

The project involved inputs from several individuals within P-LD at the University of Bath. The discussion cards were originally produced by Dr Will Brown and then refined by Dr Emily Carey. Prior to testing with industry, the cards were trialled by students at the University of Bath and some of the language was amended to improve accessibility based on student feedback. Each card included a question about technology adoption informed by the concept of legitimacy (for example, in which ways could this approach benefit or harm the organisation?) and encouraged the exploration of both positive and negative aspects during discussions. There were also cards introducing the concept of legitimacy, a set-up guide and instructions.

Rolls-Royce became aware of the legitimacy cards during an event in February 2024 in Birmingham which showcased various outputs from P-LD. A workshop was subsequently held as part of an event at the University of Loughborough at which Rolls-Royce tested the cards and expressed interest in trialling them internally. This workshop was delivered by the Knowledge Transfer Officer.

A sample set of (18) cards were provided to Rolls-Royce so the use of the cards could be tested in an industry setting without a researcher. Rolls-Royce tested the cards in three workshops (either online or in-person) with employees. After the workshop, employees were asked to complete feedback forms covering reflections on the design of the cards, whether they are usable and practical and any suggested improvements: 15 employees completed the feedback forms.

Two factors helped in delivering the project:

- The interdisciplinary approach to designing the cards. The cards were designed by an academic with a sociology background and further developed by an academic with an engineering background.
- Effective engagement between P-LD and Rolls-Royce. P-LD was supportive throughout, and Rolls Royce was responsive and committed to the project.

No challenges were identified apart from further trialling being requested to ensure the language use on the cards is 'industry' focussed. It was noted that extending the trial of the cards by delivering more workshops may have been beneficial because feedback from employees often focused on how the sessions were run rather than the contents or usefulness of the cards. Therefore, it would have been helpful to explore if, and how, feedback changed as Rolls-Royce became more familiar with delivering the workshops, and any more substantive insights on the contents of the cards.

Key benefits

The project delivered against its original objective to explore the use of legitimacy with industry to inform decision-making in digitalisation. The feedback from Rolls-Royce was positive overall (in terms of usefulness/practicalities etc.) and will be used to inform the design of a final set of cards, after the cards are trialled with other industry partners (see below).

To date the project has supported the following benefits:

- Insight into the role of people in innovation and implementation of digital solutions: the project has increased awareness within Rolls-Royce of the concept of legitimacy. This concept was new to the team and is considered helpful in encouraging richer discussions regarding the potential implementation of digital technologies.
- Networking benefits: Rolls-Royce's engagement with universities tends to be focused on engineering. Engaging with P-LD through this project has been beneficial in exploring how the business could engage with universities in a social sciences capacity (e.g. around the role of people in change/implementation of digital technologies). More broadly, Rolls-Royce's involvement in P-LD has provided networking opportunities. For example, following a P-LD event there are ongoing conversations between Rolls Royce and another industry partner regarding a potential collaboration.

The legitimacy cards have not been formally adopted by Rolls-Royce and, if they were, the cards would be used alongside existing processes. Currently, Rolls-Royce is not actively committing additional support/resources to adopting the cards. However, they remain interested in exploring the use of legitimacy and identifying other topics/areas where the cards could be used (e.g. business change).

The project has not led to any wider outcomes or impacts on the UK manufacturing sector to date. However, the cards are technology agnostic and can be used across the manufacturing sector, and indeed, across all sectors.

Role of MSI

Without the funding from MSI for P-LD, the project would not have been delivered, and therefore, the benefits would not have been realised. This is a key example of the research P-LD has delivered about the role of people in digitalisation, allowing concepts such as legitimacy to be explored. Without P-LD leading this work, Rolls-Royce would not have explored the concept of legitimacy and would instead have continued using their existing decision-making processes.

One other contributing factor was identified: the openness of Rolls-Royce employees to trialling the cards and alignment with their organisational values/behaviours. However, overall, MSI was considered the key factor in delivering the benefits outlined above.

Future prospects

The legitimacy cards are currently being trialled by several other companies. On receipt of their feedback - and considering the feedback from Rolls-Royce too - the cards will be refined and a final version developed. However, the timescale for completing this work is unknown due to the

MSI funding for P-LD ending shortly. P-LD has a one-year extension and the cards are being refined as well as investigating digitising the cards for wider uptake.

Case study: Artificial intelligence for visual inspection

This case study focuses on the 'Artificial intelligence for visual inspection' project, funded as part of the Technology Accelerator workstream within the MSI Challenge. The purpose of the case study is to illustrate how the MSI Challenge has accelerated the use of Artificial Intelligence within UK manufacturing. It is based on consultations with the two organisations involved in the project – Machine Intelligence and BAE Systems - as well as existing material available online.[71] [72]

Overview of artificial intelligence

Artificial Intelligence (AI) is a broad term that includes various applications such as machine learning, natural language processing, and advanced data analytics. AI systems can accelerate, enhance, and scale human expertise by providing deeper insights into data, making informed recommendations, and continuously learning over time. [73] In manufacturing and industry, AI can be used for predictive maintenance (e.g., forecasting when equipment and tools may need servicing), as well as optimising processes through data collected across the supply chain and production lines.

Since the technology trends work conducted as part of this evaluation in early 2022, there has been rapid development of AI systems. According to the US International Trade Administration, the UK AI market was valued at nearly £16.6bn in 2023, and is projected to expand approximately 47 times to reach £788bn by 2035.[74] But despite the well-known potential of AI, there have been challenges with technology adoption in the UK. A Manufacturing Leadership Council (2023) survey found that only around 29% of UK manufacturers have so far elevated their AI initiatives into formal corporate AI plans or strategies.[75] The main barriers to AI adoption identified were data issues (such as access, format, integration and privacy), a lack of appropriate skills, and limited understanding of the direct business benefits of investing in AI.

