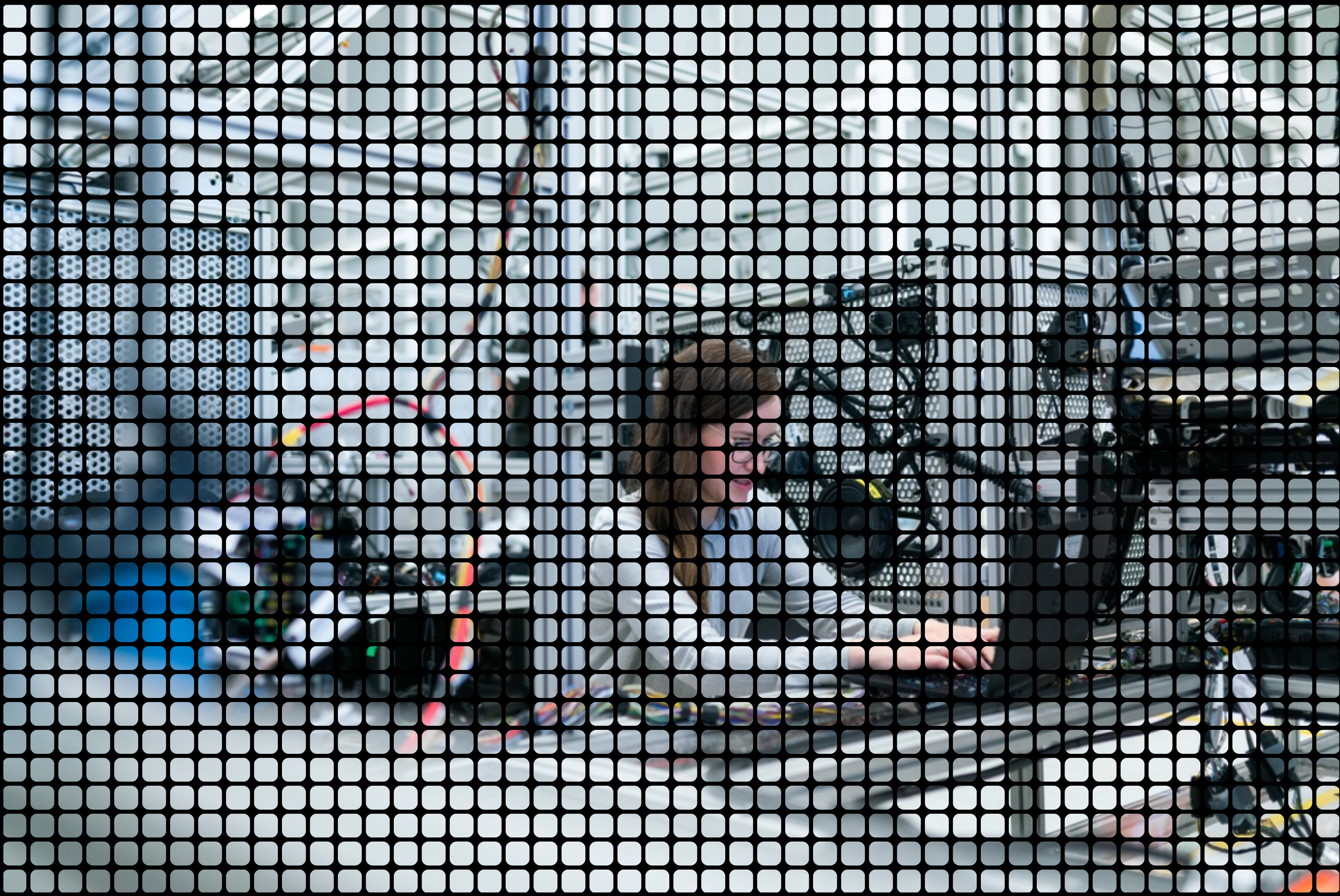

Evidence Report

Trends in Engineering Research

a quantitative analysis of engineering research publications in the UK

Hélène Draux, Cristina Rosemberg, Briony Fane, and Juergen Wastl

SEPTEMBER 17, 2024

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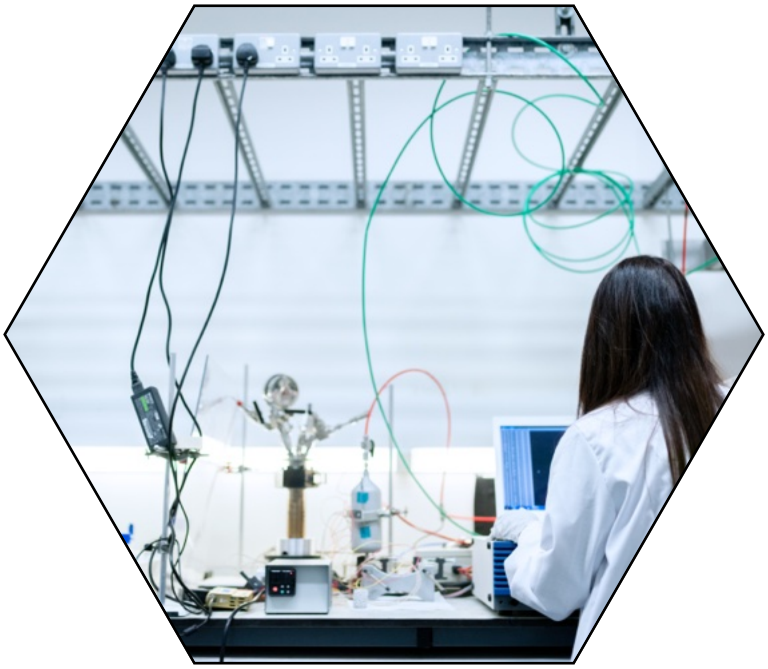


Introduction

This Evidence Report presents a quantitative analysis of the UK Engineering research output. It complements the Executive Summary Report and provides a more in-depth analysis and graphical description of Engineering. It focuses on the strengths, quality and impact both at national and international levels. In order to provide a broader context, the analysis includes a comparative assessment of the UK performance against nine countries considered to be the major contributors to Engineering research. This report combines the fields of Engineering and Computer Sciences, taking into account their significant overlap and interdisciplinary connections. This approach is supported by an examination of research output submitted to the UK REF2021 for two Units of Assessment (UoA) - UoA12 (Engineering) and UoA11 (Computer Sciences) - which demonstrate a notable intersection, and cross-submissions, between the two disciplines.

"This report combines the fields of Engineering and Computer Sciences, taking into account their significant overlap and interdisciplinary connections."

The publication data included was sourced from Dimensions, which, at the time of the report, contained more than 605,000 publications in the 19 subdisciplines of Engineering and 12 subdisciplines of Computer Sciences, published between 2007 and 2021. These publications are the corpus of research used in all subsequent analyses.

The number of research outputs in each of the 31 subdisciplines analysed ranged from small, such as 5-6,000 in Environmental Engineering (4011), Geomatic Engineering (4013), and Applied Computing (4601), to large, such as 52,000 in Materials Engineering (4016).

Main findings

International comparisons outlined in the report have highlighted that while the volume of engineering research in the UK is significant, it falls short of being a world leader. Although the reputation of engineering research is widely acknowledged, the gap between the UK and comparator countries in terms of overall research publication numbers is widening. The US and China continue to outpace the UK in the growth rate of research output across subdisciplines of engineering. However, it is worth noting that the UK exhibits strength, both in terms of volume and quality, in the field of Machine Learning (4611), which is expected to play a crucial role in a number of future global advances.

"The UK exhibits strength, both in terms of volume and quality, in the field of Machine Learning, which is expected to play a crucial role in numerous future global advancements."

Trends and strengths

An analysis of trends in research outputs, as well as academic quality as measured by citation indicators, reveals key areas of strength across engineering subdisciplines.

In general, the volume of Engineering publications increased at an annual rate of 4.8% between 2007 and 2021, and at an even higher rate of 7. 5% for the period 2012 to 2017. However, there was a deceleration in publication growth between 2017 and 2021, of 2.9%. In particular, the volume of publications saw a decline in the four subdisciplines of Software Engineering (4612) where a decline of more than 7% was observed at the end of the period 2017 to 2021.

Machine Learning (4611) was the only subdiscipline to show both the highest annual growth in research volume and the highest scientific impact (measured by Field Citation Ratio).

"Machine Learning (4611) was the only subdiscipline to show both the highest annual growth in research volume and the highest scientific impact (measured by Field Citation Ratio)."

Overall, the UK engineering research output is strong, but does not have a leading edge internationally. The standing of UK engineering research internationally is evidenced by its steady increase in collaborations with other countries and by the number of citations that it accrues. Italy, China, the US, and France are the UK top collaborators.

When comparing international research output based on the total number of publications, the US and China emerge as the top contributors, with India closely following behind. The UK does not rank within the top three countries for research publications in any of the subdisciplines examined. Similar trends are observed when considering international comparisons addressing the Technological Challenges outlined in the 'Tomorrow's Engineering Research Challenges' (TERC) report[1]. China and the US lead in all areas, with India demonstrating a significant increase in publication volume in the fields of 'transportation systems', 'materials engineering', 'health and wellbeing', 'responsible engineering', 'nature-based engineering', and 'global engineering'. In comparison, the UK falls behind China and the US, but exhibits similar trends to other countries included in the analysis.

[1] Available at: https://www.ukri.org/wp-content/uploads/2022/07/EPSRC-090822-TERCReport.pdf

The 2018 report of the Science and Technology Committee of the UK House of Commons Science and Technology Committee[2] recommended paying attention to research integrity issues and this is captured in this report through what are known as 'trust markers' (e.g. code availability, data availability, statements of conflict of interest). UK Engineering performs well in this area, with Biomedical Engineering (4003) appearing as leading in making its data and code available to enable replication of research in this field.

[2] Reproducibility and research integrity: Government Response to the Committee's Sixth report: https://committees.parliament.uk/publications/39343/documents/194466/default/

Engineering's contribution to societal challenges

Research publications in Engineering and Computer Science demonstrate a strong commitment to addressing the social, environmental, and economic dimensions of societal impact. Areas such as climate change, innovation (including supply chains), and responsible consumption are given significant attention. Evidence of this commitment can be found in the research publications produced.

"Areas such as climate change, innovation (including supply chains), and responsible consumption receive significant attention."

Main funders

The findings of the report indicate that two-thirds of the UK engineering research is funded domestically, with the Engineering and Physical Sciences Research Council (EPSRC) playing a prominent role. Internationally, both the EU and China are recognised as influential funders and co-funders during the period of analysis from 2007 to 2021. However, future international funding for UK research in this field from these two entities, as well as their overall contribution to UK engineering research, is anticipated to face challenges due to the impact of Brexit and ongoing geopolitical tensions. With the newly revitalised association of the UK with Horizon Europe, the difficulties envisioned may become unfounded.

"Two-thirds of the UK engineering and computer science research is funded by the Engineering and Physical Sciences Research Council."

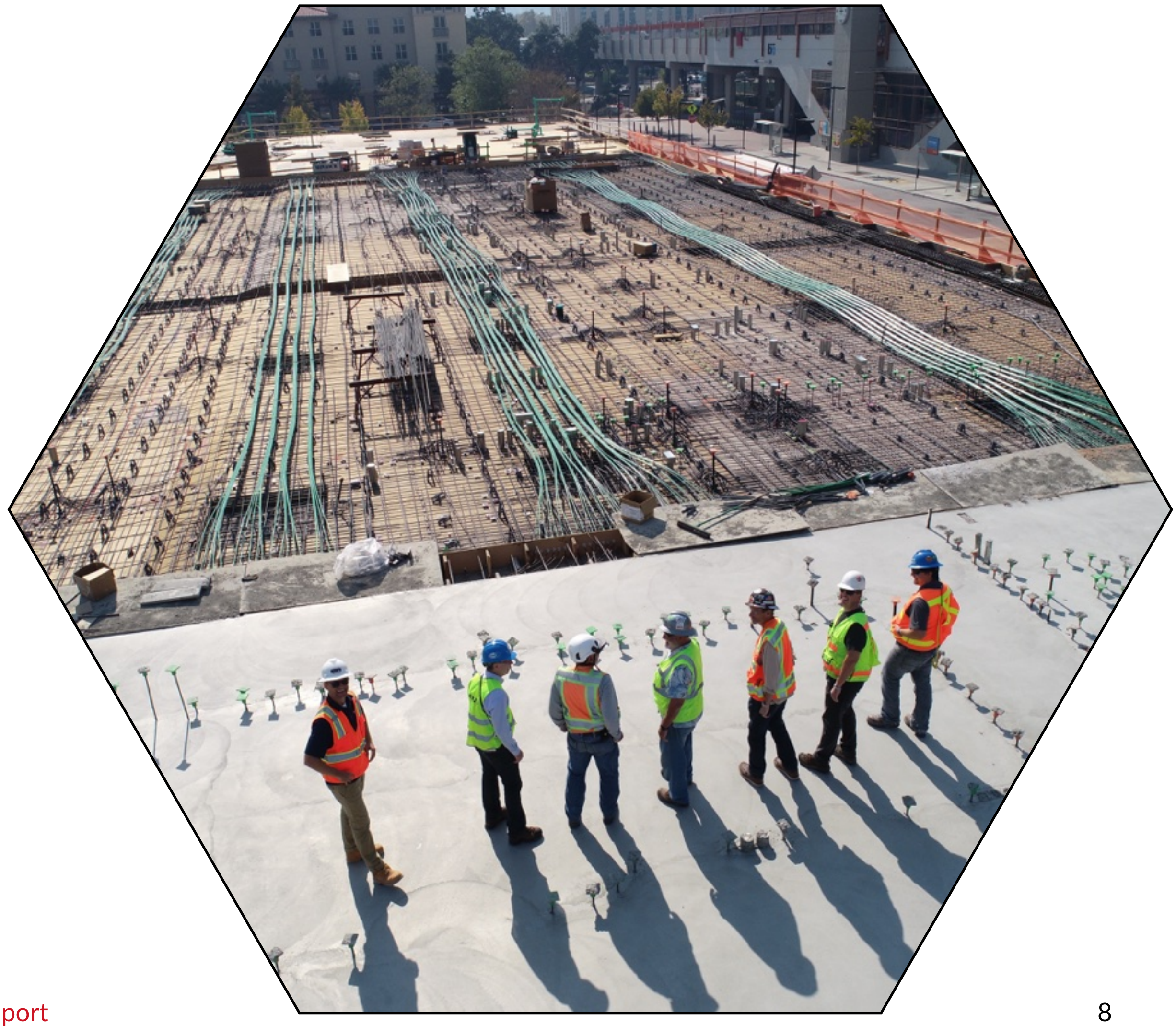
In terms of industry funding, there is a noticeable trend in several subdisciplines where corporate sector funding has either ceased or declined. This is particularly evident in a number of disciplines, including Manufacturing and Mechanical Engineering (4017), and which are of medium size from a research volume perspective. On the other hand, there is an upward trajectory in corporate sector funding, mainly originating from the US, in Computer Science disciplines such as Graphics, Augmented Reality, and Games (4607), as well as Machine Learning (4611). Given the growing significance of all things digital in today's world, this development is perhaps not unexpected.

Introduction

This report presents a quantitative analysis of Engineering research publications in the UK over a 15-year time period from 2007 to 2021 (with the exception of the research integrity analysis, for which data is available from 2010). It offers the opportunity to identify trends in research both in the UK and internationally and to highlight areas of strength in the UK. The report is based on bibliometric data contained in Dimensions, and as such results need be interpreted in the context of what is possible and appropriate to derive from such sources of information.

This approach offers both advantages and limitations. It allows for the ability to look systematically at over 135M research publications included in Dimensions and to make comparisons over time (2007 to 2021) and across countries. It does not, however, allow us to derive conclusions to explain patterns that may arise from the data in more detail including the extent to which they reveal changes in the funding landscape, policy strategies or other contextual characteristics.

Despite potential limitations, the analysis carried out in this report offers an interesting view of the UK current research activity in Engineering in areas of research quality, collaboration, impact, integrity, and funding.



Methodology

3.1 Defining engineering research and the scope of analysis

In this report, engineering research is defined as publications classified in the relevant Fields of Research (FoR) classification[3] in Dimensions for both engineering and computer science.

For the purpose of the analyses carried out in this report, and in conjunction with the Royal Academy of Engineering (the Academy), we have extended the corpus of engineering publications (comprising 19 subdisciplines) to include information and computing sciences (comprising 12 of the 14 subdisciplines) based on its crossover with engineering. The report also focuses on identifying trends across each of the 31 subdisciplines under analysis providing a finer granularity provided from exercises such as the insights emerging from the UK Research Excellence Framework (REF2021), where both fields are clustered within two Units of Assessment. Comparisons with REF2021 provide confirmation of the degree to which FoR in this study aligns with the definitions and understanding of engineering and computer science research, and confirms the crossover in the two fields.

The Research Excellence Framework (REF) is made up of four main panels (A-D) and within each are a number of discipline specific Sub-panels. Main Panel B includes two relevant Sub-panels: Computer Science and Informatics (B11) and Engineering (B12). Table 1 outlines the top 10 REF Units of Assessment present in FoR 40 (Engineering) and in FoR 46 (Information and Computing Science), where they intersect and thus are assessed jointly. The table provides a visual understanding of how they align.

Table 1 further demonstrates that the Fields of Research (FoRs) chosen in this study match well with the specific REF Sub-panels. It also reveals that engineering research publications, identified in this study, were similarly reviewed by the REF assessment panels. For example, publications categorised within one of the 19 Engineering subdisciplines were found in several units of assessment (UoA) within Main Panels A and B, as well as in subject areas of Main Panel C such as Architecture, Built Environment, and Business and Management Studies (C13 and C17), and Subpanel D32 related to Art and Design. In each case, these align closely with specific subdisciplines (e.g., Civil Engineering (4005) in C13, Information Systems (4609) in C17, and Human-Centred Computing (4608) in D32). For all but one FoRs in Information and Computing Science, the strongest link in B11 is to B12 Engineering. Only Information Systems (4609) have an even stronger link to Management Studies (C17). After the evaluation, reports from the REF Main panels and Sub-panels discussed the impact of research, with a focus primarily on its effects within an assessment unit, and to a lesser extent, across different panels.

[3] The ANZSRC Fields of Research classification is a two-level classification. It has been used to classify the methodology of the R&D research into 21 fields and 172 subfields. Dimensions performs an entity-level machine-learnt classification using the text of the title and abstract of the research outputs. When these are not available, a journal level classification is applied.

"Engineering research is defined as publications classified in the relevant Fields of Research (FoR) classification in Dimensions for both engineering and computer science."

Table 1: Crossover of Top 10 UoAs (REF2021) with publications in Fields of Research 40 Engineering and 46 Information and Computing Sciences.

Unit of Assessment Field of Research	A3	A4	B8	B9	B10	B11	B12	C13	C17	D32
4001. Aerospace Engineering	0	1	1	3	3	10	557	9	3	5
4002. Automotive Engineering	0	0	3	0	3	1	310	10	0	0
4003. Biomedical Engineering	259	32	42	19	18	52	658	2	0	9
4004. Chemical Engineering	27	0	39	7	1	3	730	39	4	8
4005. Civil Engineering	4	0	3	2	12	22	1006	262	53	11
4006. Communications Engineering	2	7	1	12	21	95	209	9	3	5
4007. Control Engineering, Mechatronics And Robotics	6	0	0	4	10	58	525	10	5	4
4008. Electrical Engineering	1	4	3	10	13	40	371	54	6	1
4009. Electronics, Sensors And Digital Hardware	7	2	11	72	5	55	394	18	2	13
4010. Engineering Practice And Education	1	0	0	0	0	22	285	10	10	7
4011. Environmental Engineering	5	0	3	1	0	0	198	27	1	1
4012. Fluid Mechanics And Thermal Engineering	6	0	8	16	161	4	916	42	3	2
4013. Geomatic Engineering	0	0	0	2	2	15	46	13	0	3
4014. Manufacturing Engineering	10	0	3	5	1	4	570	9	31	20
4015. Maritime Engineering	0	0	0	2	73	1	427	17	5	0
4016. Materials Engineering	45	1	255	163	7	11	1913	17	0	37
4017. Mechanical Engineering	3	2	5	3	6	7	668	48	5	6
4018. Nanotechnology	60	2	137	139	2	2	462	0	0	5
4019. Resources Engineering And Extractive Metallurgy	0	0	0	4	9	0	290	19	0	0
4601. Applied Computing	3	2	0	18	6	26	41	4	3	1
4602. Artificial Intelligence	6	2	2	1	9	610	128	9	45	9
4603. Computer Vision And Multimedia Computation	3	8	0	6	11	255	101	4	12	11
4604. Cybersecurity And Privacy	0	4	1	2	1	293	31	1	3	1
4605. Data Management And Data Science	13	1	6	5	11	613	216	9	76	9
4606. Distributed Computing And Systems Software	2	1	0	0	6	340	67	4	9	0
4607. Graphics, Augmented Reality And Games	1	11	1	1	0	207	51	3	3	42
4608. Human-Centred Computing	7	50	0	0	0	433	78	5	57	77
4609. Information Systems	3	1	0	0	3	125	24	5	260	3
4611. Machine Learning	10	88	1	3	18	352	102	1	16	4
4612. Software Engineering	2	0	1	0	0	321	26	0	12	1
4613. Theory Of Computation	2	0	2	1	11	174	49	0	1	1

Unless stated otherwise, each analysis is presented using FoR subdisciplines as set out in Table 1.

Again, unless stated otherwise, the analysis considers publications across the time frame 2007 to 2021.

3.2 Data - Dimensions

Publications data in Dimensions includes research from a wide range of publishers and journals. Publications are at the centre of the Dimensions ecosystem linking data across the research cycle, from grants to publications, clinical trials, policy documents, datasets, and patents; links between publications, or publications and patents or policy documents, represent citations between these entities.

Publications and grants data contain the following metadata:

3.2.1 Researchers and their affiliations

- **Researchers**: Dimensions uniquely identifies researchers who publish research outputs and receive grants.
- **Affiliations**: The institutions used by the researchers have been collected using GRID[4], which has been used with Dimensions' data. The data is at the institutional level.
- **Funders**: Research funders that either share their data with Dimensions or make them freely available are also accessible in GRID. In addition, Dimensions extracts funder data from publication acknowledgements to create a link between publications and funders. When a grant identifier is available in the acknowledgements, Dimensions links both.
- **Countries**: For affiliations that are not recognised by GRID (which captures country information), we extract the country of origin.

[4] GRID is an openly accessible database of educational and research organisations, created and maintained by Digital Science. Each organisation is assigned a unique GRID ID, and records are constantly curated. Variations in institution name are included.

3.2.2 Classifications

- **Fields of Research**: Dimensions data are mapped to Fields of Research (FoR) using machine learning; the mapping is carried out at the article level where an abstract is available. Where an abstract is not available, mapping is carried out at the journal level. Grants are also categorised using the FoR classification system. One or more FoRs can be assigned to any of the output types available in Dimensions. The current classification used in Dimensions is the 2020 update[5]. Dimensions' FoR classifier can be used to attach a label to any text; therefore, if a grant is not available in Dimensions it is possible to use external text provided by a client to classify into the relevant Field(s) of Research.
- **Sustainable Development Goals**: In a similar way, Dimensions links publications and grants to the United Nations Sustainable Development Goals (SDGs) and where appropriate, one or more SDGs can be assigned to a number of output types including grants, publications, etc. We are also able to classify any text, such as an abstract or a summary, using the SDG classifier[6].

[5] See https://www.abs.gov.au/statistics/classifications/australian-and-new-zealand-standard-research-classification-anzsrc/latest-release.

[6] See our report Contextualizing Sustainable Development Research.

3.2.3 Citations and attention

- **Field Citation Ratio (FCR)**: The FCR is a citation-based measure of the scientific influence of publications. It is calculated by dividing the number of citations a paper has received by the average number received by documents published in the same year and in the same FoR category.
- **Altmetric**: The Altmetric[7] attention score is an article-level score, indicating the extent of online attention an article has received. The source of attention tracked includes public policy documents, mainstream media outlets, blogs, citations, online reference managers, wikipedia, social media.
- **Reproducibility (Ripeta)**: Ripeta[8] and Dimensions Research Integrity have created trust markers indicating where authors have made available information about the integrity of their research (e.g. a data availability statement or providing access to the code used in the research). The Dimensions Research Integrity analysis is available for more than 33 million publications starting from 2010.

[7] https://www.altmetric.com/

[8] https://ripeta.com/

3.2.4 Grants

Dimensions contains data on grants from a wide range of funders. These grants are linked to resulting publications using acknowledgements or external data (e.g., Gateway to Research). To ensure that all funders were included in the analysis, we used the funders acknowledged in the publications and automatically extracted these using GRID functions. We also used the GRID typology to track industry funding.

3.3 TERC Technological Challenges

This report provides a bibliometric analysis across the established FoR research classifications based on areas identified in the 'Tomorrow's Engineering Research Challenges' (TERC) report. The TERC report was led by the EPSRC and aims to identify key challenges, inform future strategies in engineering research, and identify the research needed to tackle the challenges.

The TERC report identified three levels of Technological Challenges:

- Technological Challenges
- High Level Priorities
- Cross-Cutting Themes

The TERC Technological Challenges were defined using standard bibliometric methodologies such as Boolean searches (see 12.3) and by combining relevant FoRs with the appropriate UN SDGs.

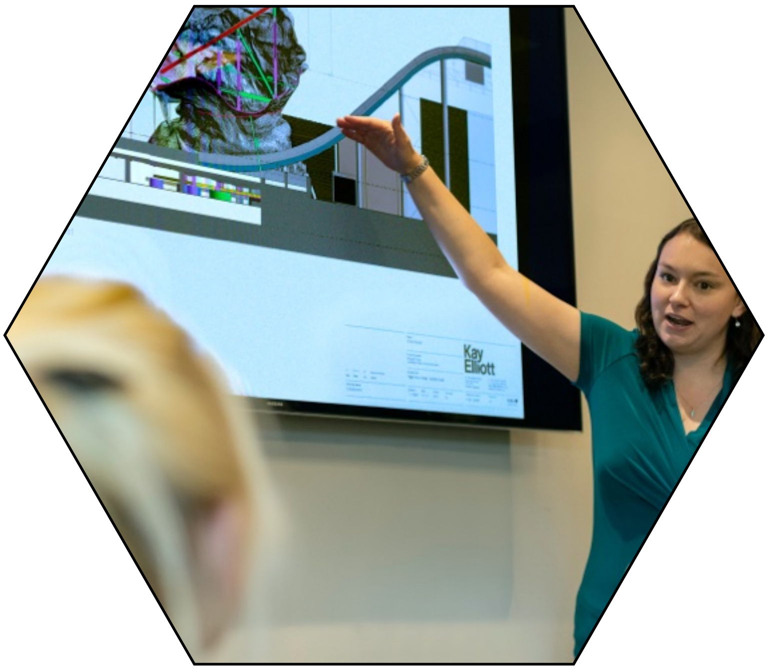
"The TERC Technological Challenges were defined using standard bibliometric methodologies such as Boolean searches and by combining relevant FoRs with relevant UN SDGs."

The feasibility of classifying bibliometric data under the cross-cutting themes and priorities identified in the TERC report was also tested (using bottom-up exploratory approaches). The nature of the classifications and the resources available for the report meant that the results were not as extensive as they could have been. The use of alternative bibliometric technologies, such as bibliometric coupling or network analysis, would provide more refined results and should be considered in any further work.

Trends

Materials Engineering (4016), Data Management And Data Science (4605), and Civil Engineering (4005) are the three strongest areas of UK research (based on volume of research publications). China and the US are the strongest international competitors in this space, with India following behind in each discipline.

Focusing on the TERC Technological Challenges, 'responsible engineering' is the UK strongest research area (based on volume of research publications). China and the US dominate across all eight areas however the UK shows an increasing trend in 'robotics and AI'.



4.1 Volume of engineering research in the UK by subdiscipline

4.1.1 UK engineering research

For the purpose of this report, we have selected both the Fields of Research for Engineering and Computer Sciences to make up Engineering. In the following analyses these two will be analysed together, as Engineering, unless otherwise stated.

A total of 605,358 research outputs (at the time of analysis) were published in Engineering research in the UK between 2007 and 2021 (including research articles, books, chapters, pre-prints and conference proceedings). This represents 17.4% of the total number of publications in the UK over that period; the UK published 3.9% of the global Engineering publications.

The volume of Engineering publications grew at an annual rate of 4.8% between 2007 and2021, and from 2012-2017 grew at an even higher rate of 7.5%. However, over the period 2017-2021 there was a deceleration of 3% in publication growth.

The top 10 FoRs (by volume of research output) account for 53% of the total number of publications over the period 2007-2021 which includes Materials Engineering (4016; 9% = 52,024 research outputs), Communications Engineering (4006; 7% = 42,723 research outputs), and Electronics, Sensors, and Digital Hardware (4009; 6% = 36,233 research outputs). (See Table 2).

The highest Compound Annual Growth Rate (CAGR)[9] in the volume of publications is in Machine Learning (4611; 11.4% CAGR) followed by Geomatic Engineering (4013; 9.5% CAGR) and Cybersecurity and Privacy (4604; 7.9% CAGR), as seen in Table 3 (see Figure 1 for a visual presentation of the trends). Taking a closer look at individual subdisciplines reveals that:

- **Strong and growing:** There are three areas where the UK is strongest (based on volume) and where growth has been the highest over the past 15 years: Materials Engineering (4016), Data Management And Data Science (4605), and Civil Engineering (4005).
- **Up and coming:** Environmental Engineering (4011) and Geomatic Engineering (4013) were in the bottom five for volume of publications but have the highest growth across the period.
- **Potential decline:** In contrast, the last five years (2017-2021) saw a decrease in the volume of publications in Software Engineering (4612; -7.1% CAGR), Theory of Computation (4613; -1.8% CAGR), Communications Engineering (4006; -1.3% CAGR) and Nanotechnology (4018; -1.2% CAGR), as seen in Table 4.

Therefore, UK engineering research output represents a significant proportion of the country's publications, contributing 17.4% domestically and 3.9% globally between 2007 and 2021, with a notable growth rate and prominence in subdisciplines including Machine Learning (4611), Geomatic Engineering (4013), and Cybersecurity and Privacy (4604).

[9] Annual growth of publication over a specific number of years.

Table 2: Top 10 published Fields of Research, 2007 to 2021.

Field of Research	Number of publications	Annual Growth (CAGR) (2007-2021)
4016. Materials Engineering	52,024	5.7
4006. Communications Engineering	42,723	2.5
4009. Electronics, Sensors And Digital Hardware	36,233	4.0
4605. Data Management And Data Science	35,361	7.1
4008. Electrical Engineering	31,495	4.4
4005. Civil Engineering	31,001	6.6
4602. Artificial Intelligence	25,612	3.1
4003. Biomedical Engineering	24,760	6.6
4007. Control Engineering, Mechatronics And Robotics	22,615	3.2
4012. Fluid Mechanics And Thermal Engineering	21,634	4.9

Table 3: Top 10 fastest growing Fields of Research, 2007 to 2021.

Field of Research	Number of publications	Annual Growth (CAGR) (2007-2021)
4611. Machine Learning	18,197	11.4
4013. Geomatic Engineering	6,098	9.5
4604. Cybersecurity And Privacy	12,096	7.9
4011. Environmental Engineering	5,370	7.2
4605. Data Management And Data Science	35,361	7.1
4014. Manufacturing Engineering	15,407	6.9
4003. Biomedical Engineering	24,760	6.6
4005. Civil Engineering	31,001	6.6
4608. Human-Centred Computing	21,105	6.4
4016. Materials Engineering	52,024	5.7

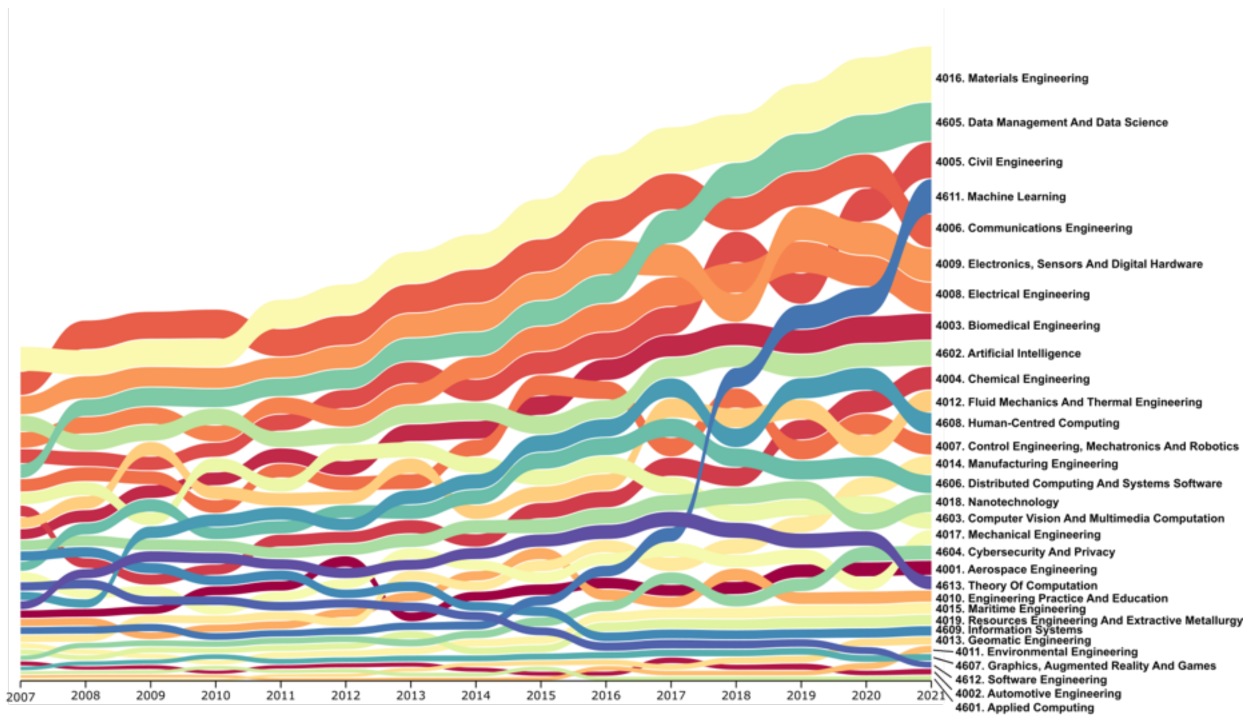


Figure 1: Rank and volume trend for engineering research in the UK, 2007 to 2021.

Table 4: Number of publications in engineering subdisciplines in the UK, 2007 to 2021.

Field of Research	Total	CAGR 2007-12	CAGR 2012-17	CAGR 2017-21	CAGR 2007-21
4611. Machine Learning	18,197	1.3	14.0	19.6	11.4
4013. Geomatic Engineering	6,098	11.7	9.6	7.3	9.5
4604. Cybersecurity And Privacy	12,096	6.1	13.6	4.3	7.9
4011. Environmental Engineering	5,370	0.8	11.8	9.4	7.2
4605. Data Management And Data Science	35,361	7.0	11.2	3.2	7.1
4014. Manufacturing Engineering	15,407	3.9	10.4	6.5	6.9
4003. Biomedical Engineering	24,760	7.0	8.5	4.3	6.6
4005. Civil Engineering	31,001	5.3	8.4	6.0	6.6
4608. Human-Centred Computing	21,105	7.2	10.1	2.0	6.4
4016. Materials Engineering	52,024	4.8	8.3	4.1	5.7
4015. Maritime Engineering	10,553	2.5	9.9	3.2	5.2
4004. Chemical Engineering	20,331	0.8	10.0	4.8	5.1
All	605,358	3.9	7.5	3.0	4.8
4012. Fluid Mechanics And Thermal Engineering	21,607	3.5	8.6	2.5	4.8
4019. Resources Engineering And Extractive Metallurgy	10,349	3.3	8.8	2.2	4.7
4601. Applied Computing	5,324	8.2	1.4	4.5	4.7
4606. Distributed Computing And Systems Software	20,645	6.4	8.2	-0.5	4.6
4001. Aerospace Engineering	14,261	7.3	0.9	5.2	4.4
4008. Electrical Engineering	31,495	2.1	10.7	0.7	4.4
4603. Computer Vision And Multimedia Computation	18,763	2.2	7.4	2.4	4.0
4009. Electronics, Sensors And Digital Hardware	36,233	4.2	7.2	0.9	4.0
4607. Graphics, Augmented Reality And Games	7,744	5.8	6.8	-0.7	3.9
4613. Theory Of Computation	16,450	4.9	7.4	-1.8	3.4
4007. Control Engineering, Mechatronics And Robotics	22,615	2.3	5.8	1.5	3.2
4602. Artificial Intelligence	25,612	0.4	4.0	4.9	3.1
4017. Mechanical Engineering	15,115	0.2	8.6	0.8	3.1
4010. Engineering Practice And Education	13,157	2.9	4.8	1.4	3.0
4006. Communications Engineering	42,723	4.7	4.2	-1.3	2.5
4002. Automotive Engineering	6,008	-0.3	7.3	-0.2	2.2
4018. Nanotechnology	20,744	5.4	2.1	-1.2	2.1
4609. Information Systems	12,892	-1.5	1.2	1.1	0.3
4612. Software Engineering	11,318	0.2	0.7	-7.1	-2.2

4.1.2 International comparisons

To understand how UK engineering research weighs up internationally, we compared research outputs from the UK with countries that had produced the highest number of research outputs in engineering and the highest citation counts. The countries selected for analysis (following discussion with the Academy) included China, the US, India, Japan, Germany, Canada, France, Italy, and South Korea.

China has been the global leader in the number of research publications since 2010 (see Figure 2). The US also saw growth in research outputs. India increased its publication rate but has remained behind China and the US. The research outputs for Germany, the UK, South Korea, Canada, and Italy also grew but at a slower rate, while research output volumes for Japan and France have remained static.

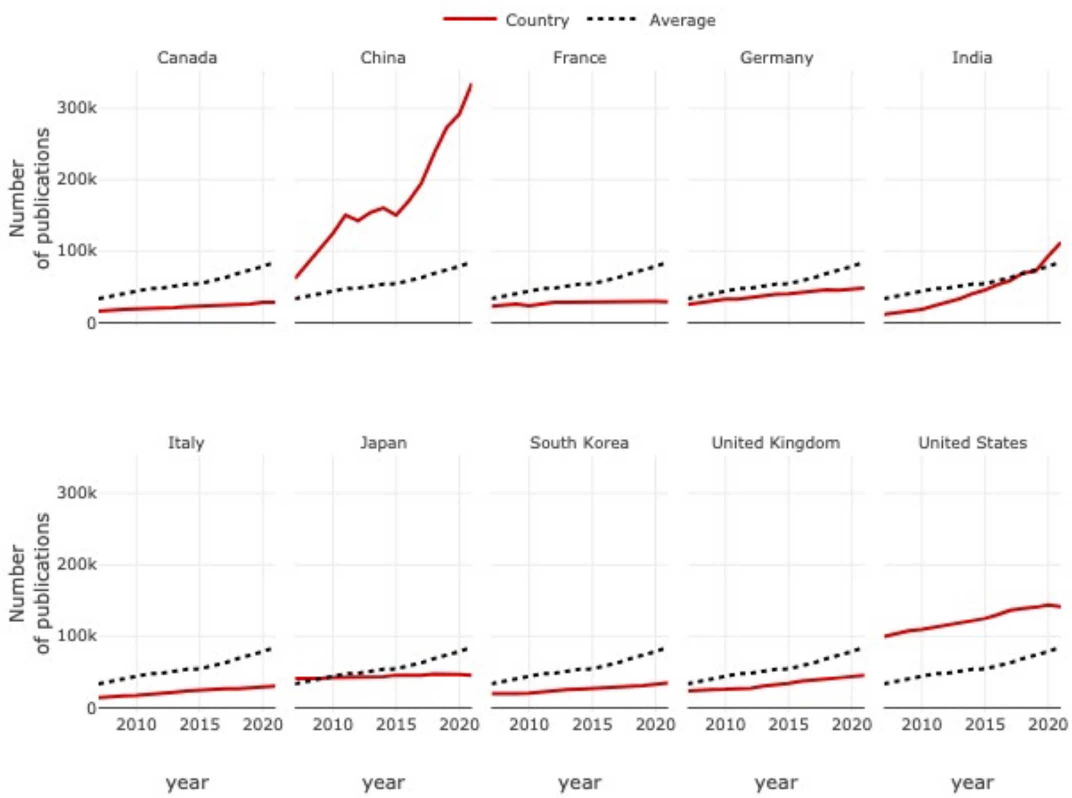


Figure 2: Number of total publications per country in the comparator countries (average is over the 10 countries).

At the level of subdisciplines, and looking at the same comparator countries, China and the US dominate across all FoRs partly due to the size of their population (see Table 5, note that each row adds up to 100%). Interestingly, the combined share of the two largest countries is greater than 50% in all but nine of the subdisciplines. For these nine, the UK has the strongest representation in Human-Centred Computing (4608; third place with 10%), close to second placed China with 13%. In Automotive Engineering (4002) and Mechanical Engineering (4017) the UK holds a 7% share of the number of outputs.

For the top three subdisciplines in the UK, by volume of research publications, Materials Engineering (4016), Data Management And Data Science (4605), and Civil Engineering (4005), a relatively high volume does not translate into a higher position internationally. Moreover, in the case of Materials Engineering (4016; 4% share of total international publications in this analysis), the UK is positioned behind nearly all other comparator countries with the exception of Canada and Italy. The UK is comparable to other countries in Data Management And Data Science (4605), and Civil Engineering (4005), with the exception of China and the US.

Table 5: Engineering Fields of Research, 2007 to 2021, by share (in %), for each country compared.

Field of Research	Canada	China	France	Germany	India	Italy	Japan	South Korea	United Kingdom	United States
4001. Aerospace Engineering	3	37	4	6	8	4	7	4	6	21
4002. Automotive Engineering	3	26	6	9	10	4	9	4	7	22
4003. Biomedical Engineering	4	21	4	8	5	5	8	5	7	32
4004. Chemical Engineering	5	40	4	7	9	4	6	5	5	15
4005. Civil Engineering	5	38	4	4	7	5	7	4	6	21
4006. Communications Engineering	5	33	5	6	8	4	6	5	6	24
4007. Control Engineering, Mechatronics and Robotics	4	34	7	6	6	5	8	4	6	19
4008. Electrical Engineering	4	31	4	6	12	4	7	5	5	20
4009. Electronics, Sensors and Digital Hardware	4	30	4	6	10	4	8	5	5	24
4010. Engineering Practice and Education	5	34	6	7	8	5	6	3	6	19
4011. Environmental Engineering	5	41	4	4	10	4	5	5	5	18
4012. Fluid Mechanics and Thermal Engineering	4	24	6	7	8	4	10	4	8	24
4013. Geomatic Engineering	5	32	6	10	5	8	5	2	6	22
4014. Manufacturing Engineering	3	35	4	11	10	3	10	4	5	14
4015. Maritime Engineering	4	34	5	4	5	4	11	5	9	20
4016. Materials Engineering	3	36	4	7	8	2	9	7	4	19
4017. Mechanical Engineering	3	30	8	8	8	4	9	4	7	19
4018. Nanotechnology	2	31	5	7	9	3	9	8	4	21
4019. Resources Engineering and Extractive Metallurgy	6	42	5	8	6	3	6	3	5	17
4601. Applied Computing	4	16	10	11	5	6	7	2	8	31
4602. Artificial Intelligence	4	34	5	6	10	5	8	3	8	17
4603. Computer Vision and Multimedia Computation	4	40	5	4	11	3	6	4	5	18
4604. Cybersecurity and Privacy	4	26	4	6	17	4	4	4	6	24
4605. Data Management and Data Science	4	36	4	5	12	5	6	5	5	18
4606. Distributed Computing and Systems Software	5	27	5	6	13	5	4	6	6	24
4607. Graphics, Augmented Reality and Games	5	22	6	11	3	3	9	4	8	29
4608. Human-Centred Computing	5	13	4	10	6	5	11	4	10	32
4609. Information Systems	5	25	5	10	8	5	4	3	9	27
4611. Machine Learning	4	36	4	5	8	3	6	3	7	23
4612. Software Engineering	7	15	7	14	7	7	4	2	9	28
4613. Theory Of Computation	7	28	6	7	8	4	4	6	8	22

4.2 Volume of engineering research, in terms of Technological Challenges

Methodological note. The analysis focuses on the eight TERC Technological Challenges identified in TERC.