Aims and objectives

Delivered by the Digital Catapult, the Made Smarter Technology Accelerator (MSTA) programme was designed to connect leading UK manufacturers with pioneering technology startups to develop innovative solutions to widespread industry challenges. The programme launched in March 2021 and welcomed seven Industry Challenge Owners, each setting out manufacturing challenges which they experience. These challenges were then published, inviting innovative businesses to provide solutions for these challenges, with £100,000 awarded to produce a Minimal Viable Product (MVP).

BAE Systems partnered with Machine Intelligence (MI) - an SME which specialises in developing AI systems for image processing - to address its challenge. BAE Systems was one of the industry

[71] Machine Intelligence Case Story
[72] Made Smarter Technology Accelerator - Machine Intelligence
[73] Maier, J. (2017) Made Smarter Review
[74] US international Trade Administration (2023) United Kingdom Artificial Intelligence Market 2023
[75] Manufacturing Leadership Council (2023) The Future of Industrial AI in Manufacturing

challenge owners for the MSTA programme. Historically, BAE Systems relied on film-based X-rays to inspect components for defects. However, this method required a radiographer to manually review the results, which is time-consuming, requires a high-level of specialised knowledge, and is subject to human error. Therefore, the challenge focused on transitioning from film-based to digital X-rays, and the development of an AI solution to analyse these digital X-ray images with high accuracy. The AI would assist human inspectors by highlighting potential issues, making it easier for them to interpret the X-rays and confirm any problems. This approach aims to support and enhance the skills of radiographers and demonstrate the effective partnership between humans and AI by showcasing how they can complement each other to achieve greater productivity.

Delivery

The project was delivered in two phases. The initial three-month phase focused on understanding BAE System's requirements before testing a proof of concept. During this phase, MI and BAE Systems worked collaboratively to build a concept specification. BAE Systems then collected and shared the data required, and MI focused on software development to understand whether the desired solution was feasible. This phase also involved understanding the user, whereby MI engaged with BAE Systems' radiographers to understand their requirements and gather feedback.

Once a proof of concept had been developed, the second nine-month phase sought to translate the proof of concept to an MVP. This included iterating the system development process using lessons learned from the first phase, drawing up additional potential capabilities (e.g. components required for traceability of results), as well as conducting testing using a greater variety of components and contexts.

One of the complexities of the challenge was the limited amount of training material available. AI systems, particularly neural networks, typically require thousands of data points for refinement and testing. However, BAE Systems' aerospace manufacturing operates on a low-volume basis, making it difficult to train a neural network effectively with the relatively small amount of training data available.

Therefore, a key factor in the successful development and adoption of the technology was the chosen AI philosophy. The project used a rule-based approach to develop its AI system, leveraging computer vision principles.[76] Computer vision is a field of AI which allows computers to interpret and make decisions based on visual data. The rule-based approach offered two advantages, critical to BAE Systems' manufacturing processes:

- Enhanced transparency: The developed solution generates a computer program that can be interpreted and examined by humans to understand how the AI system arrived at its output. This contrasts with other AI systems that provide an output without revealing the steps taken

[76] Rule-based AI systems are those which use predefined rules to make decisions or solve problems based on input data. To read more, please see: [Rule-Based System in AI]

to achieve it. This transparency is particularly crucial for BAE Systems, given the stringent regulations and vigilance required in the manufacturing process.

- Ability to handle smaller data volumes: Neural network AI systems often need large datasets for accurate training, whereas rule-based systems do not and can deliver more predictable and consistent performance using smaller data volumes.

Operator engagement was also deemed essential for successful project delivery. Radiographers provided feedback on the system's usability and shared their expertise regarding the inspection process, which informed the AI system's development. This collaborative relationship not only improved the prototype but also helped radiographers understand the system's value in enhancing their work.

Both phases of the project were supported by MSI resources, which was valued by industrial partners involved. In particular, it was noted how Digital Catapult project management support helped to drive project progress, by allowing industrial partners to focus on the technical challenges of the project and providing accountability and encouragement.

Key benefits

As a result of the project, MI's technology has gone from being a proof of concept (TRL 3) to a prototype system (TRL 6) which is now being used by BAE Systems in their weld inspection processes. The technology has successfully increased the likelihood of identifying potential issues and therefore reduced the risk of product failure. It has also sped up the process for identifying potential issues by attracting radiographers' attention directly to potential issues, and in turn boosting productivity.

Since the end of the project in 2022, MI has continued to work with BAE Systems on further projects seeking to drive the use of an AI system for visual inspection, building on the prototype developed during the MSTA project. Learning from the MSTA project has also been transferable to these projects, particularly in navigating BAE Systems' internal processes, the requirements for data sharing and further opportunities for applying AI in a highly complex manufacturing context. The project has also boosted MI's credibility and contributed to additional projects being developed with other customers across the UK manufacturing sector.

Since the completion of the project, BAE Systems has continued to engage with the Digital Catapult on other Accelerator projects, including the Factory of the Future Environmental Control System Challenge as part of the Made Smarter Sustainability Accelerator[77] and the INtelligent TrustEd SuppLy ChaIn (INTELI) CR&D project (also funded by Made Smarter).[78] In combination, these projects are seen as being important to transforming BAE Systems' manufacturing processes so that it can deliver greater manufacturing flexibility, shorter lead-times, and increased productivity.

[77] Digital Catapult (2024) Eight pioneers chart a sustainable future for UK manufacturing
[78] Digital Catapult (2022) How do you build an intelligent, trusted supply chain?

Role of MSI

Without the MSI programme, it is unlikely that MI would have collaborated with BAE Systems, and that benefits associated with the collaboration would have been realised. Not only did the Technology Accelerator programme provide an opportunity for BAE Systems to publicise its industrial challenge, it also provided dedicated funding and resource to enable industrial partners to commit to the project. Moreover, the project management resources provided by the programme were felt to be important in driving the progress of the project, which may have progressed at a slower rate otherwise.

Future prospects

MI is continuing to work with BAE Systems' FalconWorks division to explore additional applications for its AI systems, as well as now working with other UK manufacturers to address the challenges they experience in visual inspection.