- Ensure **space research** is sustainable, and design and develop technologies that will be used to explore and sustain life in space and on Earth.
- Develop sustainable, integrated, and equitable **transportation systems**.
- Accelerate environmentally sustainable and socially responsible creation and utilisation of **materials**.
- Improve whole-life **health and wellbeing** by developing sustainable, inclusive, and resilient healthcare systems and technologies resilient healthcare systems and technologies
- Co-design and embed **robotics and AI** into engineering while ensuring ethical use with transparent and equitable decision making.
- Foster socially and environmentally **responsible approaches to engineering** guided by our understanding of human behaviours and needs.
- Unlock the full potential of **nature-based engineering**.
- Deliver adaptable **global engineering solutions** that are compatible with our understanding of the planet's ecosystem understanding of the planet's ecosystem.

Following the definitions developed in the TERC report each of the challenges includes research aspects as well as issues related to use, focus, and adoption, i.e. beyond what can be captured with bibliometric data.

To operationalise the TERC Technological Challenges (and classify the bibliometric data accordingly across each of them), we followed a dual approach. We took the associated FoRs attached to the research outputs and cross-referenced them with the Dimensions classification system for Sustainable Development Goals (SDGs). We introduced the SDGs in order to attach a measure of societal impact to engineering research, thus providing an assessment of the challenges from a global issues perspective.

4.2.1 UK engineering research

Figure 3 outlines the volume (used as a measure of strength) of research in the UK by subdiscipline and reveals that 'responsible engineering' is the strongest research area in the eight TERC Technological Challenges, defined above.

"'Responsible engineering' is the strongest subdiscipline [in terms of research volume] within engineering in the UK, in the context of TERC."

- **Sustainable space research:** Defined as the intersection of space research – Aerospace Engineering (4001) – and SDGs.
- **Sustainable and equitable transportation systems:** Defined as the intersection of transport research (transportation, logistics and sup-

ply chains) with Engineering (FoR 40) and the environmental and social pillars of the SDGs (as seen Section 10).

- **Environmentally and socially sustainable materials research:** Defined as Materials Engineering (4016) and the environmental and social pillars of SDGs (as seen Section 10).
- **Sustainable, inclusive, and resilient health research:** Defined as Engineering (FoR 40) and SDG3: Good Health and Wellbeing.
- **Ethical Use with transparent and equitable robotic and AI research:** Defined as the intersection between autonomous systems, trust, ethics and AI, and responsible AI[10], and the social pillar of SDG.
- **Responsible engineering:** Defined as the intersection between the Engineering (FoR 40), Information and Computing Science (FoR 46), with the environmental and social pillars of the SDGs.
- **Nature-based engineering:** Defined with a Boolean search where any of the following terms is identified: Nature inspired, nature based, bio inspired, bio based, bio processing, bio mimicry (either as a single term or separate ones, with and without hyphens, etc) in either Engineering (FoR 40) or Information and Computing Sciences (FoR 46).
- **Global engineering:** Defined as the publications at the intersection of Engineering (FoR 40) with at least two SDGs from two different pillars.

[10] the Boolean search for these narrowly defined fields of research was created during a project for the Trustworthy Autonomous Systems award

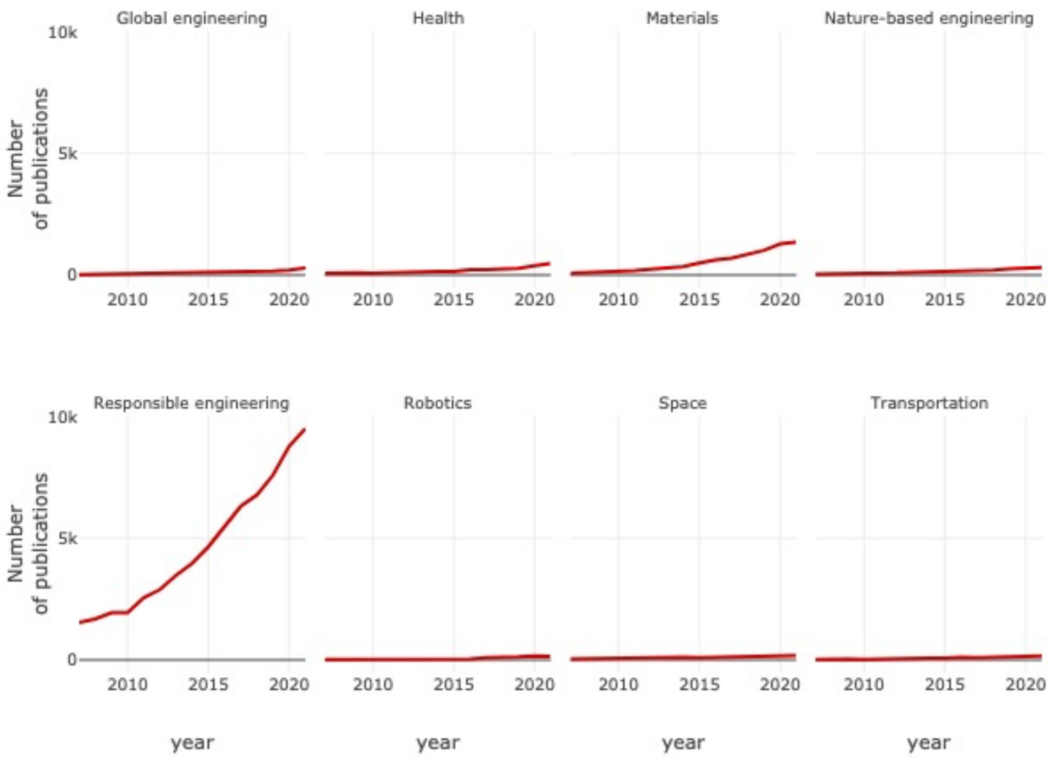


Figure 3: Time trends for UK engineering research publications across the TERC Technology Challenges.

4.2.2 International comparisons

We compared UK trends for each of the eight TERC Technological Challenge areas with trends for each of the comparator countries.

Similarly to the results shown above, China and the US have the greatest volume of research publications compared to the UK. A substantial increase in the volume of publications in India was also observed, in particular, in the following areas of 'transportation systems', 'materials engineering', 'health and wellbeing', 'responsible engineering', 'nature-based engineering' and 'global engineering'.

Although the UK lags behind the US, China, and, to a lesser degree, India, it is aligned with the other selected comparator countries.

A more varied picture emerges when considering the subdisciplines 'space research' and 'robotics and AI'. Looking at 'space research', even though China and the US hold strong, the UK is in line with trends seen for Germany and India and is ahead of a number of the other countries (see Figure 4).

A more varied picture emerges when considering the subdisciplines 'space research' and 'robotics and AI'. Looking at 'space research', even though China and the US hold strong, the UK is in line with trends seen for Germany and India and is ahead of a number of the other countries (see Figure 4). For 'robotics and AI', the volume of UK research output reveals trends that follow the same direction as the US and China, and has a stronger research profile by the rising trends in research volume than five of the comparator countries (see Figure 8).

Figures 4-11 are presented below reveal trends in the volume of research for the TERC Technological Challenges.

4.2.3 Space research

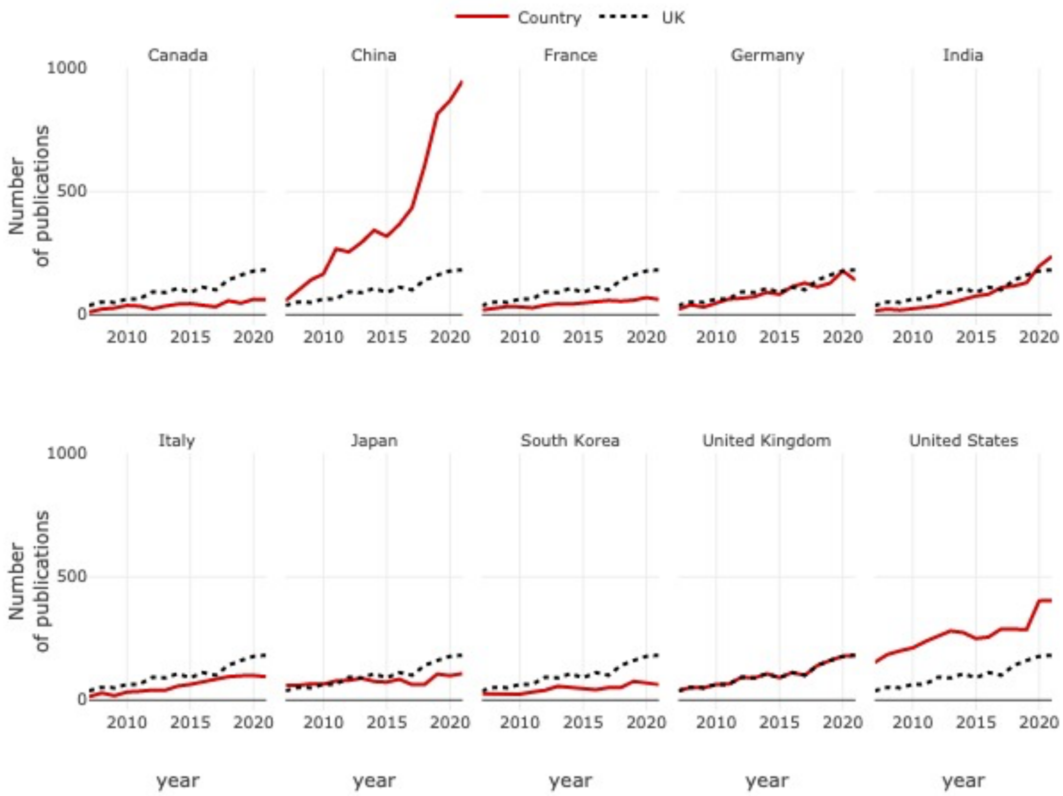


Figure 4: Time trends for number of publications in sustainable space research (as defined in the TERC) for the UK and comparator countries.

4.2.4 Transportation systems

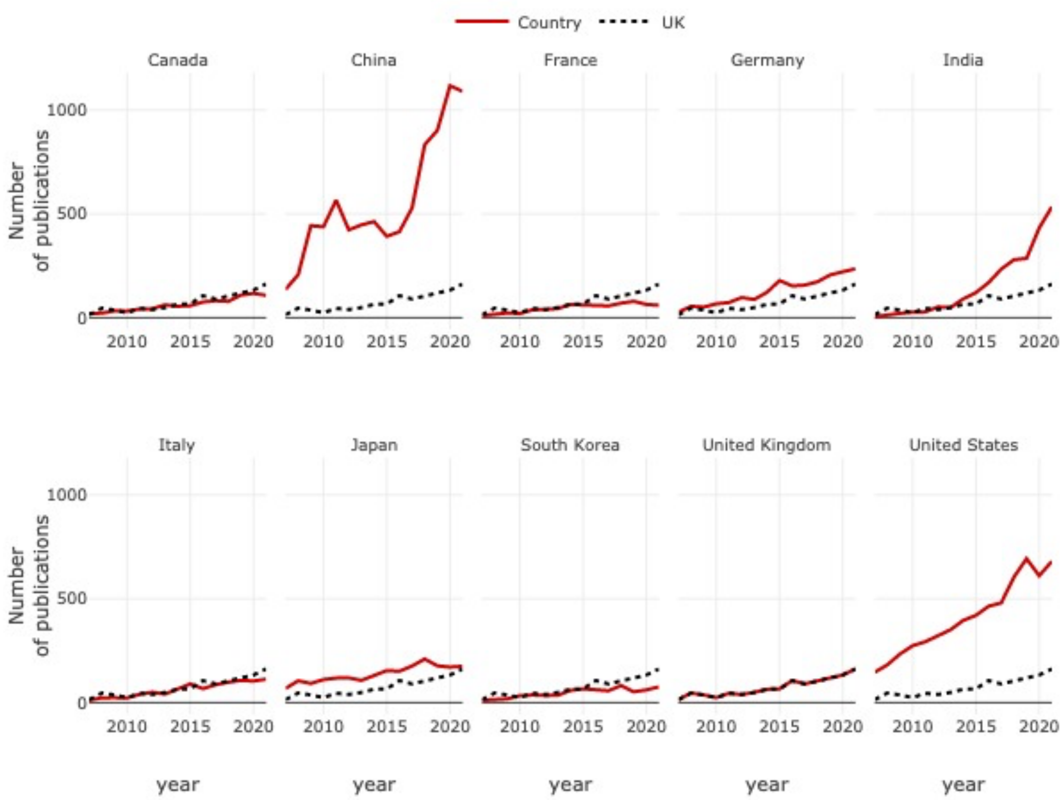


Figure 5: Time trends for publications in sustainable and equitable transport research (as defined in the TERC) for the UK and comparator countries.

4.2.5 Materials research

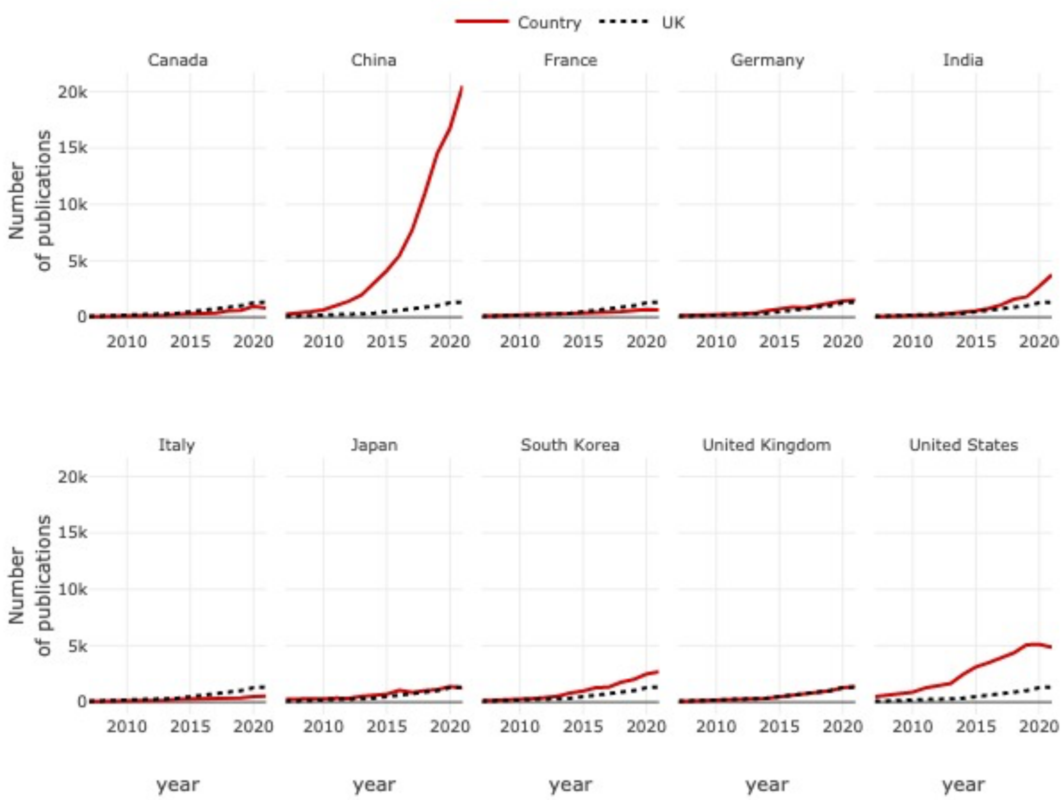


Figure 6: Time trends for publications in environmentally and socially sustainable materials research (as defined in the TERC) for the UK and comparator countries.

4.2.6 Health and wellbeing

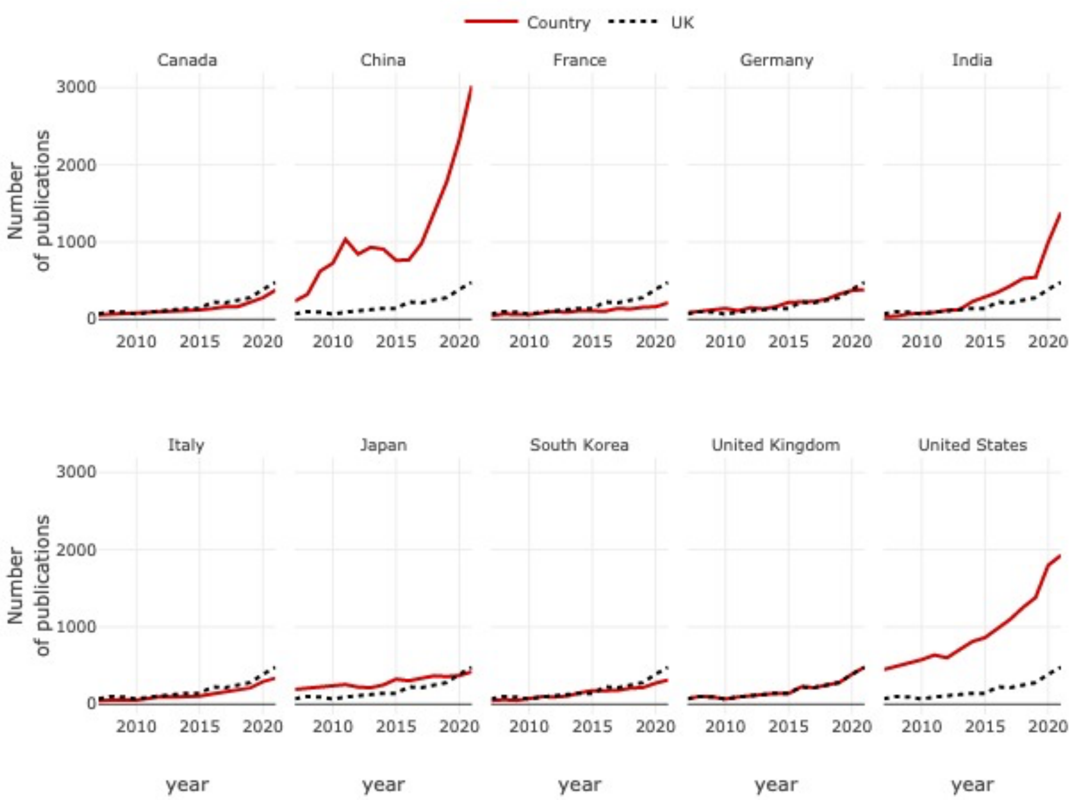


Figure 7: Time trends for publications in sustainable, inclusive, and resilient health research (as defined in the TERC) for the UK and comparator countries.

4.2.7 Robotics and AI

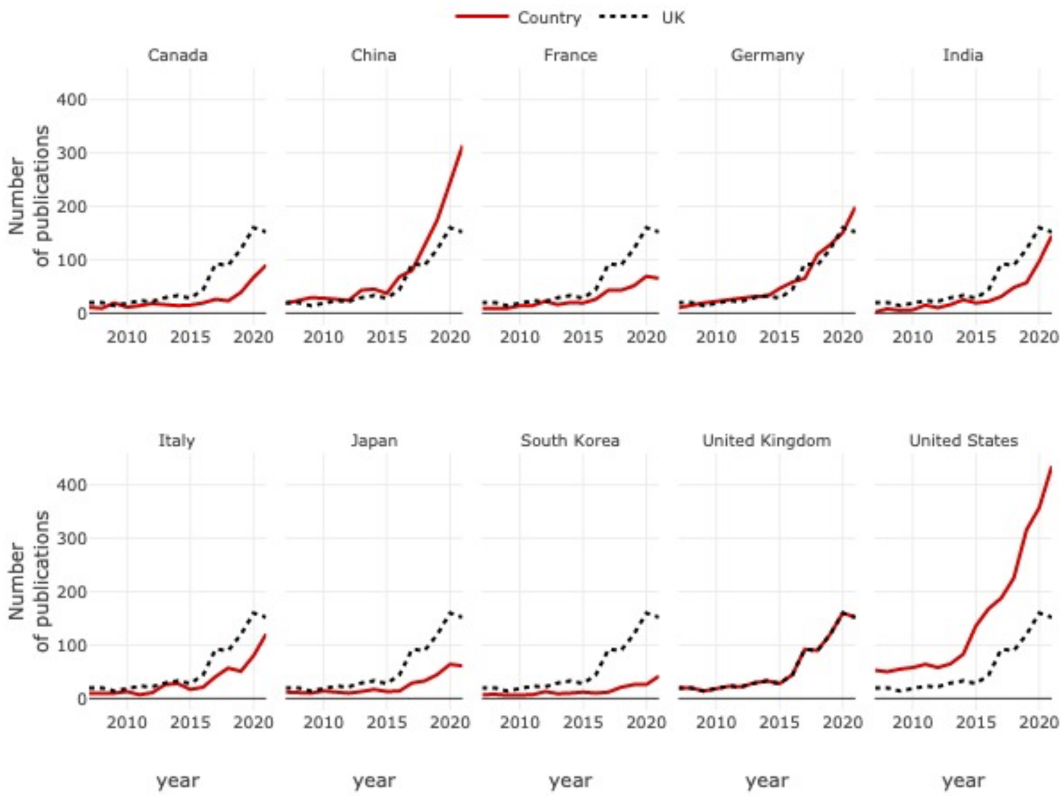


Figure 8: Time trends for publications in ethical use with transparent and equitable robotic and AI research (as defined in the TERC) for the UK and comparator countries.

4.2.8 Responsible engineering

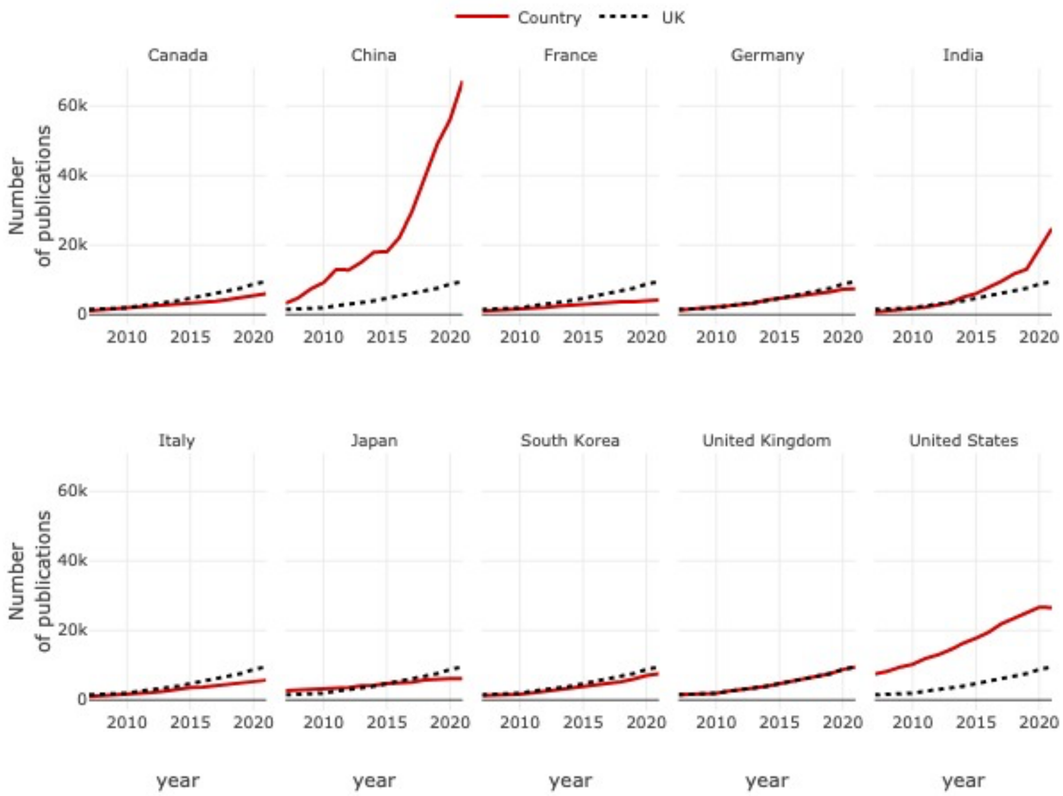


Figure 9: Time trends for publications in socially and environmentally responsible approaches to engineering research (as defined in the TERC) for the UK and comparator countries.

4.2.9 Nature-based engineering

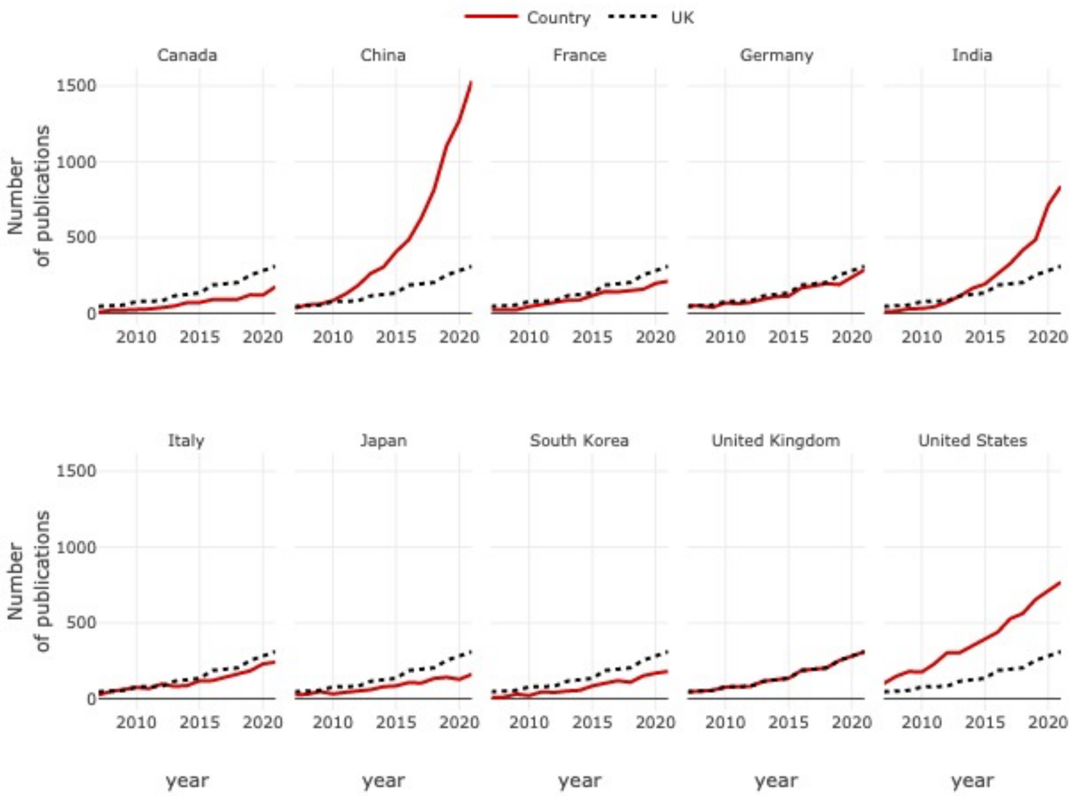


Figure 10: Time trends for publications in nature-based engineering research (as defined in the TERC) for the UK and comparator countries.

4.2.10 Global engineering

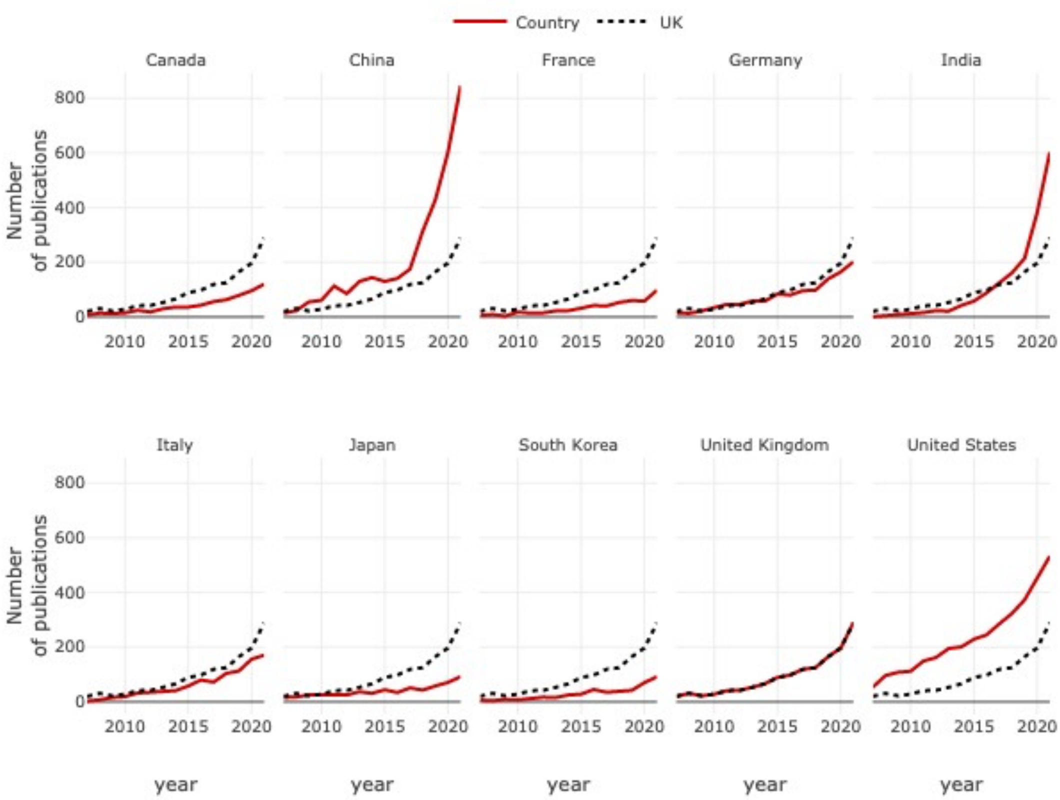


Figure 11: Time trends for publications in global engineering research (as defined in the TERC) for the UK and comparator countries.

Strengths

The UK strongest subdisciplines, measured using field research citation rates, are Applied Computing (4601), Graphics, Augmented Reality And Games (4607), and Machine Learning (4611).

Across all (combined) engineering research, the UK sits in second place (behind the US) for top cited publications.

5.1 UK engineering research

The UK REF2021 exercise highlighted the quality of engineering research in the UK (notwithstanding the fact that this assessment exercise generates the incentives to submit the most outstanding research outputs). As indicated in the REF Main Panel B report, “the submissions to Sub-panel 12 (Engineering) showed real strength and diversity in UK Engineering during the seven-year assessment period. The overall quality of research was found to be very high with 91% of outputs assessed for originality, significance and rigour as being of at least internationally excellent quality.” Similarly, results were obtained for Sub-panel 11 (Computer Science and Informatics), where 87% of the outputs were also found to be of at least excellent quality internationally.

In this section, we look more broadly at scientific impact in order to analyse trends in the data and draw comparisons amongst the subdisciplines.

First, looking at the Field Citation Ratio (FCR), which takes account of differences in citation patterns across FoRs, we note that for most of the subdisciplines, a steady citation performance indicates consistency with the average FCR for FoRs.

Subdisciplines in which Field Citation Ratios are high include Applied Computing (4601), Graphics, Augmented Reality And Games (4607), and Machine Learning (4611) - all are part of Information and Computer Science (46). For example, Machine Learning (4611) not only has the highest annual growth rate for volume of research publications but also the highest scientific impact.

“Machine Learning (4611) not only has the highest annual growth rate for volume of research publications but also the highest scientific impact.”

Citation rates in the Communications Engineering (4006) subdiscipline increase with time, as seen in Figure 12, but at the same time reveal a decrease in the volume of publications in the most recent years of the time frame (CAGR -1.3%, as seen in Table 4).

Table 6: Top 10 FoRs based on CAGR, 2007 to 2021.

Field of Research	Average FCR	CAGR 2007-21	Ranking (based on CAGR)	Number of publications (2007-2012)	Ranking (based on number of publications)
4611. Machine Learning	3.3	11.4	31.0	18211	16.0
4014. Manufacturing Engineering	3.1	6.9	26.0	15407	14.0
4601. Applied Computing	3.0	4.7	17.5	5324	1.0
4613. Theory Of Computation	3.0	3.4	10.0	16449	15.0
4608. Human-Centred Computing	2.9	6.4	23.0	21106	21.0
4607. Graphics, Augmented Reality And Games	2.9	3.9	11.0	7747	5.0
4015. Maritime Engineering	2.9	5.2	21.0	10552	7.0
4609. Information Systems	2.8	0.3	2.0	12892	10.0
4602. Artificial Intelligence	2.8	3.1	7.5	25621	25.0
4005. Civil Engineering	2.8	6.6	24.5	30996	26.0

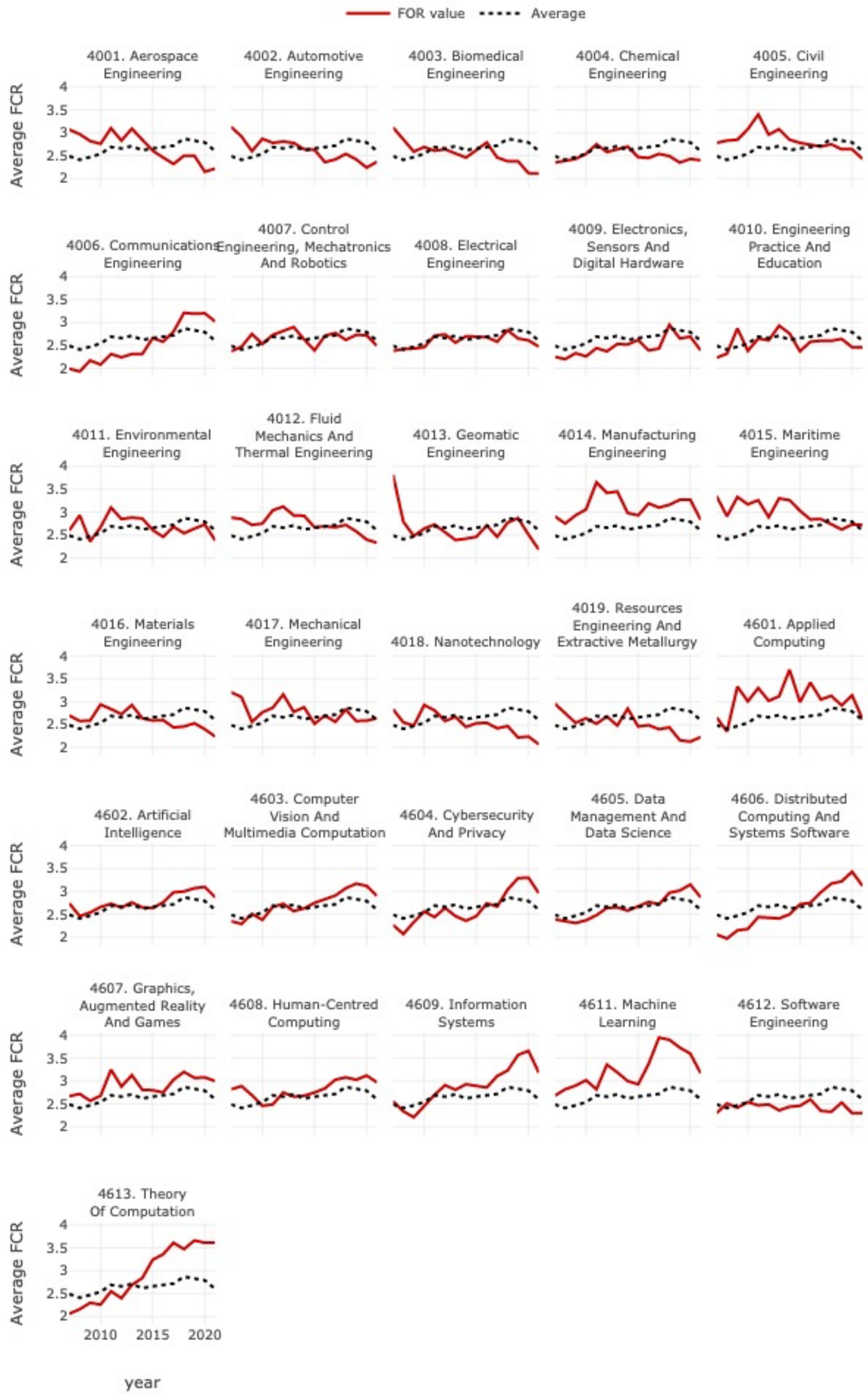


Figure 12: Field Citation Ratio trends for UK engineering, 2007 to 2021 (average based on the combined total of the 31 Fields of Research).

Table 7: Top 1% publications for each Field of Research in the UK, from 2007 to 2021.

Field of Research	Number of publications in the top 1%	Number of publications	Percentage of publications in the top 1%
4601. Applied Computing	145	5324	2.7
4611. Machine Learning	440	18197	2.4
4607. Graphics, Augmented Reality And Games	141	7744	1.8
4603. Computer Vision And Multimedia Computation	316	18763	1.7
4609. Information Systems	214	12892	1.7
4613. Theory Of Computation	241	16450	1.5
4602. Artificial Intelligence	336	25612	1.3
4014. Manufacturing Engineering	192	15407	1.2
4605. Data Management And Data Science	422	35361	1.2
4009. Electronics, Sensors And Digital Hardware	390	36233	1.1
4006. Communications Engineering	455	42723	1.1
4606. Distributed Computing And Systems Software	224	20645	1.1
4608. Human-Centred Computing	233	21105	1.1
4604. Cybersecurity And Privacy	126	12096	1.0
4612. Software Engineering	114	11318	1.0
4013. Geomatic Engineering	52	6098	0.9
4007. Control Engineering, Mechatronics And Robotics	180	22615	0.8
4008. Electrical Engineering	263	31495	0.8
4010. Engineering Practice And Education	87	13157	0.7
4018. Nanotechnology	142	20744	0.7
4016. Materials Engineering	292	52024	0.6
4005. Civil Engineering	176	31001	0.6
4011. Environmental Engineering	28	5370	0.5
4003. Biomedical Engineering	117	24760	0.5
4017. Mechanical Engineering	57	15115	0.4
4015. Maritime Engineering	47	10553	0.4
4001. Aerospace Engineering	52	14261	0.4
4019. Resources Engineering And Extractive Metallurgy	26	10349	0.3
4012. Fluid Mechanics And Thermal Engineering	61	21607	0.3
4004. Chemical Engineering	64	20331	0.3
4002. Automotive Engineering	14	6008	0.2

5.2 International comparisons

The scientific impact of the UK research is globally leading in contrast to the volume of its research. We approach this analysis by looking at both the top 1% (based on citation rates) for engineering publications (see Table 8) and the geometric mean of FCR[11] by country (see Table 9) and by subdiscipline (Table 10) and trends (in Figure 13).

We note that the US and the UK had the highest share of top publications 1% with Canada behind the UK. Several Asian countries (including Japan, South Korea and India) are at the bottom of the table for the percentage of the top 1% publications. China, although with only half the share of the top 1% publications of the US, ranks second for the total number of publications in the top 1% based on the strong lead for the total number of publications in Engineering.

"The US and the UK had the greatest share of publications in the top 1% with Canada behind the UK."

[11] The geometric mean is often used to calculate performance - it is the average calculated by taking the square root of all the numbers multiplied together.

Table 8: Top 1% publications in the Engineering field in the benchmarking countries, from 2007 to 2021.

Countries	Number of publications in the top 1%	Number of publications	Percentage publications in the top 1%
United States	18,188	1,813,859	1.0
United Kingdom	4,532	491,624	0.92
Canada	2,454	328,289	0.75
Germany	3,491	573,816	0.61
France	2,230	414,169	0.54
Italy	1,741	336,181	0.52
South Korea	1,635	386,227	0.42
China	10,738	2,622,724	0.41
India	1,568	687,767	0.23
Japan	1,437	657,572	0.22

Table 9 provides a more nuanced look at the quality of engineering publications, applying the geometric mean FCR, revealing that the UK has the highest score of all the countries included. Moreover, only the UK, consistently above 2.5, and South Korea, at 2.25, maintain their average FCR over the time period.

China's FCR increased from below 2 (a value of 2 is twice the world average) from 2007 to 2013 to 2.52 in 2018 (see Figure 13). However, more recently, China suffered a decline similar to that in other countries. The biggest decline across the time span is evident for India, which has seen a reduction from 2.31 in 2007 to 1.75 in 2021. Japan performs consistently below all other countries for this measure of scientific impact.

Both Aerospace Engineering (4001) and Biomedical Engineering (4003) subdisciplines continue to show good performance in the UK compared to other countries. In fact, the UK ranks highest in Aerospace Engineering (4001) research (with a 2.6 average FCR, i.e., 2.6 times the global average of 1), followed by Italy and Canada (both with 2.5 average FCR), while for Biomedical Engineering (4003) the UK holds second place with Canada, South Korea, and the US (all with a 2.5 average FCR) and only behind China (with 2.6 average FCR) as seen in Table 10.

Table 9: Trend of the geometric mean FCR across selected countries, from 2012 to 2021.

Year	Canada	China	France	Germany	India	Italy	Japan	South Korea	UK	US
2007	2.33	1.73	2.25	2.25	2.31	2.29	1.65	1.81	2.49	2.54
2008	2.4	1.69	2.29	2.26	2.19	2.33	1.63	1.94	2.41	2.54
2009	2.42	1.67	2.28	2.25	2.15	2.42	1.64	2.04	2.47	2.49
2010	2.5	1.66	2.42	2.25	2.07	2.47	1.66	2.14	2.54	2.56
2011	2.64	1.69	2.38	2.42	1.96	2.53	1.67	2.22	2.69	2.63
2012	2.64	1.86	2.34	2.28	1.94	2.64	1.66	2.21	2.66	2.61
2013	2.58	1.96	2.31	2.31	1.92	2.58	1.63	2.22	2.71	2.59
2014	2.56	2.1	2.22	2.23	1.84	2.49	1.59	2.22	2.62	2.52
2015	2.52	2.37	2.19	2.23	1.83	2.48	1.56	2.26	2.66	2.53
2016	2.54	2.39	2.2	2.15	1.82	2.41	1.59	2.28	2.69	2.44
2017	2.53	2.46	2.13	2.13	1.82	2.44	1.56	2.37	2.72	2.49
2018	2.67	2.52	2.15	2.17	1.81	2.46	1.58	2.44	2.87	2.56
2019	2.68	2.48	2.09	2.14	1.85	2.35	1.6	2.49	2.84	2.53
2020	2.57	2.45	2.1	2.15	1.8	2.4	1.62	2.48	2.79	2.38
2021	2.39	2.23	2.0	2.06	1.75	2.28	1.61	2.4	2.6	2.19

Table 10: Average FCR for Engineering subdisciplines - international comparisons.

Country Field of Research	Canada	China	France	Germany	India	Italy	Japan	South Korea	UK	US
4001. Aerospace Engineering	2.5	1.9	2.3	2.0	1.8	2.5	1.5	2.2	2.6	2.2
4002. Automotive Engineering	2.5	2.3	2.5	2.1	2.3	2.5	1.5	2.2	2.6	2.5
4003. Biomedical Engineering	2.5	2.6	2.1	2.3	2.2	2.3	1.8	2.5	2.5	2.5
4004. Chemical Engineering	2.4	2.6	2.4	1.8	2.4	2.6	1.8	2.4	2.5	2.5
4005. Civil Engineering	2.6	2.0	2.7	2.3	1.9	2.8	1.5	2.3	2.8	2.4
4006. Communications Engineering	2.4	1.9	2.1	2.0	1.6	2.2	1.6	2.0	2.5	2.2
4007. Control Engineering, Mechatronics And Robotics	2.6	2.0	2.2	2.2	1.8	2.5	1.5	2.2	2.6	2.5
4008. Electrical Engineering	2.4	1.9	2.0	2.1	1.7	2.5	1.6	2.0	2.6	2.4
4009. Electronics, Sensors And Digital Hardware	2.3	1.8	2.0	2.0	1.7	2.3	1.6	2.2	2.5	2.2
4010. Engineering Practice And Education	2.7	1.8	2.2	2.1	1.8	2.5	1.4	2.3	2.5	2.2
4011. Environmental Engineering	2.4	2.6	2.4	2.5	2.4	2.6	1.9	2.5	2.6	2.5
4012. Fluid Mechanics And Thermal Engineering	2.4	2.4	2.5	2.2	2.2	2.6	1.5	2.2	2.7	2.4
4013. Geomatic Engineering	2.3	2.0	2.2	2.4	1.7	2.4	1.6	2.1	2.6	2.5
4014. Manufacturing Engineering	3.0	2.0	2.5	2.1	2.4	2.9	1.5	2.2	3.1	2.6
4015. Maritime Engineering	2.5	2.0	2.6	2.4	1.9	2.9	1.5	2.1	2.9	2.4
4016. Materials Engineering	2.5	2.7	2.2	2.2	1.9	2.3	1.7	2.4	2.6	2.5
4017. Mechanical Engineering	2.6	2.5	2.0	2.2	2.3	2.7	1.5	2.2	2.8	2.5
4018. Nanotechnology	2.4	2.8	2.1	2.3	2.0	2.3	1.8	2.4	2.5	2.7
4019. Resources Engineering And Extractive Metallurgy	2.5	2.2	2.4	1.6	1.9	2.3	1.8	2.1	2.5	2.4
4601. Applied Computing	2.8	2.3	2.1	2.6	2.3	2.8	1.8	2.6	3.0	2.7
4602. Artificial Intelligence	2.7	2.0	2.2	2.4	2.0	2.5	1.5	2.2	2.8	2.7
4603. Computer Vision And Multimedia Computation	2.5	2.1	2.3	2.5	1.7	2.5	1.6	2.0	2.8	3.0
4604. Cybersecurity And Privacy	3.0	2.2	2.4	2.4	1.8	2.7	1.8	2.2	2.8	2.9
4605. Data Management And Data Science	2.6	2.0	2.0	2.1	1.8	2.4	1.5	2.1	2.7	2.6
4606. Distributed Computing And Systems Software	2.8	2.2	2.2	2.2	1.7	2.6	1.8	2.1	2.7	2.8
4607. Graphics, Augmented Reality And Games	2.7	2.2	2.5	2.9	1.7	2.4	1.5	2.0	2.9	3.2
4608. Human-Centred Computing	2.7	2.2	2.3	2.5	1.9	2.6	1.5	2.1	2.9	2.7
4609. Information Systems	2.7	1.9	2.3	2.3	1.9	2.6	1.4	2.4	2.9	2.8
4611. Machine Learning	3.1	2.7	2.6	2.9	2.1	2.8	1.8	3.1	3.3	3.3
4612. Software Engineering	2.6	1.6	2.1	2.2	1.7	2.5	1.6	1.8	2.4	2.4
4613. Theory Of Computation	2.8	2.2	2.4	2.4	1.6	2.5	1.7	2.2	3.0	2.9

Figure 13: Trends for the geometric mean FCR for comparator countries, from 2012 to 2021.