BAE Systems is continuing to invest in adoption of AI solutions in its manufacturing processes, building its own internal data science capabilities, and continuing to work with SMEs to drive AI development. Specifically, this project will feed into further development of BAE's Factory of the Future – a state-of-the-art facility which leverages cutting-edge technologies to revolutionise the production of military aircraft.[79]

More widely, rapid developments in AI are expected to continue. The UK Government's recent AI Opportunities Action Plan recognises how continued investment and adoption of AI is critical to driving economic growth in the UK.[80] Make UK (the UK Manufacturer's organisation) highlights the importance of AI in developing future digital factories, and the opportunities it presents for production line automation, predictive maintenance, inventory management, and quality control.[81] However, the report also identifies a number of challenges associated with adoption of AI, most significantly in system integration issues and high costs of implementation.

[79] BAE Systems (2025) Factory of the Future
[80] Department for Science, Innovation & Technology (2025) AI Opportunities Action Plan
[81] Make UK (2024) Future Factories Powered by AI

Case study: Batch.Works AI 3D Printing Factory Network

This case study focuses on the Batch.Works' AI 3D Printing Factory Network project, delivered as part of the Sustainable Factories programme. The purpose of the case study is to demonstrate how the MSI Challenge has supported development of additive manufacturing technology. It has been informed by two consultations, one with a member of Batch.Works, another with a member of Plus X Innovation, supplemented by additional information from MSI.

Overview of additive manufacturing

According to Additive Manufacturing UK (AMUK), *"AM is a method of making production parts and products directly from design data, building accurate components by adding layers of material to obtain the final shape with minimal waste and no expensive dedicated tooling. It permits radical product re-design and creates new material properties."*[82] AM is used in high value manufacturing sectors such as: aerospace; space; automotive (including motorsport); energy generation equipment; defence; rail; marine; consumer goods (sport, leisure, jewellery); general industrial products; health, pharmaceuticals, and medical equipment.

In AMUK's report, ''Additive Manufacturing UK National Strategy 2018-25", the UK AM market in 2015 was valued at \$359m (£235m), roughly 6.9% of the \$5.2bn global market value at that time. By 2022 the global market for AM was \$17bn, with the UK market valued at \$690m (£560m) or 4% of the global AM market, demonstrating the challenge of remaining internationally competitive.[83]

Since 2012, the UK's EPSRC and Innovate UK's combined investment in additive manufacturing R&D, including capital grants, has been well over £200m and the UK Research Mapping Report[84] found that research funding doubled from £15 million committed in 2012, to £30 million in 2014.

Aims and objectives

Batch.Works is a London-based manufacturer that combines 3D-printing and recycled materials to produce products for global brands like Timberland and M&S. Batch.Works applied to the Sustainable Smart Factory CR&D competition within the MSI programme for a project called 'AI 3D Printing Network Across the UK'. Batch.Works brought together an existing partner, Plus X Innovation, a workspace and innovation support provider, and a new partner, Matta Labs, an AI research spinout from the University of Cambridge. The project was intended to co-create an automated 3D printing facility using robotic control and AI to scale for local batch production, resulting in: reduction of printing fail rate; reduction of embodied carbon in products; improvement of life-cycle circularity for new products; improved resource efficiency; and

[82] AMUK 2015 "What is Additive Manufacturing" page
[83] AMUK National Strategy 2018 – 25 AM-UK_Strategy_Publication_Amends_Novermber_Digital.pdf
[84] Hague, R., Reeves, P. and Jones, S., (2016), Mapping UK Research and Innovation in Additive Manufacturing, published by Innovate UK, https://www.ukri.org/wp-content/uploads/2021/12/IUK-071221-3DPrintingMappingUKAdditiveManufacturing.pdf

increased profitability. Ultimately, more accurate and reliable AM at scale was expected to support more localised manufacturing and circular manufacturing.

Delivery

The project involved several different work packages:

- developing an AI computer vision system to monitor the Fused Deposition Modelling (FDM) process and to automate the real-time capture of errors, application of corrections, or re-printing decisions. FDM is a designed approach that uses a thermoplastic material to build a three-dimensional object by layer-by-layer deposition
- developing a factory user interface showing live feedback of the process
- creating hardware FDM machinery that allowed for continuous, autonomous production, including the print and part removal processes
- development of a digital product tracking system using AI to allow for the tracing of product life cycle
- creation of a demonstrator factory at Plus X Innovation's hub in Brighton where Plus X Innovation worked with SMEs and students to print more than 2,000 parts to test the technology workflow and train Matta's AI models.

For Batch.Works, a key factor in successful delivery was their role as a manufacturer of 3D printing products, which allowed them to collect and receive data directly from their own production. For Plus X Innovation, having a vast network of big entrepreneurs and innovators allowed them to integrate the demonstrator into an active innovation environment.

Batch.Works valued the support from the MSI team, which felt reassuring rather than scrutinising helped Batch.Works to manage the project delivery and produce high-quality reports.

"At the time, it was the first time we'd won a large project, and we were still a relatively young company though we're bigger now. The support we received helped us avoid feeling overwhelmed and we could really rely on the MSI team as well as the monitoring officer, who made us feel that they were genuinely there to help."

Batch.Works member

The project also benefited from favourable market conditions, with increased demand for local production using recycled materials.

Delivery was affected by Matta Labs, one of the partners, winning another grant around the same time, which led to a reduction in their team. Combined with Batch.Works' own relative newness as a business, both partners took a few months to settle into the project. Technical delays also led to a slightly reduced window for user testing by Plus X Innovation.

Plus X Innovation's plan to scale the technology commercially through project hubs was not achieved because of the challenges of finding appropriate properties and making the models financially viable. Only two hubs instead of five were developed.

Key benefits

The technologies were designed to integrate as a cohesive system for fully automated, AI-driven manufacturing. This has been advanced by the project and some are in use in the Batch.Works production environment, achieving an approximate 50% gain in efficiency. At the project outset, the technologies were at TRL 3-4, progressing to TRL 6-7 by the end of the project. Since the end of the project, they have continued to develop to TRL 7-8. The AI computer vision system to monitor and control the FDM process is now at pre-commercial deployment with external users. The monitoring hardware (cameras, sensors) is now ready for commercial scaling. The FDM machinery for continuous, autonomous production (part removal system) has a production-ready system in pilot phase. The factory management user interface (UI) has been internally integrated for Matta Labs, Batch.Works and Print Scheduler.

The material marking and tracking system is the only technology that is not yet implemented at scale by Batch.Works. However, it still progressed from an initial concept (TRL 2) to a functional prototype (TRL 5) within the project lifespan. Some of the elements have been applied through a spin-off company, Kibu Family, which produces headphones for children.

Benefits from the integration of the technologies include:

- a reduction in failed print rates from 10% to 1%
- up to 90% of energy saving per print cycle through reduced idle heating compared to continuous heating
- a reduction in wasted material from failed prints by 80% due to AI-powered failure detection and auto-stopping mechanisms.

Over the next three years, after commercialisation, an estimated 1,685 tonnes of CO_2 emissions will be avoided, according to an ISO14040-compliant Life Cycle Assessment (LCA). By 2029, projected material savings are expected to reach 1,380 tonnes. Additionally, the project's future advancements in the UPID tracking system, including the use of a QR tracking system for closed-loop recycling and a digital ID system for accurate sorting and reprocessing, will facilitate recycling and remanufacturing, further reducing the demand for virgin plastic.

This solution is designed to be highly adaptable, suitable, and affordable for businesses of all sizes, and relevant to multiple sectors. While designed primarily for end-consumer products, it can be adapted to other industries. The system is designed to be as plug-and-play as possible, increasing accessibility for companies with limited digital readiness.

"(...) We already have customers who are interested in adopting the software and hardware technologies we've developed. So, in a way, this project has certainly accelerated the adoption of these types of technologies."

Batch.Works member

Plus X benefited from project in terms of strengthening their AI network through the collaboration with Matta Labs, the AI spin-out partner, and learning more about the additive manufacturing sector.

"3D printers are at the heart of our maker spaces, and many of the companies we work with use them for prototyping. However, I don't think we've had the chance to promote them on such a large scale before. "

Plus X innovation member

Batch.Works benefitted through engaging with potential customers at Plus X's events and getting feedback. Batch.Works has also successfully raised £750K in private equity to date and expect to raise more.

Role of MSI

The partners reported that the MSI programme was fully additional as the project would not have happened without MSI support. For all partners but particularly Plus X Innovation, the funding was critical to giving them the resource to be involved in the project. The partners also valued the collaborative nature of the project, which they acknowledged may not have happened at all without MSI, and the advisory support from MSI.

"For us, the support we've received has been crucial, especially as a small company. The [MSI] programme has helped us mature, particularly through how the projects are run, the reporting structure, and the time management involved. These are all vital aspects of business and project management, and I believe they've been helpful in advancing us."

Batch.Works member

Learning

Key lessons for project partners included:

- The value of having mature partners in the consortium. Whilst '3D Printing Factory Network Across the UK' is a success story in this context and involving early-stage companies can offer fresh ideas, having a larger, more experienced partner is advantageous. Experience, coupled with extra resource to help to steer projects in the right direction with fewer delays, is especially important with larger, more ambitious projects.
- The importance of aligning the work packages with the overall technology roadmap.

- The resource required to manage multiple project tasks simultaneously.
- The value of flexibility in a programme that allows a project to evolve in response to emerging insights.
- The use of demonstrators in supporting engagement with different stakeholders and potential customers.

Future prospects

Consultees saw potential for the technology to evolve, for instance, to handle higher temperature materials or different types of materials. The technology can be adjusted to meet the requirements of different materials. The partners (Batch.Works and Plus X Innovation) are seeking further funding to continue the research, collaborator with academia and progress the technology.

"After completing the project, we continued to search for grants that could sustain and further the work, because it wasn't just about finishing the project—it was about building upon it. We're still running another UK project to push the technology further."

Batch.Works member

Case study: "Business in a Box" Sensor Monitoring Solution

This case study focuses on Devtank's Lighthouse project, delivered as part of the Smart Manufacturing Data Hub (SMDH). The purpose of the case study is to demonstrate how the MSI Challenge has supported development of Internet of Things (IoT) technology. It has been informed by two consultations, one with two members of Devtank and another with a member of the Smart Manufacturing Data Hub, supplemented by existing material available from MSI and Devtank.

Overview of Internet of Things

According to the definition by the Institute of Electrical and Electronics Engineers (IEEE), *"Internet of Things (IoT) envisions a self-configuring, adaptive, complex network that interconnects things to the Internet through the use of standard communication protocols"*.[85] IoT can be applied to manufacturing settings by enabling machine-to-machine communication, big data, and intersection of information technology and operational technology. These applications are referred to as the Industrial Internet of Things (IIoT).

The UK manufacturing sector generally has a low uptake of IIoT technology, particularly among SMEs. Research conducted by Eseye (an IoT connectivity solutions provider) found that UK businesses have relatively lower levels of connectivity compared to the US, and this gap looks set to widen.[86] Evidence from the technology trends element of the evaluation identified a number of barriers to technology development and adoption of IIoT. One key barrier included uncertainty in Return On Investment (ROI) combined with significant upfront costs. Indeed, manufacturers report a lack of resources to invest in IIoT technologies as a key factor preventing adoption.[87] As such, there is a need to provide lower-cost solutions and demonstrate the value associated with IIoT to convince UK manufacturers (particularly SMEs) that it is a worthwhile investment.

Aims and objectives

Founded in 2014, Devtank is an SME specialising in test equipment and smart monitoring solutions, supplying businesses worldwide. One of its core products is the OpenSmartMonitor, a low-cost 'Plug & Play' solution for manufacturers that uses sensors to monitor various production parameters including energy usage, humidity, temperature, sound, and particulates. Data are visualised on an app to help manufacturers understand their energy usage and environmental conditions.