5.2.1 Share of the global top 1%

In the context of highlighting scientific excellence internationally, we also look at each of the countries share of global top 1% cited publications. This measure reveals that the UK is lagging behind both the US and China but just ahead of Germany and India. This may be explained by the UK performance in Computing Science, where it outperforms Germany, and in the head-to-head comparison between the UK and Germany, Germany's lead over the UK in Engineering is less pronounced.

When we look at the global top 1% cited publications in Engineering (excluding Computer Science in this case), made up of subdisciplines within this field, the scientific impact of the UK is equal to that of India and South Korea (see Table 11). The number of US top 1% cited publications, as a measure of scientific impact in Information and Computing Science (FoR 46), which consists of the subdisciplines in this field, is notable, with more than twice the percentage of publications in the global top 1% than China and exceeds all other comparator countries. For the main field, Engineering (FoR 40), China has a higher percentage of global top 1% cited publications and the UK lags behind both the US and China (see Table 11). The relative strength in performance of Anglo-American countries in Information and Computing Sciences (FoR 46) may be influenced by corporate contributions to research underpinning publications - some of the biggest research-active companies are based in the US and the UK.

"The relatively notable performance of Anglo-American countries in Information and Computing Sciences (FoR 46) may be influenced by corporate contributions to the research underpinning publications - some of the biggest research-active companies are based in the US and the UK."

Table 11: International comparison of percentage of publications in the top 1% (2007-2021).

Country	40 Engineering & 46 Information and Computing Science	40 Engineering	46 Information and Computing Science
United States	19.6	18.5	23.1
China	14.8	16.3	9.4
United Kingdom	2.7	2.4	3.1
Germany	2.6	2.6	2.7
India	2.2	2.4	1.8
South Korea	2.1	2.4	1.3
Japan	1.8	2.1	0.8
Canada	1.8	1.7	2.0
France	1.5	1.5	1.4
Italy	1.3	1.3	1.4

The share of the top 1% cited publications for each comparator country is shown in Figure 14. The dotted diagonal lines indicate equal share value of the top 1% cited publications in engineering. The greater the distance from the dotted line, the greater the share of Engineering (towards the x-axis) or Computer Science (towards the y-axis). Four countries (Italy, France, Canada, and Germany) are very close in level of quality for FoR 40 Engineering and FoR 46 Information and Computer Sciences. Four Asian countries, Japan, South Korea, India and China, show increased performance in top 1% cited publications in Engineering (FoR 40) than in Information and Computer Sciences (FoR 46), and the UK, US and Canada show increased performance in Information and Computer Sciences over Engineering.

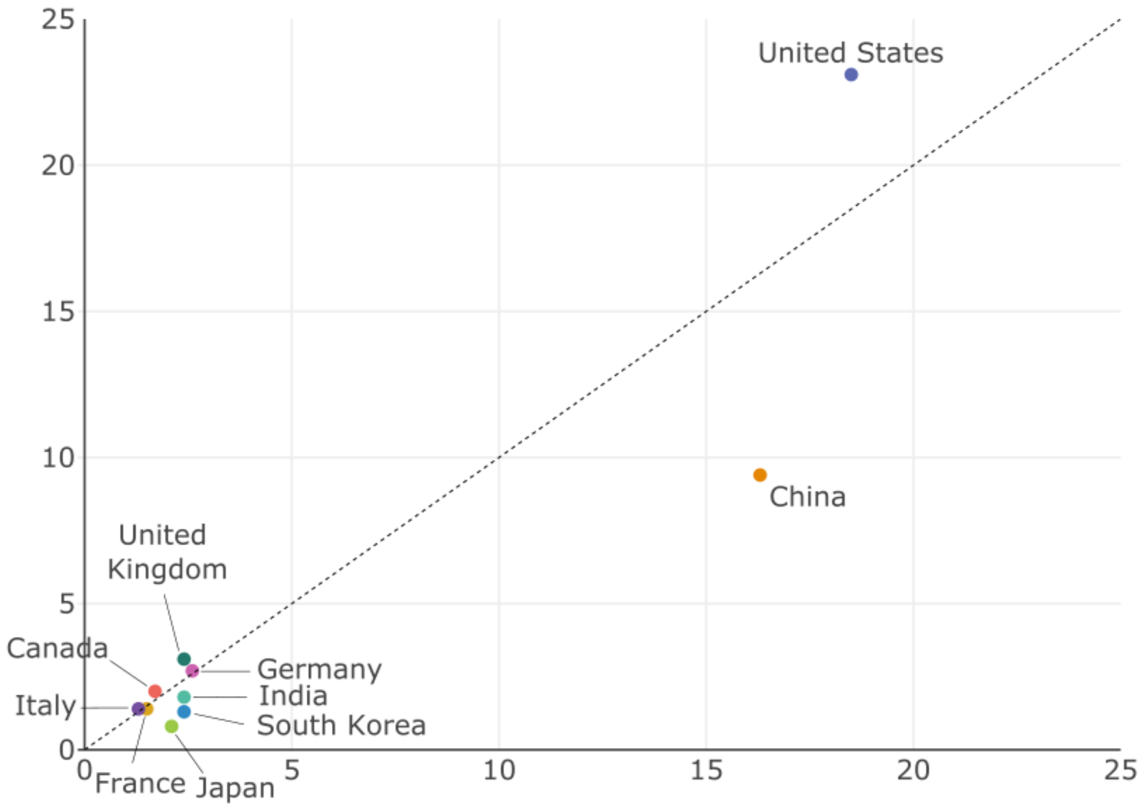


Figure 14: Share of top 1% cited publications in FoR 40 Engineering (x-axis) vs FoR 46 Information and Computing Sciences (y-axis) across the selected countries.

5.3 Tomorrow's Engineering Research Challenges (TERC): Technological Challenges

We compared UK trends based on FCR for each of the eight TERC Technological Challenge areas against international trends.

Similarly to the results shown above, the UK FCRs (used as a measure of research quality) are notable, particularly in 'space research' and 'responsible engineering', outperforming all other countries included.

China, although performing well in 'materials' (Figure 17) and 'nature-based engineering' (Figure 21) and having a higher FCR than the UK from 2012 onwards, did not have higher FCRs in other areas. However, for 'health and wellbeing' (Figure 18), China performed better during the last seven years catching up and reaching an FCR of 2, still lagging the UK performance with a FCR of 2.7 (Figure 18).

Figures 15 to 22 shown below show trends in FCR for the comparator countries for the TERC Technological Challenges.

5.3.1 Space research

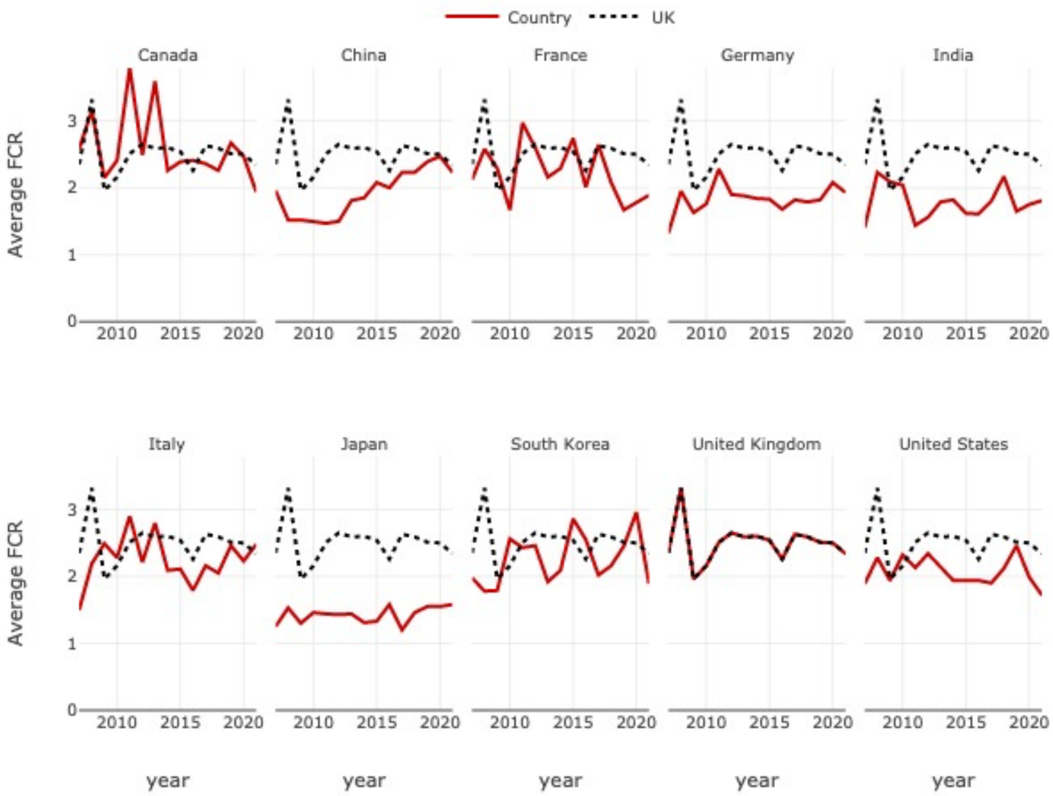


Figure 15: Trends for Field Citation Ratios in sustainable space research (as defined in the TERC) across comparator countries.

5.3.2 Transportation systems

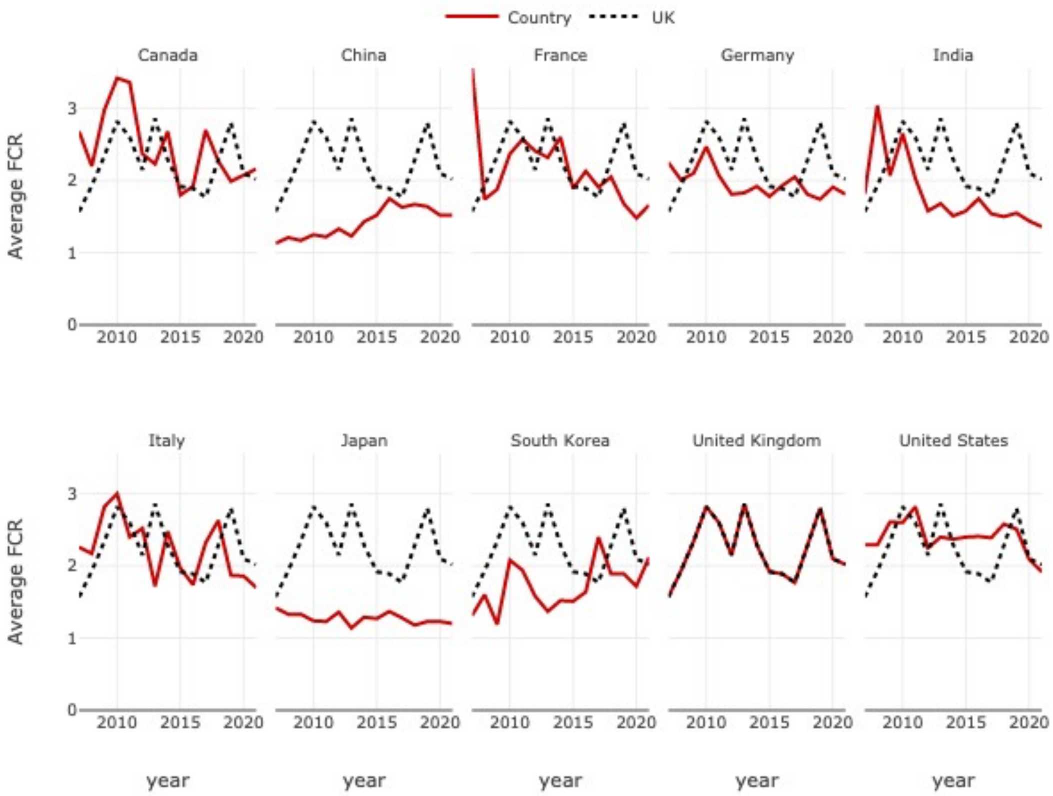


Figure 16: Trends for Field Citation Ratios in sustainable and equitable transport research (as defined in the TERC) across comparator countries.

5.3.3 Materials research

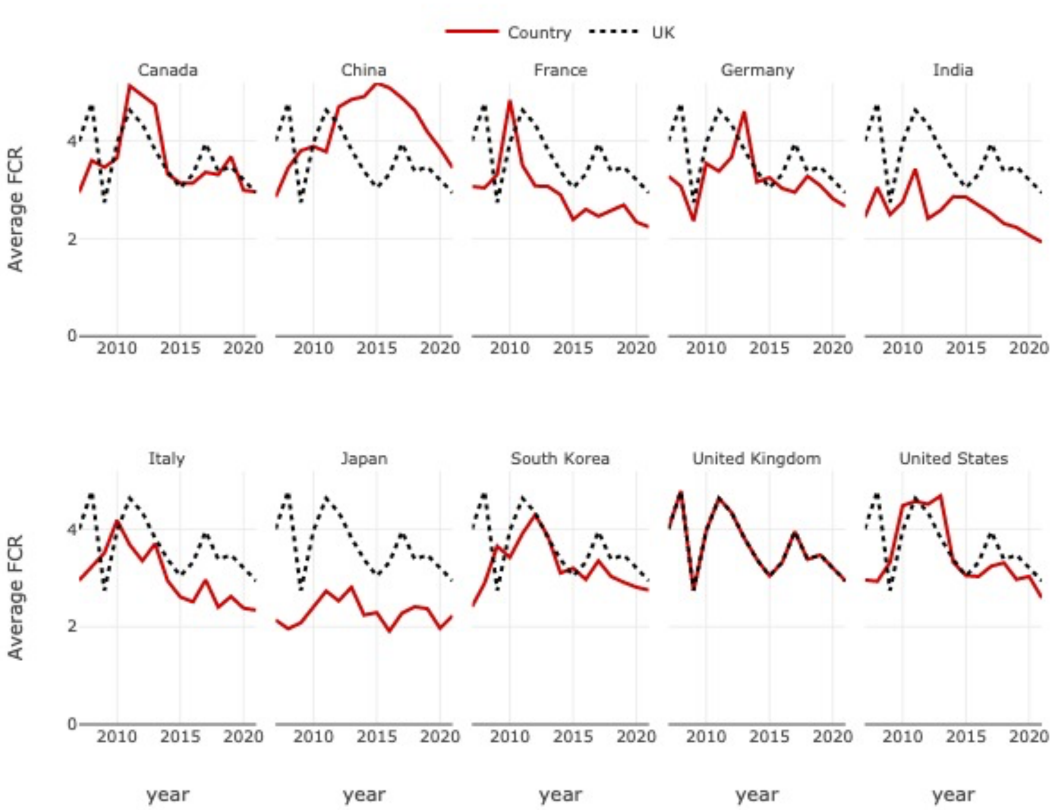


Figure 17: Trends for Field Citation Ratios in environmentally and socially sustainable materials research (as defined in the TERC) across comparator countries.

5.3.4 Health and wellbeing

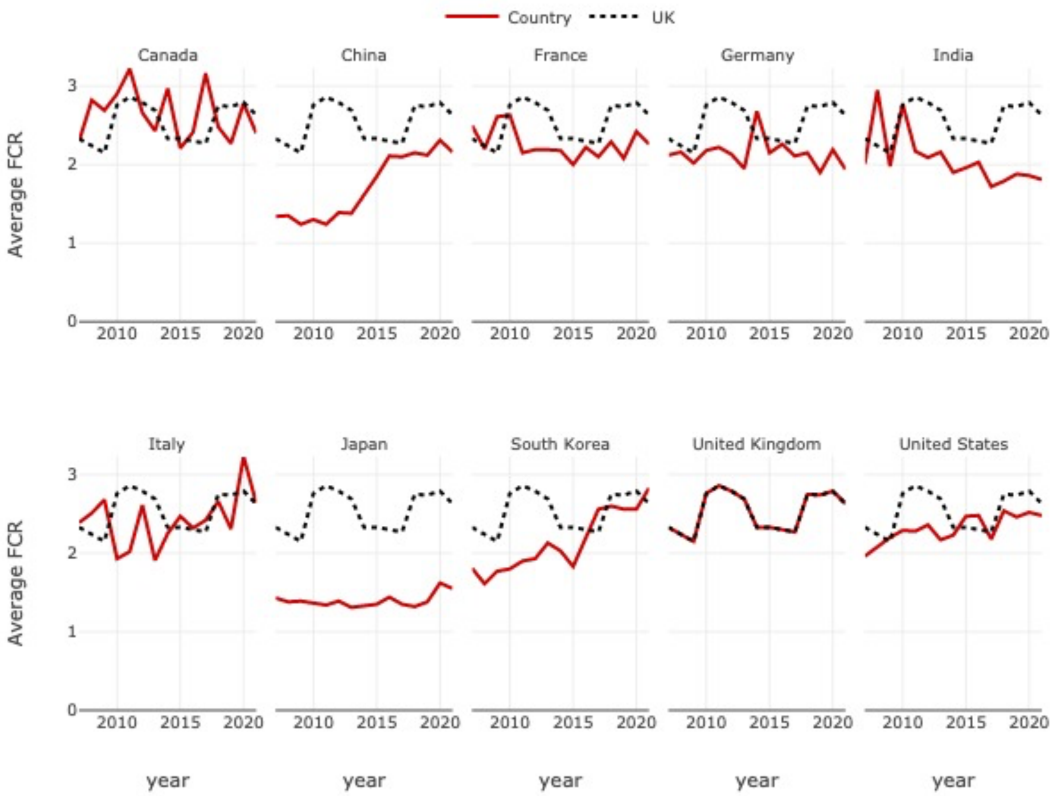


Figure 18: Trends for Field Citation Ratios in sustainable, inclusive, and resilient health research (as defined in the TERC) across comparator countries.

5.3.5 Robotics and AI

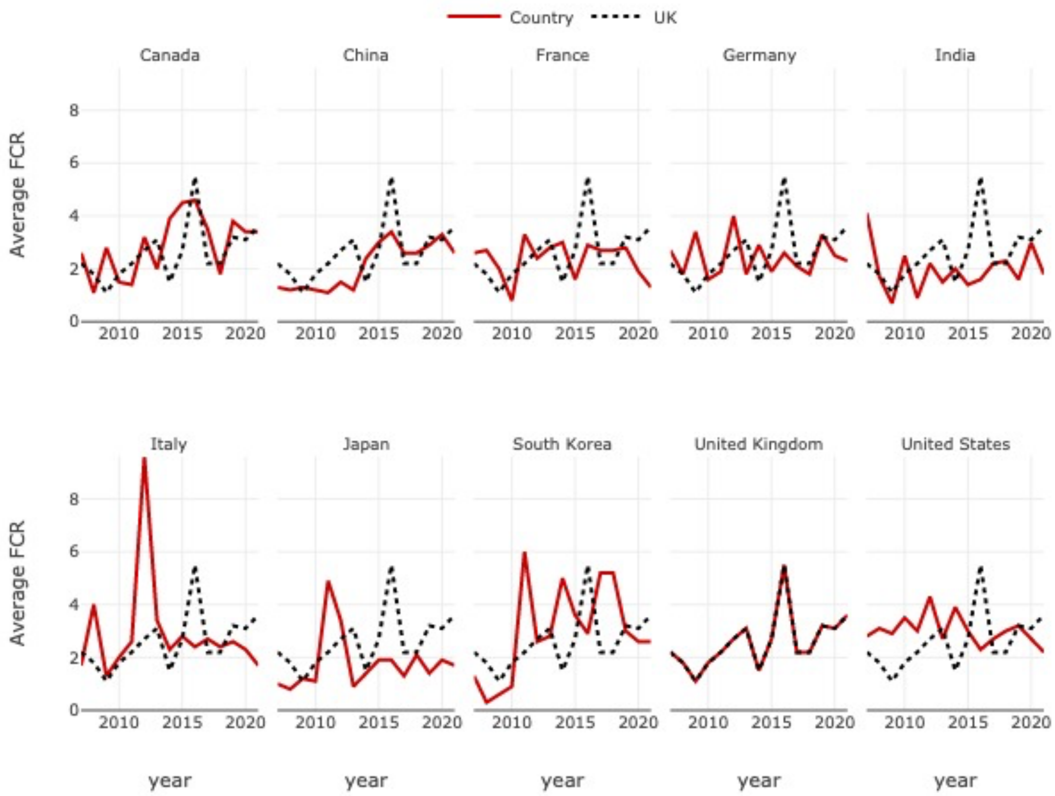


Figure 19: Trends for Field Citation Ratios in ethical use with transparent and equitable robotic and AI research (as defined in the TERC) in comparator countries.

5.3.6 Responsible engineering

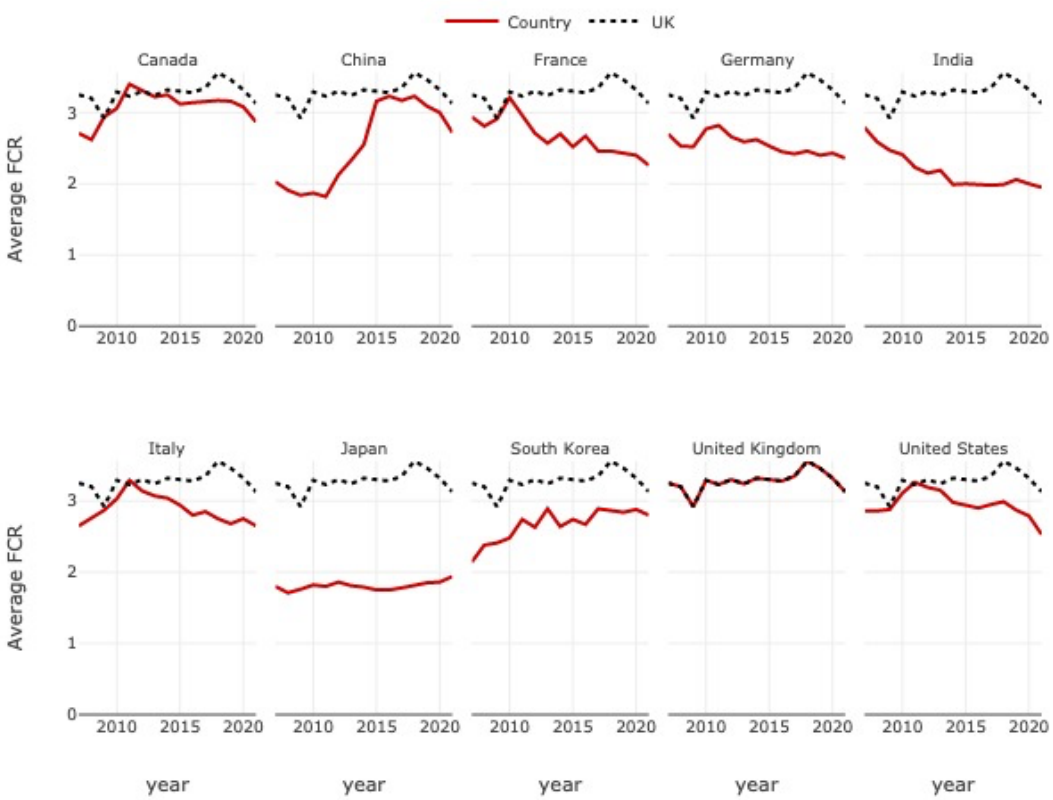


Figure 20: Trends for Field Citation Ratios in socially and environmentally responsible approaches to engineering research (as defined in the TERC) across comparator countries.

5.3.7 Nature-based engineering

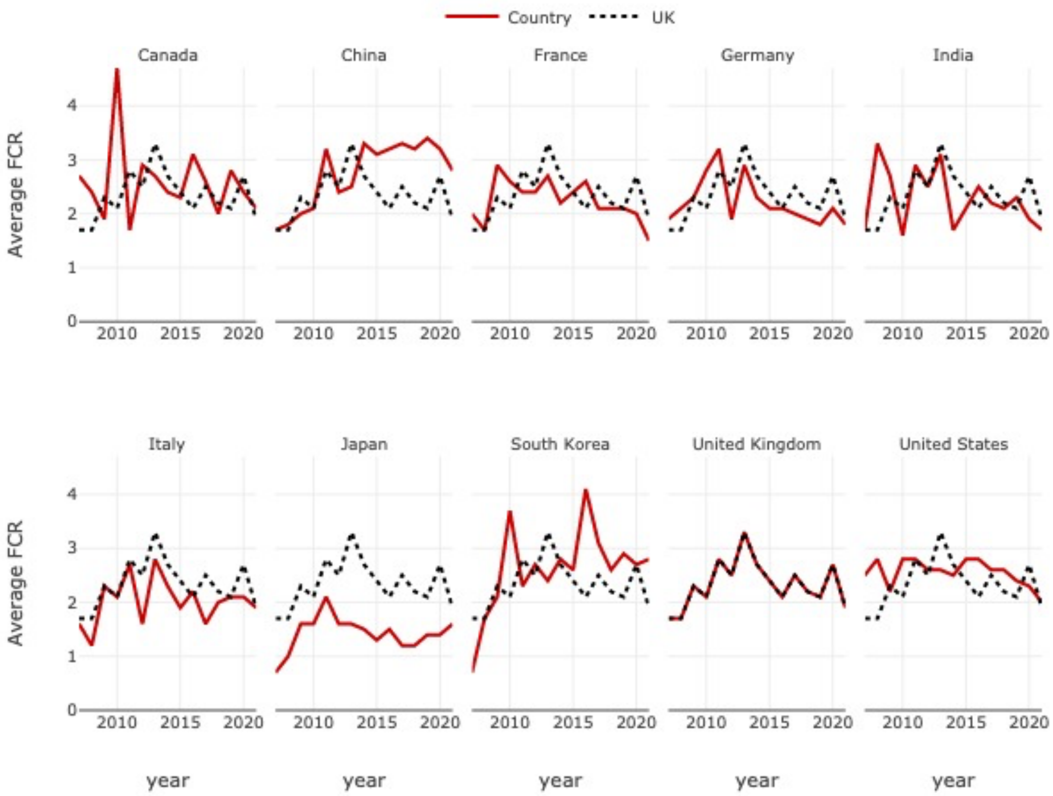


Figure 21: Trends for Field Citation Ratios in nature-based engineering research (as defined in the TERC) across comparator countries.

5.3.8 Global engineering

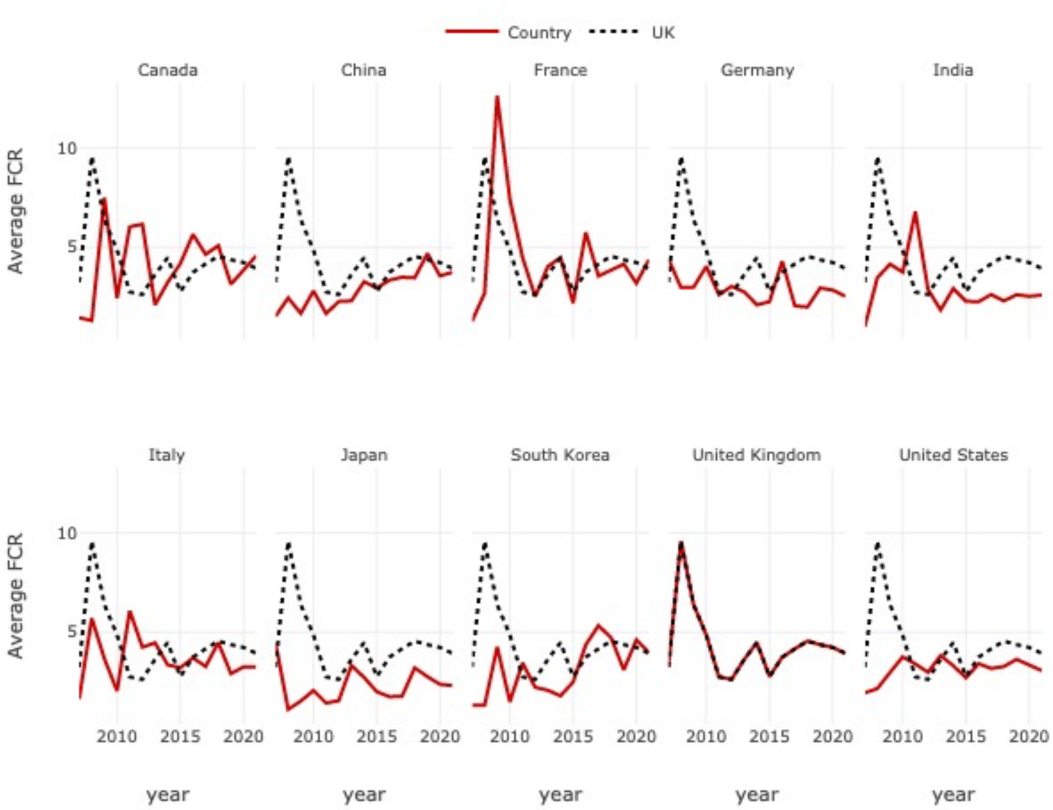


Figure 22: Trends for Field Citation Ratios in global engineering (as defined in the TERC) across comparator countries.

Major funders

The majority of funders (as highlighted in the acknowledgement section of publications) are UK based with the top funder being EPSRC.

The two top non-UK funders and co-funders are the European Commission and the National Natural Science Foundation China. Four of the 10 biggest funders and co-funders are based in China, the remainder are based in Europe.

This section of the report explores the major funders and co-funders of UK engineering research based on funding bodies named in the acknowledgements within a publication. On this basis, the analysis does not focus on the monetary value of funding but rather provides a 'signal' of organisations active in funding UK engineering research.

6.1 National funding

In the UK, the EPSRC is the largest funder / co-funder of UK engineering research, with the Royal Society the second largest, based on the numbers of publications acknowledging funders (see Table 12). The EPSRC accounts for more than two-thirds of engineering research funding / co-funding. Other UKRI constituent funding bodies (NERC, MRC, BBSRC, Innovate UK and STFC) account for six of the top 10 funders of engineering research in the UK.

"In the UK, the EPSRC is the largest funder / co-funder of UK engineering research."

Non-UKRI funders in the top 10 include the Royal Society, the Royal Academy of Engineering, Wellcome Trust, and Leverhulme Trust.

Table 12: Number of Engineering publications funded by the top 10 funders in the UK, from 2007 to 2021.

Funder	Number of publications
Engineering and Physical Sciences Research Council (EPSRC)	151,486
Royal Society	15,664
Natural Environment Research Council (NERC)	8,134
Medical Research Council (MRC)	7,467
Biotechnology and Biological Sciences Research Council (BBSRC)	6,852
Wellcome Trust	5,749
Royal Academy of Engineering	5,731
Science and Technology Facilities Council (STFC)	5,416
Leverhulme Trust	5,297
Innovate UK	5,291

6.2 International funding and co-funding

Internationally, and perhaps more surprising, the two top non-UK funders / co-funders of international collaborative Engineering research are the European Commission and the National Natural Science Foundation China. However, we note that the number of publications that have been published as a consequence of these two funding streams (121,000) does not reach that for the top UK funder, the EPSRC (151,000).

"Internationally, and perhaps more surprising, the two top non-UK funders / co-funders of international collaborative engineering research are the European Commission and the National Natural Science Foundation China."

Other non-UK funders that are prominent are the European Research Council and the Chinese Ministry of Science and Technology, which together fund the same number of awards as the Royal Society, the second highest UK funder in Engineering.

Interestingly, four of the 10 biggest funders / co-funders acknowledged for UK research in Engineering are based in China, the remainder being in Europe. There are no US funders of engineering research in the top 10, even though the US is a key producer of publications in this field, second to China (see Table 13). Chinese funders are named as co-funders in 18.8% of all UK publications in Engineering.

"Four of the 10 biggest funders / co-funders acknowledged for UK research in Engineering are based in China, the remainder being in Europe."

In the evolving landscape of international support for UK engineering publications, particularly from the EU and China, the anticipated challenges – stemming from Brexit and ongoing geopolitical tensions – might be mitigated, especially with the UK reinvigorated partnership with Horizon Europe. It is crucial to note that China's role in funding UK engineering research is not necessarily direct; rather, it operates through a model of co-funding alongside UK funders. Importantly, co-funding of a publication does not necessarily involve direct funding of UK researchers. Although our analysis does not allow us to quantify the prevalence of different models, the existence of very large-scale transnational European funding programmes suggests that it will often be the case that UK researchers will be directly receiving money from those European programmes, whereas for Chinese partnerships it will more often be partnerships between UK and Chinese researchers, each receiving funding from their respective government. The extent and significance of these partnerships is still notable (especially when compared to the many other engineering nations with whom UK researchers partner without receiving funding directly), and further analysis of their dynamics merits. The extent of the partnerships underlines the many shared objectives in advancing engineering research.

Of interest here (see Table 13) is the lack of US funders in the top 10 global funders / co-funders of UK engineering research (as of June 2023) with overall 20,774 publications being funded by a US-based funder.

Table 13: Number of UK Engineering publications funded / co-funded by the top 10 global funders, from 2007 to 2021.

Funder	Country	Number of publications
European Commission	-	65,913
National Natural Science Foundation of China	China	55,396
European Research Council	-	16,265
Ministry of Science and Technology of the People's Republic of China	China	15,381
China Scholarship Council	China	10,135
Ministry of Economy, Industry and Competitiveness	Spain	6,050
Ministry of Education of the People's Republic of China	China	6,018
Deutsche Forschungsgemeinschaft	Germany	4,954
Australian Research Council	Australia	40,69
Japan Society for the Promotion of Science	Japan	3,879

6.3 Funding from industry

Methodological note. For this analysis, we used the GRID typology shown below. The typology is manually curated by Digital Science.

- Archive
- Company
- Education
- Facility
- Government
- Healthcare
- Non-profit
- Other

We consider everything not categorised as 'Company' to be non-industry.

Dimensions indexes grants that are publicly available or shared by their funder; companies' funding is not as widely shared as academic funding, hence the potentially limited view shown here. Nevertheless, traces of industrial funding are available in Dimensions.

As such and similarly to the above section, the analysis of funding is based on acknowledgements of funding as communicated in published research. Numbers represent what is accessible; non-disclosed funding is not available for analysis.

Figure 23 shows that the funding received from industry is relatively small and, since 2015, represents between 1% and 3% of named funders based on the communication of the funding support from industry in the acknowledgement sections of publications.

Figure 23 below reveals that industry funding is highest in Aerospace Engineering (4001), and this funding has remained more or less stable over recent years but below that of 10 years ago (> 5%). Companies such as Rolls-Royce and Airbus support the majority of publications that include acknowledgement to industry. Manufacturing Engineering (4014) and Mechanical Engineering (4017) both received a considerable amount of industry funding at the beginning of the time period for analysis, but both disciplines saw a decline in funding more recently.

By contrast, increases over time (albeit smaller) were seen for industry funding in Graphics, Augmented Reality And Games (4607), and in Machine Learning (4611), with key funders including Google, Nvidia, and Microsoft. In an increasingly digital world, this is perhaps not surprising.

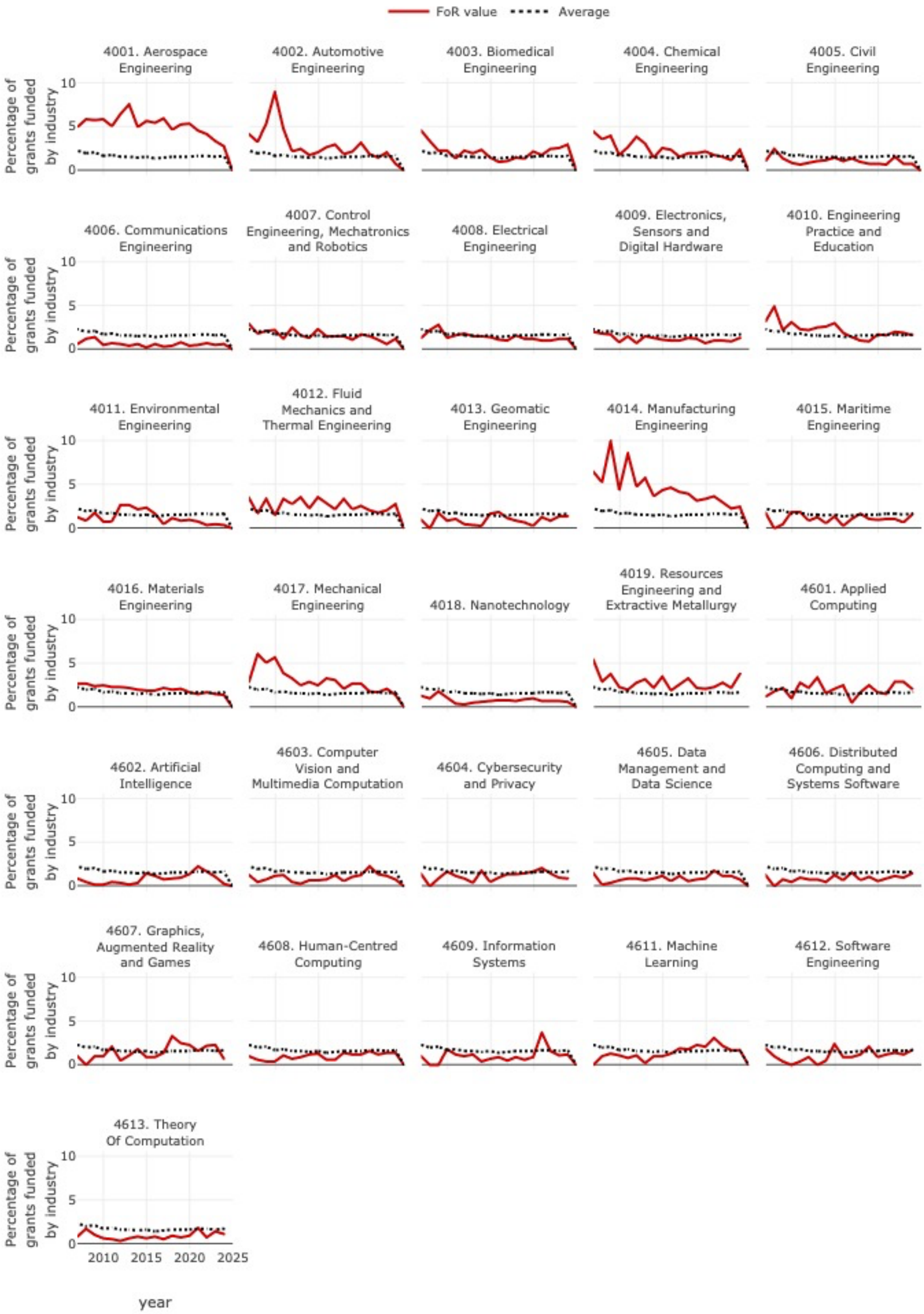
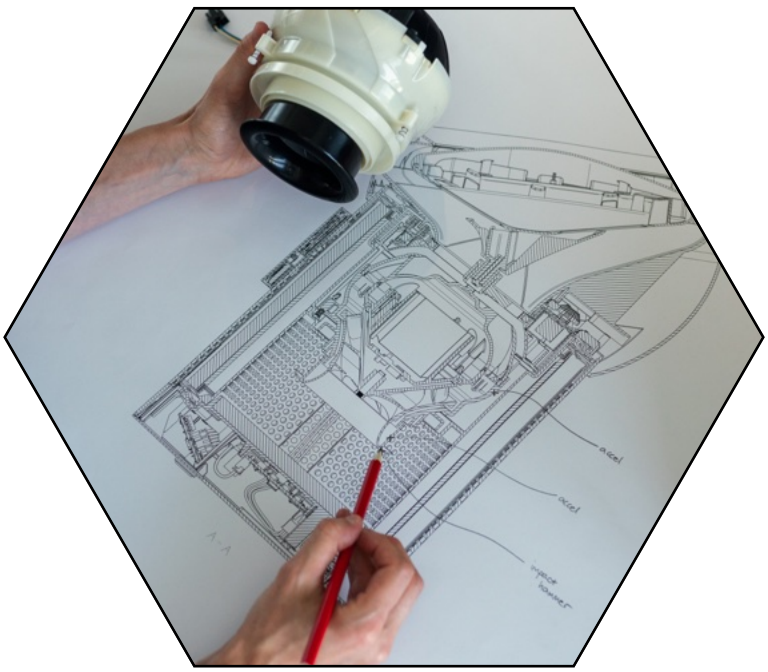


Figure 23: Time trends for percentage of UK engineering research grant funding by industry.

Research integrity and reproducibility

Trust markers for research integrity have become increasingly important to assess the quality, reproducibility and usability of data, from data and code availability to statements relating to ethical approvals and potential conflicts of interest.

Comparing the UK across facets of research integrity against an international average reveals that compliance across the engineering sector particularly in Biomedical Engineering (4003) for data and code availability is generally good.



Methodological note. Research integrity has become high on the UK policy agenda. In 2023, a report by the House of Commons Science and Technology Committee recommended that greater attention be given to research integrity[12]. This in turn led to the creation of the UK Committee on Research Integrity in 2022.

There is currently no common framework to assess research integrity and reproducibility, and in this report, we have made use of information available via 'Dimensions Research Integrity', which has the ability to measure the uptake and usage of trust markers across the global published landscape, based on the analysis of 33M full-text articles from 2010 onwards. It tracks data availability, code availability, ethics statements, author contributions statements, and competing interests statements.

It is important to mention here that different subdisciplines will be different with regard to the trust markers that are included. For example, a code availability statement will be included in a discipline that uses code in the research but will not be included in research that does not use code.

7.1 Research integrity in UK engineering research

Trust markers for research integrity - the explicit statements on a paper such as funding, data availability, conflict of interest, author contributions, and ethical approval - represent a contract between authors and readers that proper research practices have been observed. Trust markers highlight a level of transparency within a publication and reduce the reputational risks of allowing non-compliance with research integrity policies to go unobserved.

[12] Reproducibility and Research Integrity. Sixth Report of Session 2022–23.

7.1.1 Data and code availability

Data availability is the trust marker relating to the information about data collected and used to inform the research contained in a 'data availability statement' in publications. It has increased substantially across all areas of engineering. In particular, Biomedical Engineering (4003) reveals a continuous upward trend for inclusion of data availability statements in its research output. We detect in Dimensions that 20% of publications in Biomedical Engineering (4003) include a 'data availability statement'. Moreover, the inclusion of data availability statements in Machine Learning (4611) research outputs was seen to be greater than in other subdisciplines between the years 2012-2016 before decreasing in number, reaching below-average values by 2022 (see Figure 24).

Code availability is similar to the data availability trust marker but relates to a code availability statement. It does not follow the same patterns observed for data availability with fewer publications making the code behind the research publicly available (directly or indirectly, as the trust marker only detects if the section is available within the document). This is likely to reflect the nature of the research - more publications have data underpinning research than code.

Code availability is greatest in publications in the field of Engineering (FoR 40), in particular Geomatic Engineering (4013). For Computer Science publications, Applied Computing (4601) and Machine Learning (4611) have the best code availability, as seen in Figure 25, which outlines FoR values in red and the UK average as dotted lines.