This project focused on developing Devtank's OpenSmartMonitor solution. Prior to involvement with the MSI programme, Devtank had developed a prototype version of the OpenSmartMonitor but had a limited number of industry partners with which to test the product. Devtank was

[85] IEEE (2015) Towards a definition of the Internet of Things (IoT)
[86] Eyese (2024) Eseye 2024 State of IoT Adoption Report
[87] Microsoft (2022) IoT Signals: Manufacturing Spotlight

focused on identifying opportunities for further piloting the technology, to help them progress the technology from a prototype to a product which they could sell to market.

Devtank sought relevant opportunities with support from the Smart Manufacturing Data Hub (SMDH). The SMDH aims to support small and medium-sized manufacturers to become more competitive by harnessing data. SMDH funded a number of Lighthouse Projects, which provided grant funding for technology providers (such as Devtank) to engage with manufacturing SMEs and install subsidised IoT technologies to increase the amount of data collected by businesses. These data are then analysed by SMDH data scientists to generate business insights.

Delivery

The Lighthouse Project provided funding to allow Devtank to supply its OpenSmartMonitor solution at a discounted rate to 50 businesses. As part of this, customers agreed to share their anonymised data with the SMDH for use as part of its Manufacturing Data Exchange Platform (MDEP). These data were analysed by SMDH's data scientists to generate business insights and ultimately inform decision making to improve business productivity and sustainability. Businesses were able to view data dashboards via the Data Hub, providing a live visualisation on machine and factory environment parameters.

SMDH was critical to generating referrals for Devtank's OpenSmartMonitor. During the project, SMDH Business Development Officers engaged with businesses across the country to promote the OpenSmartMonitor technology to SMEs, before then generating referrals for businesses likely to benefit from adopting the technology. This meant that Devtank was able to access 50 SMEs from across the country, spanning different manufacturing sub-sectors including electronics, machinery, and food & beverage manufacturing. Not only has this helped to create a larger scale of adoption (prior to the project, Devtank only had a handful of customers), but it has also helped in the development of the solution too, as Devtank has received feedback from a diverse client base which has varying needs and operating conditions.

The project's success was largely due to the interoperability of Devtank's OpenSmartMonitor technology. Its sensors support various connectivity options, such as LoRaWAN, WiFi, Power-over-Ethernet (PoE), and 4G/LTE, ensuring compatibility with a wide range of networks. This versatility made the product suitable for many SMEs, regardless of the networks their machinery uses. This has been particularly important for manufacturers with legacy systems, allowing them to benefit from the technology and realise its benefits even with limited investment in new machinery.

The increasing importance and urgency of meeting Net Zero targets, as well as significant increases in energy costs, has led to UK manufacturers to seek opportunities to make their operations more energy efficient. OpenSmartMonitor's capabilities address this challenge directly, meaning that the solution has become increasingly relevant for industry needs.

Key benefits

The primary benefit for Devtank has been the opportunity to develop its product from a prototype to a product which is ready to be implemented at scale, representing progress from TRL 7 to TRL 9. The programme has enabled this by providing access to manufacturing SMEs, and part-funding their adoption of the technology. This approach has generated valuable feedback from businesses to refine the product and also created a series of use cases that enhance the solution's marketability.

Increasing the scale of technology adoption has also aided Devtank's own manufacturing journey, helping it to understand the capacity and capabilities it needs in order to manufacture a product at scale. For example, Devtank has hired an additional software engineer who is responsible for onboarding new customers. It has also evaluated its supply chain, to ensure that it has sufficient access to the required materials for producing greater quantities of the hardware.

Product refinement and understanding the requirements for ensuring scalability have ultimately led Devtank's to develop its Sustainable Business Intelligence (SBI) model. While other solutions require an engineer visit to install hardware, the SBI model seeks to provide SME manufacturers an 'out of the box' digital dashboard to start registering data in real-time straight away. This has significantly increased the potential scalability of OpenSmartMonitor and resulted in a low-cost solution which is accessible to a wide range of manufacturing SMEs. This model provides export opportunities too, where Devtank is seeking to partner with international resellers to provide their solution across both Europe and Asia.

While the wider benefits to industry are likely to be realised in the longer-term, the project has demonstrated the types of impact which can be expected. Some examples include:

- A door manufacturer used the solution to improve machine efficiency and cut energy use, while also capturing humidity and temperature data to better control the storage of its timber materials and products.
- One manufacturer was able to identify relatively high particulates in the working environment and is now seeking to improve air quality and provide a healthier working environment for its employees.
- Another manufacturer was able to identify a faulty automatic lighting system which used excess electricity overnight.

If adopted more widely, the potential cumulative impact of energy and environment monitoring (and associated data-driven decision-making) at scale is expected to have a significant impact on the UK manufacturing sector. Expected benefits from the technology include increased productivity, reduction in carbon emissions, greater resource efficiency, and improved employee wellbeing. It is also expected that making this technology more accessible may help UK manufacturing SMEs to start their digital transformation and investigate other opportunities relating to other IDTs, compounding the anticipated benefits.

Although SME manufacturers are likely to experience these benefits most directly, it is anticipated that these advantages will permeate through the supply chain. Larger manufacturers are expected to benefit from a more competitive, resilient UK manufacturing base with enhanced digital capabilities.

Role of MSI

Without the MSI programme, consultees reported that adoption of the OpenSmartMonitor solution would likely have been much slower. MSI funding helped to de-risk the installation of monitoring technologies, as well as helping to demonstrate the value which the technology can provide to businesses. Business development support provided by the programme also helped to extend the Devtank's presence across the UK, accessing businesses they would have not otherwise been able to reach.

While the MSI programme did not directly fund development of the technology itself, it did support commercialisation of the technology. By funding adoption of the technology, this helped Devtank to establish feedback loops with industrial partners, contributing towards improvement of the OpenSmartMonitor solution. Industrial partners had different needs and operated in a range of sub-sectors environments meaning the feedback received was representative of the UK manufacturing base and the product was refined to meet a range of needs.

Learning

There were three key reasons the project was able to deliver significant benefits both to Devtank and the broader UK SME manufacturing sector:

- **Focus on commercialisation**: While Devtank was experienced in receiving UKRI/IUK funding, much of this funding has focused on earlier TRL stages. In contrast, the SMDH Lighthouse project placed an emphasis on translating an existing product into industry and provided support through both funding (to de-risk investment for SMEs) and business development capacity (to enhance Devtank's access to customers). This support was considered critical to progressing OpenSmartMonitor to the point of significant scaling.
- **MSI's co-investment model**: As part of the project, Devtank was required to provide match funding of three times the allocated grant funding. Under MSI's co-investment model, this match funding could be a benefit in-kind, meaning Devtank's staff time spent on the project could be monetised and count towards the match funding requirements. This helped to make the grant-funding accessible for small technology developers (like Devtank), which may have limited initial reserves to meet traditional match funding requirements.
- **Adopting a one-to-many approach**: Many IUK/UKRI funding programmes invite consortia to collaborate and deliver innovation. However, this Lighthouse project demonstrates the potential benefits of a 'demand-led' approach, whereby a technology developer is supported by business development capability to access the market, and referrals are generated based on industry partners most interested in a given innovation. This approach brought together

a diverse mix of industrial partners, as well as helping to engage with industry beyond those within pre-existing networks.

Future prospects

The future for OpenSmartMonitor is focused on scaling up the technology to potentially thousands of SMEs in the UK and globally. While the Lighthouse Project aided this to some extent, there is a continued need for support in relation to accessing markets and raising awareness amongst industry as to the benefits of adopting the IoT technology. There are opportunities for further developing the sensor technology too, including compatibility with 5G/6G networks, an ability to measure additional parameters, and integration with other IDTs (e.g. AI-powered IoT sensors).

Case study: Certified AM Parts Finished with Intelligence Robotics Engine (CAMPFIRE)

Overview of robotics

CAMPFIRE (Certified AM Parts Finished with Intelligent Robotics Engine) was a £535k CR&D project aiming to advance the role of robotics in additive manufacturing processes at the post-processing manufacturing phase. The project was led by Rivelin Robotics as the technology and capability provider and had three other funded partners who provided use cases in three different sectors: GKN Aerospace (Aerospace), Attenborough Dental (Medical) and Material Solutions (Energy). Additionally, there were two unfunded partners on the project – Saint Gobain Abrasives and Yaskawa UK – who provided some of the hardware and materials used in the project.

When creating parts via additive manufacturing they frequently have some form of support structure that supports overhanging sections during manufacturing and prevents warping. These supports must be removed before the manufactured piece can be quality assessed and go into operation. The process of removing these structures is almost entirely done by hand using power tools in a costly, risky and time-consuming process. Due to the bespoke nature of many pieces created by additive manufacturing, conventional methods for support removal (where the exact same process is repeated multiple times) are not feasible.

To solve this problem, Rivelin Robotics had developed a high TRL prototype of a robotic 'micro-factory' that can, using sensors, software and hardware, remove support structures automatically but in a way that is bespoke for each piece. The interface of this micro-factory is configured such that a computer-literate non-expert could use the technology. Prior to the project, however, Rivelin was not able to demonstrate that the prototype could meet the 'proof points' that customers would need to see before they would purchase the technology (e.g. that it works to certain tolerances and on certain materials).

Aims and objectives

The aim of the CAMPFIRE project was to take the existing robotic micro-factory prototype and bring it to a production standard, demonstrating the utility of this prototype in three sectors, Medical, Aerospace and Energy. The project aimed to: 1) understand the requirements of potential customers in these sectors (e.g. what quality assurance processes would the part need to pass, what tolerances would need to be adhered to); 2) improve the technology to meet these requirements; and 3) demonstrate that the prototype worked in each of these sectors.

Whilst the project was limited to these three sectors, the technology is potentially applicable to any sector that uses additive manufacturing and other metal manufacturing techniques (e.g. metal casting, laser powder bed manufacturing, sandcasting) and materials (e.g. ceramics and polymers).

Delivery

Project delivery began with discussions between the lead and the project partners to capture their requirements, for example what technologies they were using to remove support structures, what metals they were using etc. Rivelin used these requirements to develop their technology. Throughout this process, the partners would send unfinished parts to Rivelin who would use their prototype to finish the pieces and send them back to the partners to be quality assured. One of the partners, GKN Aerospace, had a micro-factory deployed at their site in Bristol to undertake the finishing. During the project, the underlying software was also improved, going from one standard to the next.

One activity planned at project outset, but ultimately not delivered, was the use of machine learning within the micro-factories to improve their accuracy and precision. Concerns about the sensitivities of collecting machine learning data on commercially sensitive parts led to this aspect being removed from the project, although it may be re-considered after the end of the project.

Factors that helped the delivery of the project included the technical competence of the lead partner, their ability to solve problems and the flexibility shown in dealing with requirements of different sectors, frequent discussions between the lead and the partners and the teamwork this engendered, and the range of perspectives brought by partners from different sectors which offered learning opportunities.

Only one factor was cited as hindering the project, which was the decision that Yaskawa would not be involved in the integration of a manufacturing cell into its enclosure because the activity was perceived as too risky for logistical and commercial reasons. Instead, the lead delivered two demonstrators to GKN.

Key benefits

Through the project, the technology was progressed from a prototype to production standard, moving from TRL 6 to TRL 8, with TRL 9 anticipated shortly. The lead can now evidence adherence to the requirements of different sectors, allowing them to take advantage of commercial opportunities in these sectors. There is a possibility that one of the partners will look to adopt the technology soon and Rivelin is currently in discussion with two large US-based companies, who, if they chose to proceed, would have a positive impact on Rivelin's ability to grow.

Another outcome from the project was the development of Rivelin's sales process for potential customers because of the potential sensitivities associated with proprietary parts. This process involves the customer sending parts to Rivelin under either an NDA or an export licence, and Rivelin undertaking feasibility checks on these pieces to see if they would work with their system.