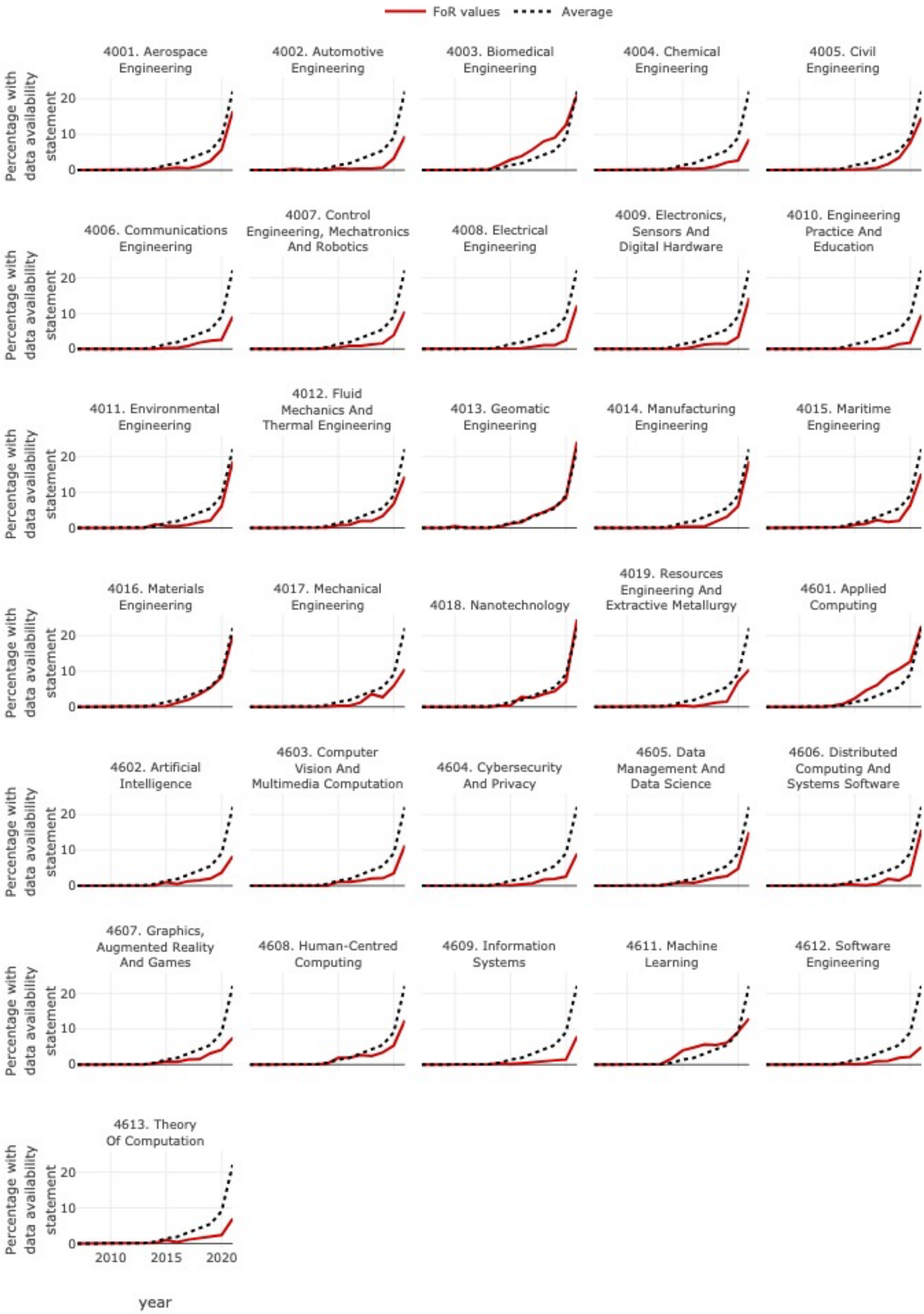


Figure 24: Percentage of data availability statements for UK engineering research (dotted line is UK average).

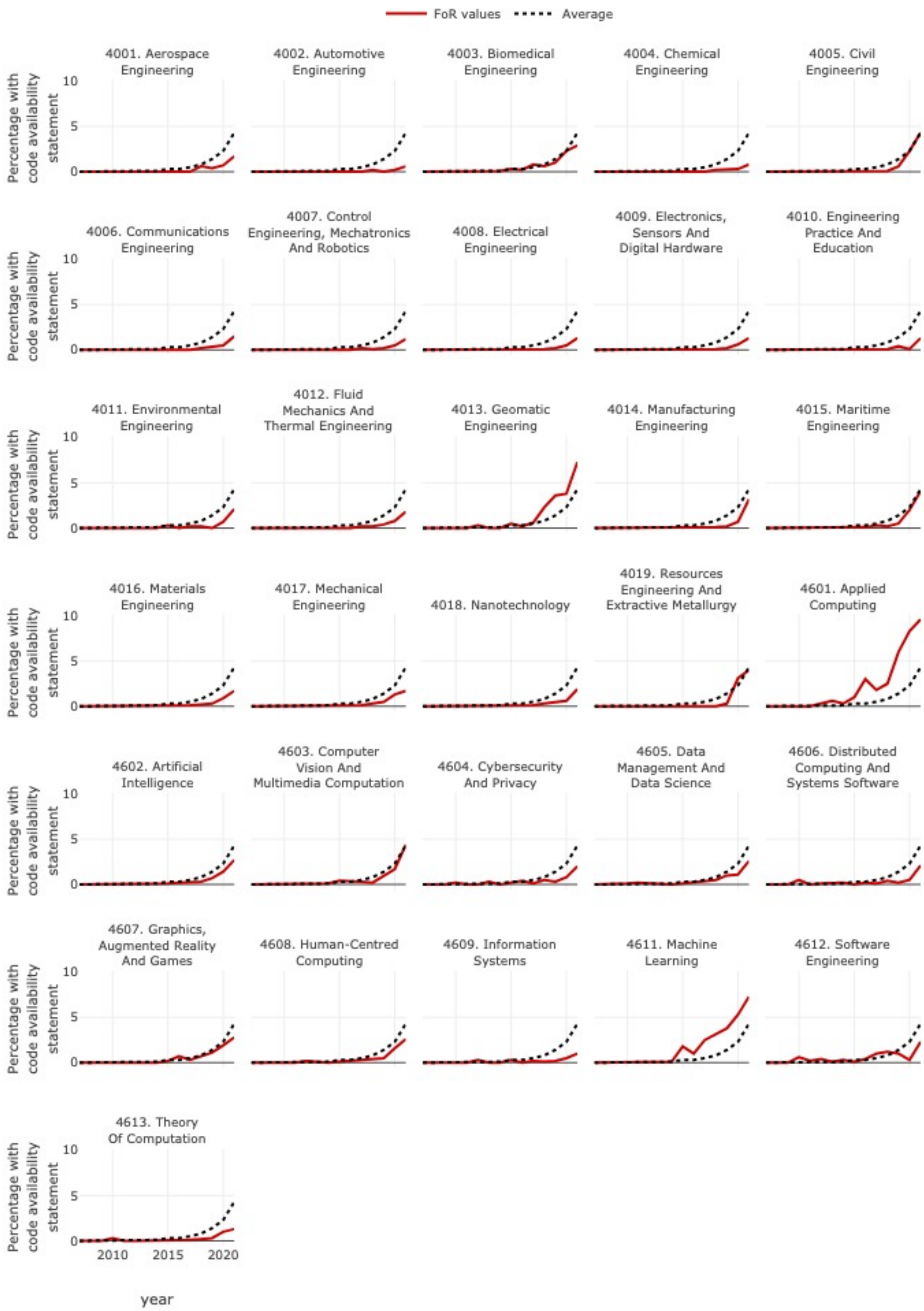


Figure 25: Percentage of code availability statements for UK engineering research (dotted line is UK average).

7.1.2 Ethics approval and conflict of interest statements

With regard to ethics approvals and conflicts of interest statements, we identified the percentage of publications that include an ethics approval statement (which highlights where ethical approval was obtained). Not all research requires ethical approval, but it is expected that publications will acknowledge one if it is required (e.g., "this research did not contain any studies involving animal or human participants, nor did it take place in any private or protected areas").

The subdiscipline Biomedical Engineering (4003) includes 12% publications with ethics approval statements, and for Human-Centred Computing (4608) 10% of publications include ethics approval statements. Likewise, Machine Learning (4611), Computer Vision, Environmental Engineering (4011) and Geomatic Engineering (4013) each include 5% of publications that have ethics statements. See Figure 26, which shows FoR values as a red line and the UK average as dotted lines.

Finally, we look at the inclusion of statements for 'conflicts of interest' where we see a higher percentage of research publications in disciplines within Engineering that include a 'Conflicts of Interest' statement than in disciplines within Computer Science, with the exception of Applied Computing (4601). There could be several explanations for this difference, including the fact that engineering researchers may feel the need to distance the research from powerful industrial players and further state the independence of their research, and a stronger culture to do so in comparison with researchers in the Computer Sciences fields (see Figure 27).

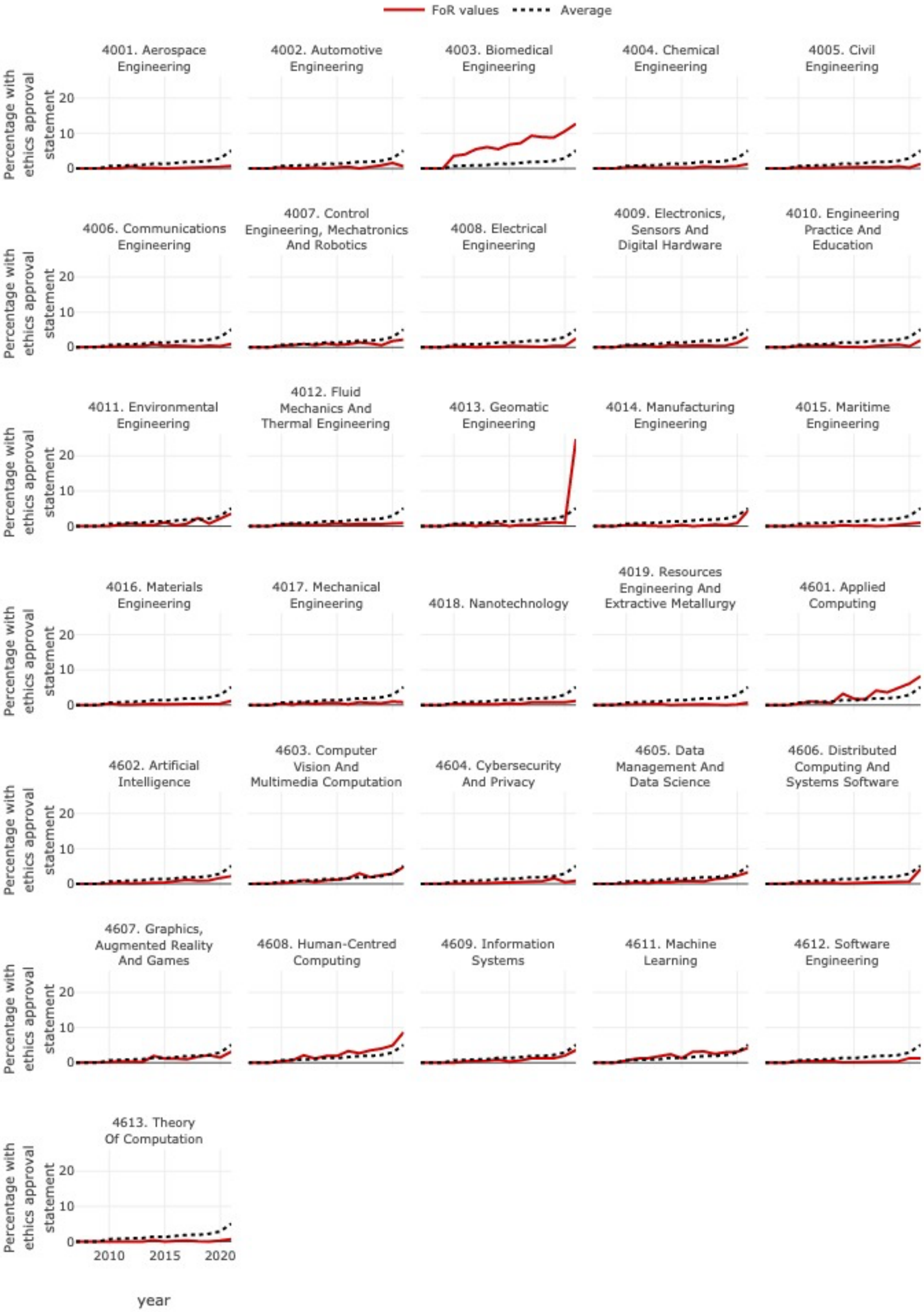


Figure 26: Percentage publications that include ethics approval statements (dotted line is UK average).

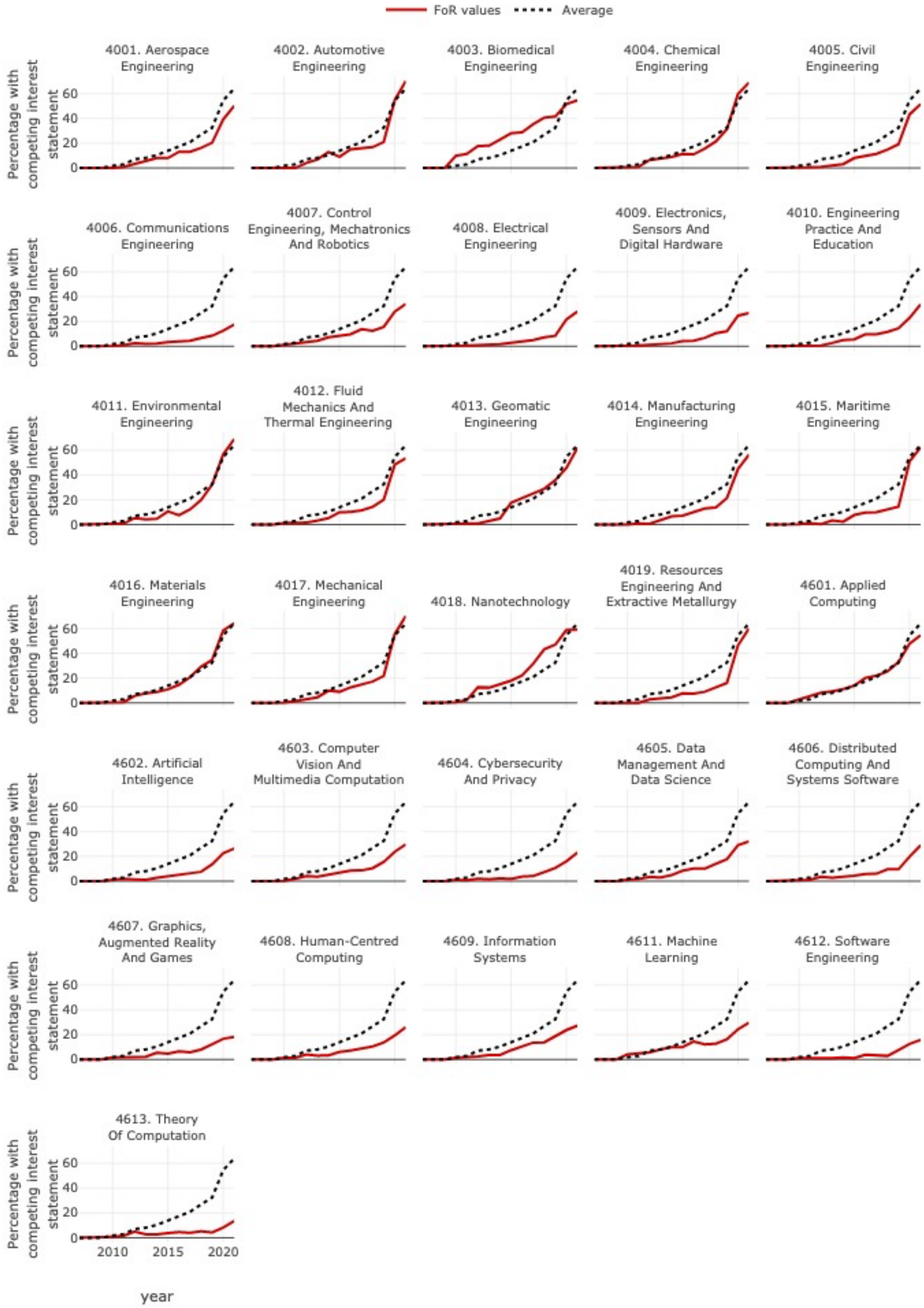


Figure 27: Percentage of publications that include conflicts of interest statements (dotted line is UK average).

7.2 Data integrity - international comparisons

7.2.1 Data and code availability

The analysis of data and code availability, Figures 28 and 29, respectively, reveal general upward trends for the UK for both, with the UK value as a dotted line and the average for the comparator countries as a red line.

All countries follow an upward trajectory; however, India and Japan increasingly include statements for data and code availability, at a slower rate. This is most pronounced for code availability (Figure 29), where the other Asian countries in this comparison, including China and South Korea are also slower to include statements. We cannot rule out the fact that their research focus is not in areas where code availability statements would be mandatory; however, given that the shape of the world is increasingly moving towards the digital age, it is perhaps unlikely to account for this.

Compliance with data availability (Figure 28), also reveals an upward trend for all countries, but for the majority, this trend is most apparent in recent years, and again, India and Japan trail in compliance. Regarding the UK, the upward trajectory is only surpassed by South Korea, Germany, China, and Italy.

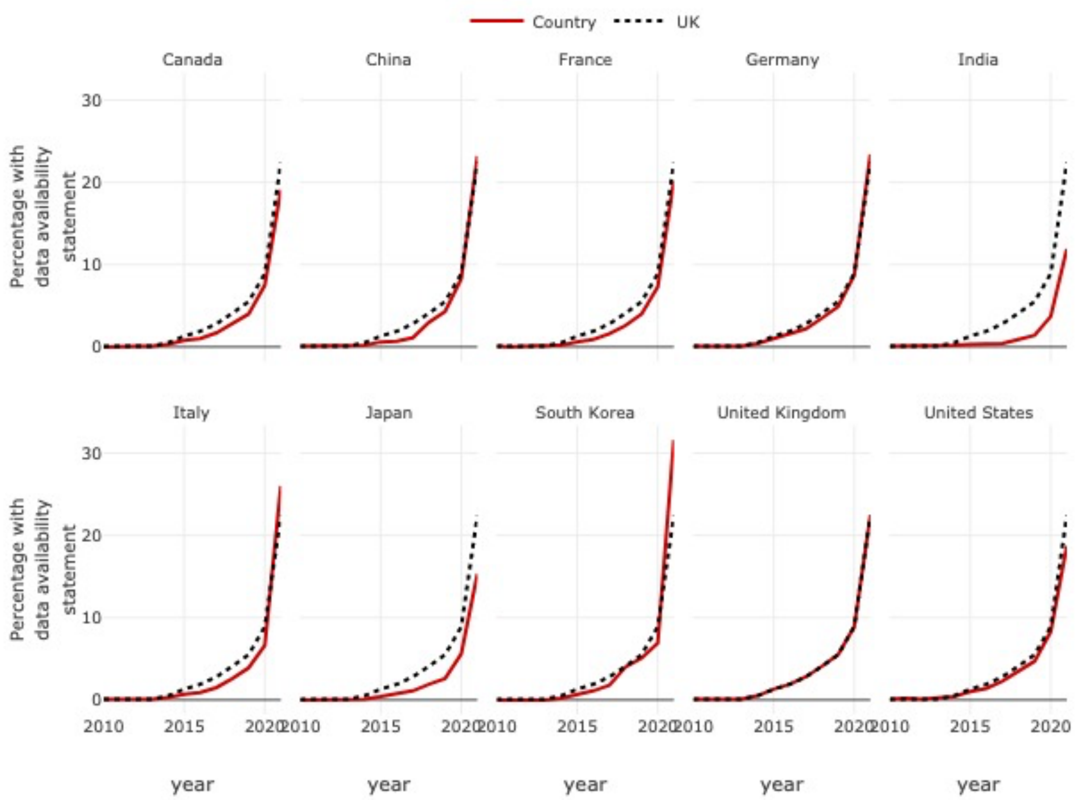


Figure 28: Data availability - international comparisons.

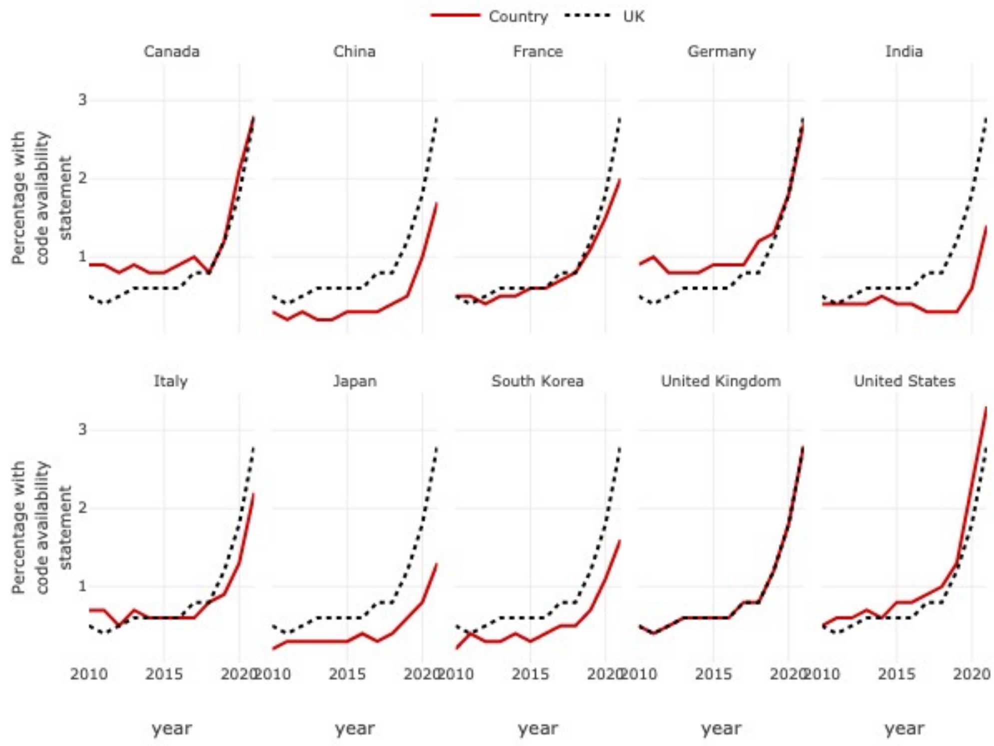


Figure 29: Code availability - international comparison.

7.2.2 Ethics statements and conflict of interest statements

Generally, the number of ethics statements included in research publications in engineering in the UK and comparator countries is comparatively low. It is likely that the need for the inclusion of ethics approval is not as great in engineering disciplines as it is in other fields of research. A similar picture emerges for engineering across the comparator countries where the inclusion of ethics approval statements increases dramatically, but again the numbers are small (Figure 30).