There are multiple potential productivity benefits to the UK manufacturing community of adopting this technology. First, by using a robot instead of a human, post-processing can occur at anti-social hours (increasing productivity by up to 50%) and allow businesses to assign their staff to more skilled roles. Second, accidental errors - where a piece is incorrectly post-processed, resulting in wasted materials and a slowdown in the production - are less likely. The lead estimated that adopting a microfactory results in a 75% cost reduction per productive hour[88], and the SME partner estimated that adopting this technology might save between £100k to £150k a year.

A separate advantage of the technology is the improvement to the health and safety of staff. Post-processing of this type has an explosive risk due to the production of metal dust which can ignite, as well as exposing workers to toxic contaminants and causing possible vibration related injuries. By using a robot in place of a human, these risks are mitigated, potentially saving lives and compensation for injuries.

Another benefit associated with using a robot instead of a human is that a robot can keep a detailed digital record of post-processing work, which will provide a higher level of traceability compared to manual operatives.

For project partners, the project improved their capabilities and knowledge of robotics and 'practical' Innovate UK projects, and an improvement to their management practices to deal with an Innovate UK project over such a short deadline.

Role of MSI

The MSI funding allowed Rivelin to de-risk the final stage of the technology development by allowing collaboration with partners who otherwise would not have been financially able, or willing, to do so, and it was the collaboration that would give confidence to potential customers in similar sectors. One of the partners indicated that, as an SME, they could not have afforded to fund research like this. Consultees also reported that, in the absence of the MSI funding, the project would have taken far longer to achieve the benefits it has achieved, although estimations of how much longer varied between two and five years.

To a lesser extent, it was thought that the advice and guidance of the project monitoring offer was important to the project. In particular, the project lead stated that, because the MSI funding helped to accelerate their technology to production standard they were now engaging with blue-chip companies in the US, which would otherwise have taken far longer. The recruitment of new staff hired by Rivelin also supported the project.

Involving end-users in the project, as enabled by MSI, was seen as keen to achieving the outcomes, because it provided the lead with direct insights into industry requirements, as well as real world testing of their technology. The project lead cited the importance of this as the key learning for them from the project.

[88] Normalised across daily, weekly, and monthly operating scales.

Future prospects

Potential future developments of the technology include a new generation of the software involved in the technology (Netshape), which uses AI to improve the quality of outputs, and application to other manufacturing techniques and materials. Rivelin anticipated both the hardware and software being regularly updated in a process of continuous improvement and localised manufacturing production in the US and the EU, the latter of which already has a committed facility.

Since fieldwork for this case study was undertaken the lead has sold multiple 'r1000' microfactories to customers in the US for deployment in Q3 2025, as well as being in advanced talks with a British Manufacturer about future deployment and further commercially focussed R&D.

Case study: DM2 - Platform Five (Network and Skills), Extended Reality

This case study focuses on the Digital Medicines Manufacturing Research Centre, funded by the MSI Challenge. Specifically, it focuses on Platform Five (Network and Skills), and the Centre's role in advancing Extended Reality technology in the manufacturing sector. The study is informed by consultations with the University of Strathclyde (lead organisation) and The Glasgow School of Arts (project collaborator).

Overview of extended reality

Extended Reality (XR) is the collective term for immersive technologies which seek to merge physical and virtual environments. XR includes three related but distinct technologies:

- Virtual Reality (VR) – a fully virtual experience, which works through a headset, and where only the virtual world is viewed. In manufacturing, use cases may include creation of 3D models as part of product design and prototyping, or creating virtual training environments for workers.
- Augmented Reality (AR) – virtual elements are overlaid onto the real world, such as digital instructions overlaid onto physical workstations to guide workers through assembly processes or comparing real-time images of products with digital models to identify defects.
- Mixed Reality (MR) – anchored virtual elements that can interact with the real world (i.e. digital objects which respond to changes in the physical environment and vice versa). Manufacturing-relevant examples include remote collaboration by allowing users to view and manipulate 3D models in real-time, and the creation of interactive training environments.

The Made Smarter review highlights the importance of adopting XR technologies in manufacturing, noting that "*effective communication of data, concepts and ideas [...] enable greater productivity, reduce risk, improve quality and optimise production*".[89]

While there are some examples of industry applications, the general uptake of XR technologies is low within the UK. A 2020 survey by The Manufacturer concluded that only 29% of UK manufacturers had either adopted or were actively considering the use of augmented reality, compared to 71% of manufacturers adopting Internet of Things technology, and 63% adopting automation/robotics.[90] Technology trends work conducted during this evaluation recognised key barriers to the adoption of XR technologies, including a lack of understanding about the potential applications and the value it can bring to industry.

[89] Maier, J. (2017) Made Smarter Review, page 107
[90] The Manufacturer (2020) Annual Manufacturing Report 2020

Aims and objectives

The lack of appropriate skills in the workforce has been highlighted as a key industry challenge, with manufacturers struggling to attract, retain, and train workers.[91] XR technologies can help to address this challenge by capturing the expertise of experienced workers and transferring the knowledge through immersive training to less experienced individuals. Additionally, XR technologies offer the potential to improve the working environment for machinery operators by visualising data in a way that is easy to interpret.

Led by CMAC at the University of Strathclyde, the Digital Medicines Manufacturing (DM^2) Research Centre seeks to address challenges in the medicines manufacturing sector. As part of its funding, DM^2 has delivered five 'integrated platforms' to drive development and adoption of industrial digital technologies (IDTs) which will benefit the medicines manufacturing supply chain.[92] This includes the DM^2 Network & Skills Platform (Platform Five), which aims to address labour market challenges by upskilling the medicines manufacturing workforce. Platform Five focuses on the adoption element of IDTs, using XR technologies as a mechanism for machine operatives to engage with and respond to data presented to them. These immersive technologies are intended to enhance training, safety, virtual collaboration, and understanding of manufacturing processes, in turn boosting productivity.

Delivery

As part of the DM^2 Network & Skills Platform, CMAC collaborated with The Glasgow School of Art (GSA) to develop applications using XR technologies. Examples include:

- An MR app which visualises real-time data on a virtual dashboard. The app connects with cloud data to track key manufacturing parameters (e.g. tablet weight), and alerts users to potential issues in the process (e.g. if the tablet weight is above/below specification).
- An AR app which uses Microsoft Dynamics 365 Guides to overlay and visualise data allowing the user to correctly operate manufacturing equipment using virtual 3D models, designed to assist training.[93]

Successful development of these apps has required a muti-disciplinary team spanning CMAC and GSA. This has included expertise relating to 3D modelling, software development, manufacturing, and user experience. The multi-disciplinary team was critical to the project's successful delivery, helping to ensure that the app development considered a range of perspectives, and is therefore better designed for adoption.

Rapid developments in the XR hardware – specifically in mixed reality headsets (e.g. Meta Quest 3, Apple Vision Pro) – have positively influenced project delivery. Significant investment in XR technologies has been ongoing and will persist, with new devices featuring enhanced capabilities

[91] T-Mobile for Business (2022) How Augmented Reality Helps Manufacturers Cope with Labor Crunch
[92] UKRI (2024) Innovation Case Study - DM^2
[93] CMAC (2023) DM^2 1st-Gen Demonstrators

and functionality being launched every year. These developments were anticipated by the DM^2 team, and so the apps have been built to be compatible with future devices, helping to ensure their longevity.

The multi-platform approach of DM^2 has also positively influenced delivery. The centre's exploration of opportunities across multiple different IDTs has allowed for data collected by other mediums (e.g. Internet of Things) to then be visualised using XR technologies, helping to compound the benefits of IDT adoption.

Key benefits

To date, the apps have primarily been used by researchers and students within CMAC laboratories. This has benefited other platforms within DM^2 and helped to demonstrate the linked benefits of joining up IDTs. Immersive training modules have also been developed, which will be launched via the SkillsFactory in Spring 2025. These training modules will be accessible to students and industry partners, helping to both address existing skills gaps and raise awareness around the benefits of immersive training.

While there have been some benefits associated with the apps themselves, the project has also established the infrastructure required for developing and deploying XR apps in future. This includes creating 3D models of CMAC equipment (which can be reused), establishing a reliable and high-speed network infrastructure to support real-time data transmission, building sufficient server and cloud computing capacity able to handle large volumes of data used by XR apps, and providing comprehensive training for employees to effectively use XR technologies. The focus on developing infrastructure has been particularly important given the limitations of existing hardware (including substantial processing power, short battery life, heat dissipation and user-experience issues), which mean that apps developed by DM^2 are a work in progress, as opposed to final product. While the apps developed by DM^2 are not final products, the infrastructure created will provide a foundation for future app development.

Learning from Platform Five will be directly transferable to future research. CMAC has recently been successful in securing funding for MediForge – one of UKRI's Manufacturing Research Hubs[94] – which aims to pioneer an Industry 5.0 approach to manufacturing, and in turn enable more sustainable, resilient and human-centric medicine production. The £11m project will be led by the University of Strathclyde in collaboration with a number of other academic partners, including The Glasgow School of Art. XR technologies will be central to activities conducted by the MediForge Hub, which will seek to develop more use cases for the IDT, including its potential application in building digital twins and facilitating virtual collaboration.

One area of great interest has been the use of AR in combination with digital twin modelling. For example, real-time information has been overlaid (via a headset) onto the Mixed-Suspension Mixed Product Removal crystaliser (MSMPR) and the Self-Driving Tableting DataFactory platform, showing live monitoring information for both the live experiment and its digital

[94] UKRI (2024) Hubs launched to create a sustainable future for manufacturing

model.[95] This allows for differences between the live experiment and the digital model to be assessed in real-time, and for suitable adjustments to be made to the digital model to refine its accuracy. An accurate digital model enables experiments to be run digitally, helping to increase access (as multiple researchers can access the model simultaneously) and reduce energy and material consumption through fewer physical experiments. Other examples of anticipated future benefits associated with XR technologies include:

- Greater productivity by addressing skills challenges within the manufacturing, as immersive training provides opportunity for scale (as multiple people practice simultaneously using digital models) and enhanced understanding (as experiential learning boosts memory retention and recall).
- Improved resource efficiency, as XR apps which visualise real-time data can help to address issues more quickly and therefore minimise manufacturing errors.

Role of MSI

Without the MSI programme, it is unlikely that the use cases would have been developed, and that the benefits – both realised and expected – would have occurred in the same way. This was particularly true in terms of the scale of activity which MSI enabled, and without the programme, it is likely that the activities delivered would have been in isolation, over a longer period of time.

The funding also facilitated collaboration between CMAC and GSA, and therefore the multi-disciplinary approach to app development. Without the MSI programme, collaboration between the two institutions would have been challenging, given the amount of time and resource required.

It was felt that the programme has been important in demonstrating the value of XR technologies within manufacturing, while also highlighting that further work is required in order to drive adoption among industry.

Future prospects

XR technologies are something which will continue to be of interest, both for CMAC, the wider manufacturing industry, and the technology industry as a whole, for the range of benefits offered. XR technologies will be included as part of activity delivered by MediForge. Meta have announced plans to release an improved Meta Quest, and Apple have continued to invest in their Vision Pro device. As XR hardware becomes more immersive, accessible, and affordable, user confidence in the technology is expected to grow, facilitating easier adoption across various industries including manufacturing.

[95] A crystalliser is a device used to purify active pharmaceutical ingredients by controlling the formation of solid crystals from a solution. To read more, please see: [Crystallization in the Pharmaceutical Industry]

SQW

Contact

For more information:

Osman Anwar
Director, SQW
T: +44(0)7834 885084
E: oanwar@sqw.co.uk

9 Coates Crescent
Edinburgh
EH3 7AL

www.sqw.co.uk

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