However, a different picture emerges for the conflict of interest statements (see Figure 31). Both South Korea and China reveal much sharper increases in the inclusion of statements over the time span. One possibility for this is potential partnerships with industry. Drilling deeper into the data could reveal the reason for this with more certainty.

Internationally, the UK trails China and South Korea but includes conflict of interest statements at almost approximately the same rate as France and Italy. As with a number of other international comparisons, India and Japan are least likely to include statements.

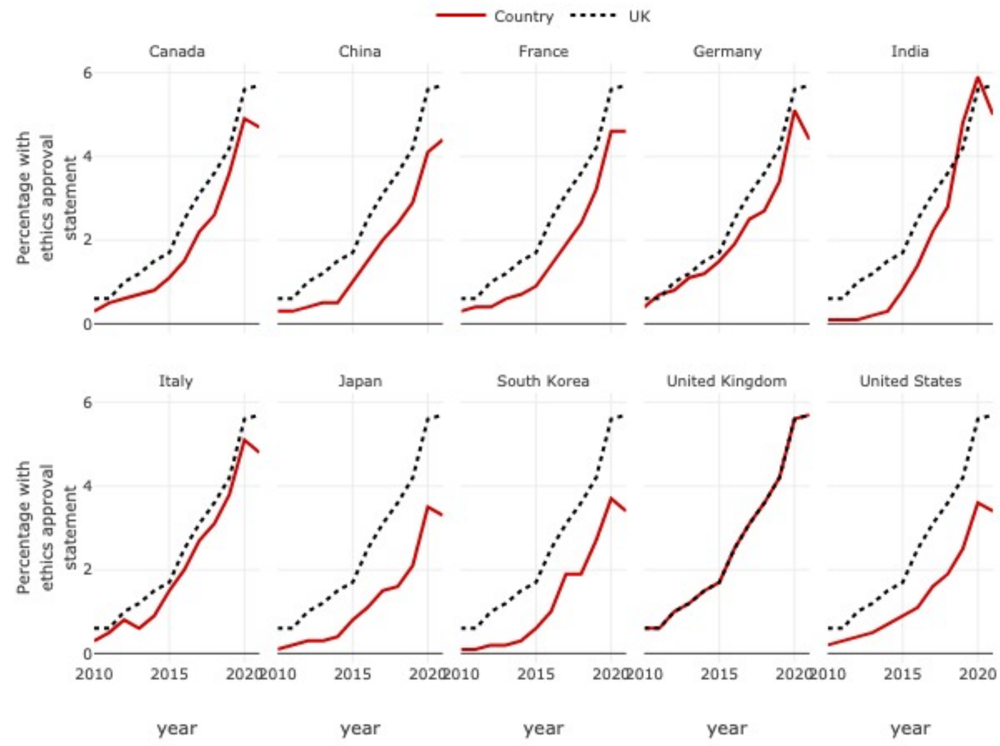


Figure 30: Publications with ethical approval statements - international comparisons.

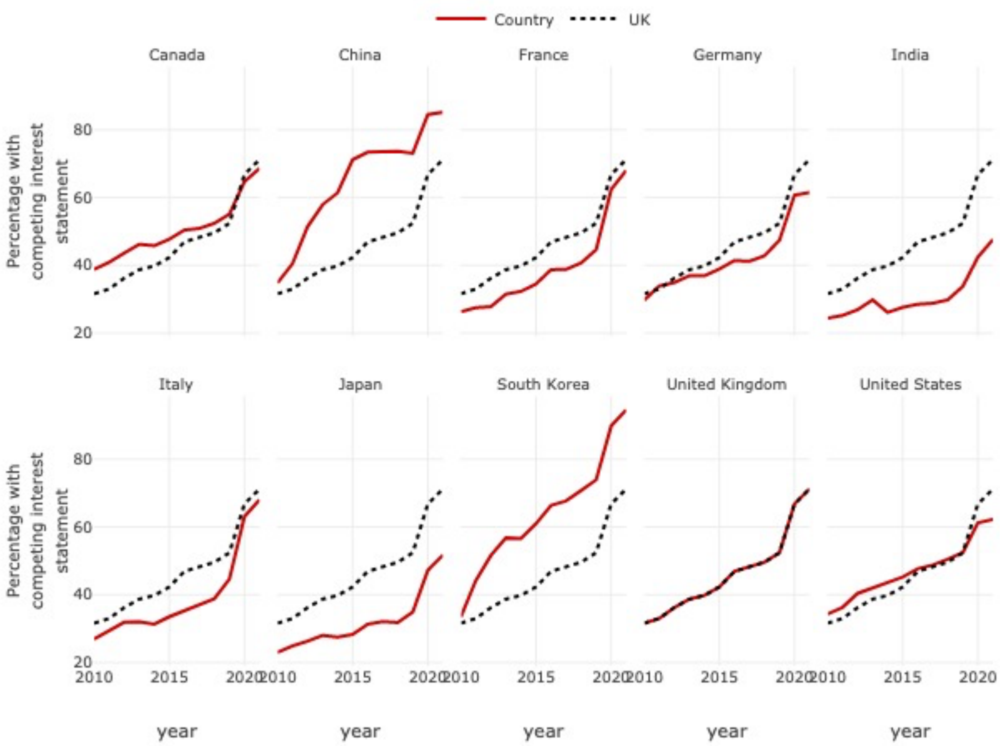


Figure 31: Publications with conflict of interest statements - international comparisons.

National and international collaboration

The majority of research conducted in engineering is carried out in collaboration either at a national level, or with international collaborators.

National collaborations and collaborations with industry have been in decline in the engineering subdisciplines.

Methodological note. We consider international collaboration as a publication where affiliations come from at least two different countries. This includes: authors based in multiple countries (they have two or more affiliations), or two or more authors based in different countries, the latter being the most frequent occurrence.

However, a single author can be affiliated with multiple institutions but this would not be considered international collaboration.

8.1 Collaboration

The majority of research carried out in engineering is carried out in collaboration either with authors within the UK or with international collaborators. Single authorship is not common.

"The majority of research carried out in engineering is carried out in collaboration either with authors within the UK, or with international collaborators."

Table 14 below outlines all subdisciplines, in descending order, by number of publications. For each subdiscipline, the table outlines the share of:

- Single authorship
- National collaborations (with more than one author within the UK)
- Bilateral collaborations (with one other country) and
- Multilateral collaboration (with more than two countries)

Table 14: Collaboration in engineering and computing publications published from 2007 to 2021.

Field of Research	Number of publications	Percentage of single author publications	Percentage of national publications	Percentage of bilateral publications	Percentage of multilateral publications
4016. Materials Engineering	51,198	5.3	33.9	40.9	20.7
4006. Communications Engineering	42,130	5.7	37.7	39.2	18.2
4009. Electronics, Sensors And Digital Hardware	35,680	5.3	39.8	39.6	16.2
4605. Data Management And Data Science	34,747	6.6	35.7	41.6	17.4
4008. Electrical Engineering	30,917	6.0	38.9	42.0	14.3
4005. Civil Engineering	28,722	11.7	32.7	42.8	15.1
4602. Artificial Intelligence	25,149	10.1	35.6	40.9	14.6
4003. Biomedical Engineering	24,414	5.6	39.6	36.7	18.7
4007. Control Engineering, Mechatronics And Robotics	22,209	7.5	36.9	43.2	13.7
4012. Fluid Mechanics And Thermal Engineering	21,188	8.4	38.6	40.6	13.8
4018. Nanotechnology	20,593	4.0	32.7	41.0	22.8
4608. Human-Centred Computing	20,514	13.2	37.3	32.9	17.8
4606. Distributed Computing And Systems Software	20,353	6.3	35.4	38.2	21.1
4004. Chemical Engineering	19,764	6.7	35.0	42.1	17.2
4603. Computer Vision And Multimedia Computation	18,526	5.4	37.5	43.0	15.2
4611. Machine Learning	17,910	7.8	34.0	42.2	17.4
4613. Theory Of Computation	16,309	7.0	33.5	40.8	19.6
4014. Manufacturing Engineering	14,943	7.3	41.8	39.3	13.0
4017. Mechanical Engineering	14,535	8.0	37.3	41.1	14.9
4001. Aerospace Engineering	13,832	7.7	41.9	38.8	12.7
4010. Engineering Practice And Education	12,678	9.7	38.2	41.8	12.1
4609. Information Systems	11,893	19.6	33.0	35.1	14.8
4604. Cybersecurity And Privacy	11,612	12.8	34.7	35.2	18.9
4612. Software Engineering	10,925	14.1	34.0	35.6	18.0
4015. Maritime Engineering	10,091	10.3	34.7	41.7	15.2
4019. Resources Engineering And Extractive Metallurgy	9,865	10.2	31.6	42.8	17.6
4607. Graphics, Augmented Reality And Games	7,526	8.4	40.6	37.2	14.8
4002. Automotive Engineering	5,838	6.3	42.5	40.4	12.0
4013. Geomatic Engineering	5,823	9.5	25.3	38.7	27.9
4011. Environmental Engineering	5,190	7.5	29.2	42.7	22.2
4601. Applied Computing	5,046	13.0	34.5	35.1	19.0

8.2 International collaboration in the UK engineering Fields of Research

Increase in UK collaborations internationally is evident in all engineering subdisciplines, both bilaterally and multilaterally. However, bilateral collaboration is the most common, with nearly 40% of publications, including two authors in two countries, in each of the subdisciplines, and in the latter years of the analysis evidence of an upward trend emerges (see Figure 32). Multilateral collaboration, although a less frequent form of collaboration, also reveals upward trends in all subdisciplines (see Figure 33).

Italy, China, the US and France are the top UK collaborators. They appear most frequently across subdisciplines and are also in the top five countries across all 31 subdisciplines in the analysis. Collaboration with France is apparent in 30 of the 31 subdisciplines.

"Increase in UK collaborations internationally is evident in all engineering subdisciplines."

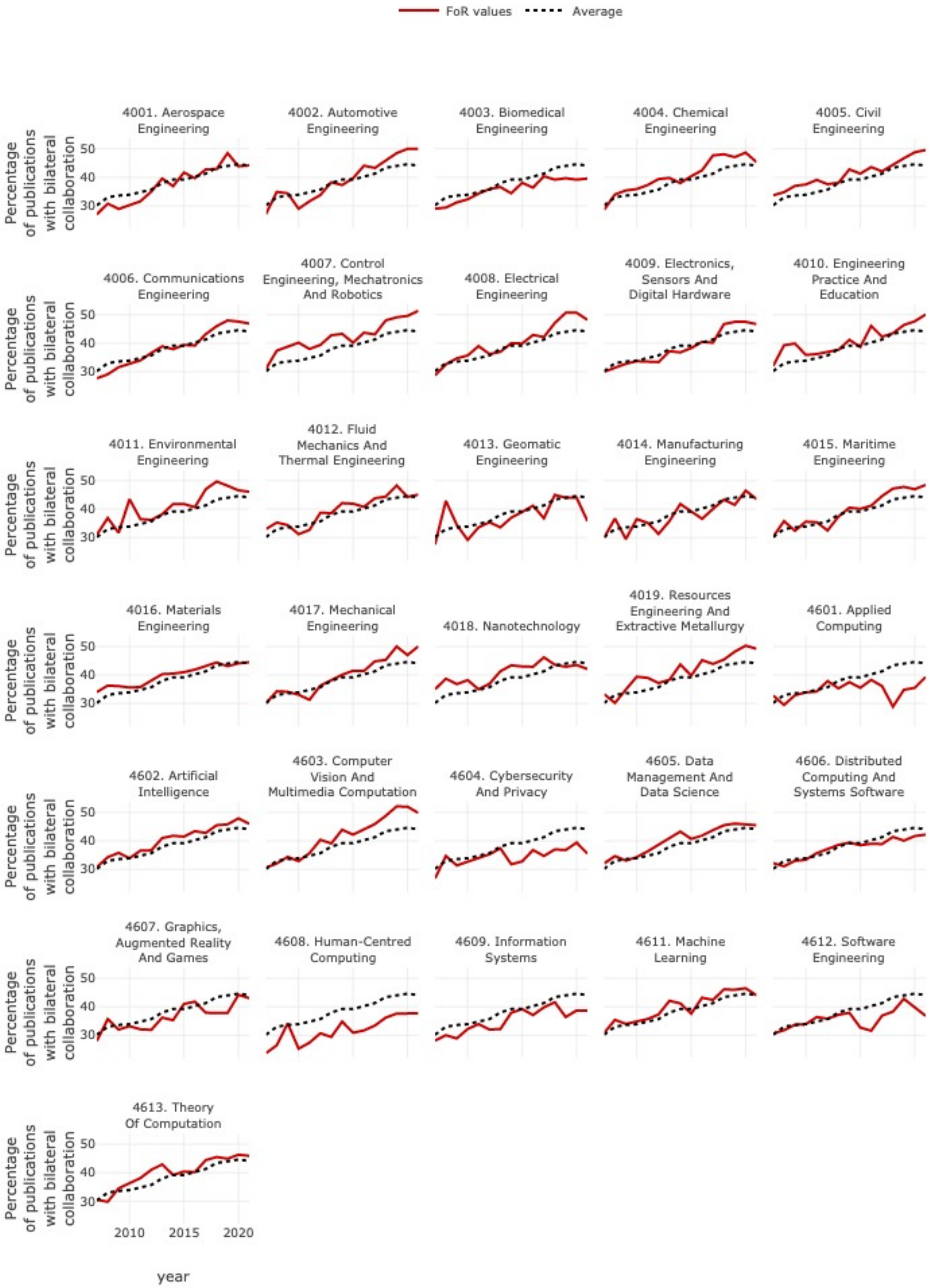


Figure 32: Percentage of UK engineering publications that include bilateral collaborations.

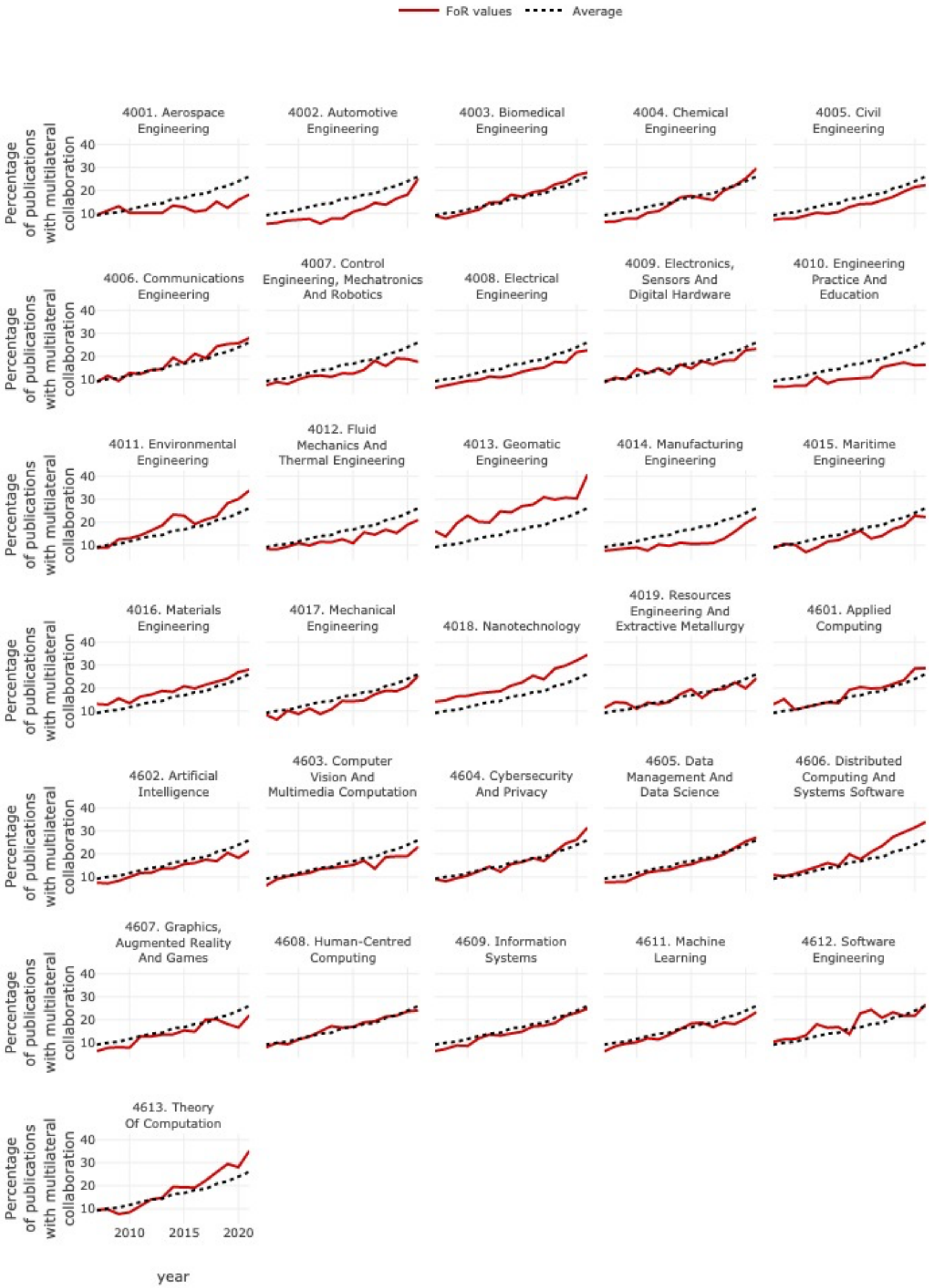


Figure 33: Percentage of UK engineering publications that include multilateral collaborations.

8.3 Domestic collaboration in the UK engineering Fields of Research

Domestic collaboration in engineering (papers with more than one author, each affiliated with UK institutions) is in decline in all subdisciplines. For a number of the subdisciplines domestic collaborations have decreased by 50% since 2007 as seen in Figure 34.

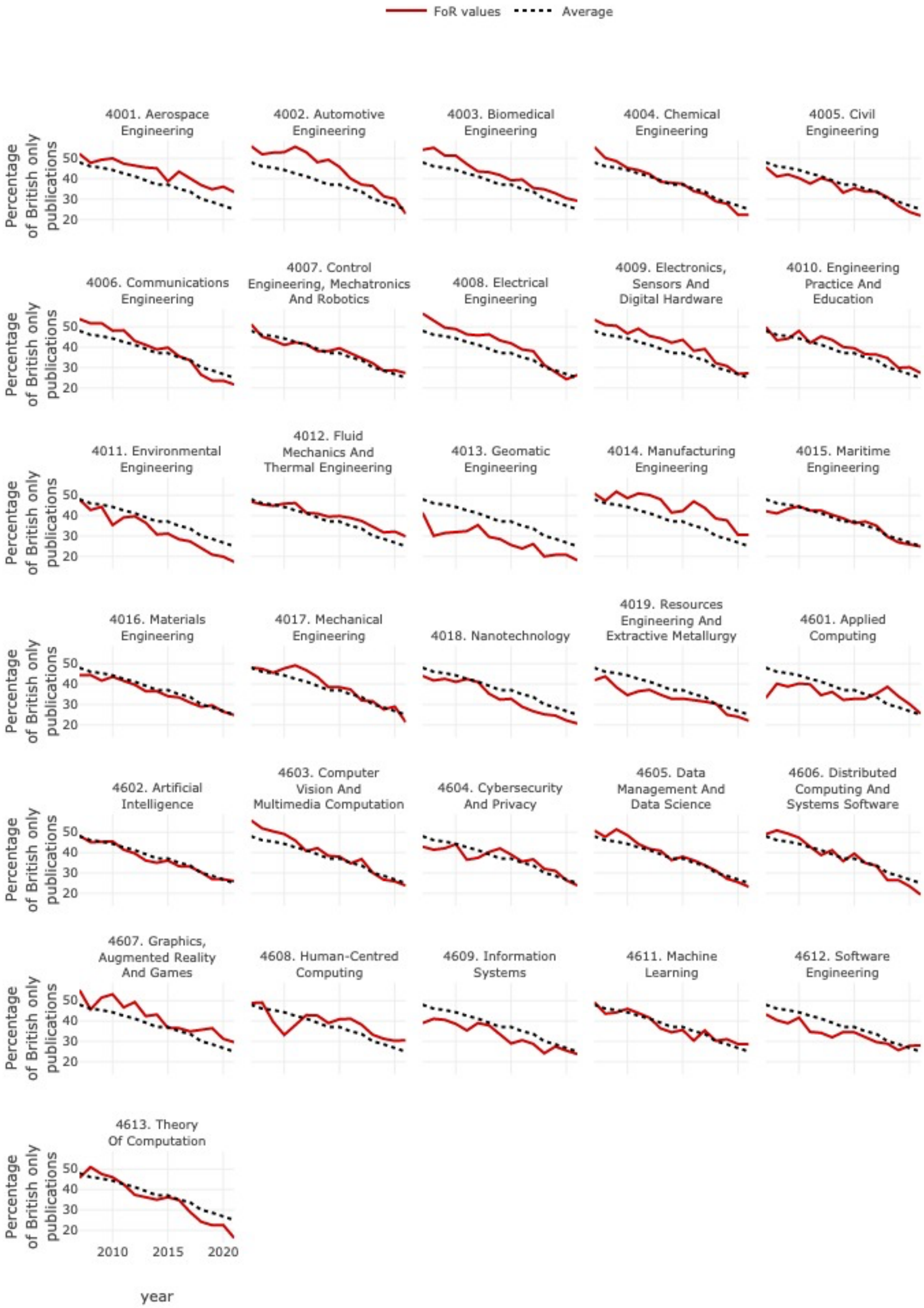


Figure 34: Percentage of UK collaborative engineering publications across the subdisciplines.

8.4 Collaborations with industry in UK engineering

Research in most engineering subdisciplines shows a decrease in the number of collaborations with industrial partners (all subdisciplines but Manufacturing Engineering (4014) below 5%, see Figure 35).

Several of the subdisciplines in particular reveal a significant decrease in industrial partnerships. For example, Automotive Engineering (4002) has seen a decrease from 12% to 3%. Only a few subdisciplines have maintained a consistent level of industrial partnership including Control Engineering, Mechatronics and Robotics (4007), Biomedical Engineering (4003), and Machine Learning (4611), just above or in line with the average.

Trends of this nature are hard to explain; however, it is a possibility that funding constraints may in part account for this decline, leading to a decrease in corporate engagement or the academic focus of more academic collaboration in general, particularly in an international context.

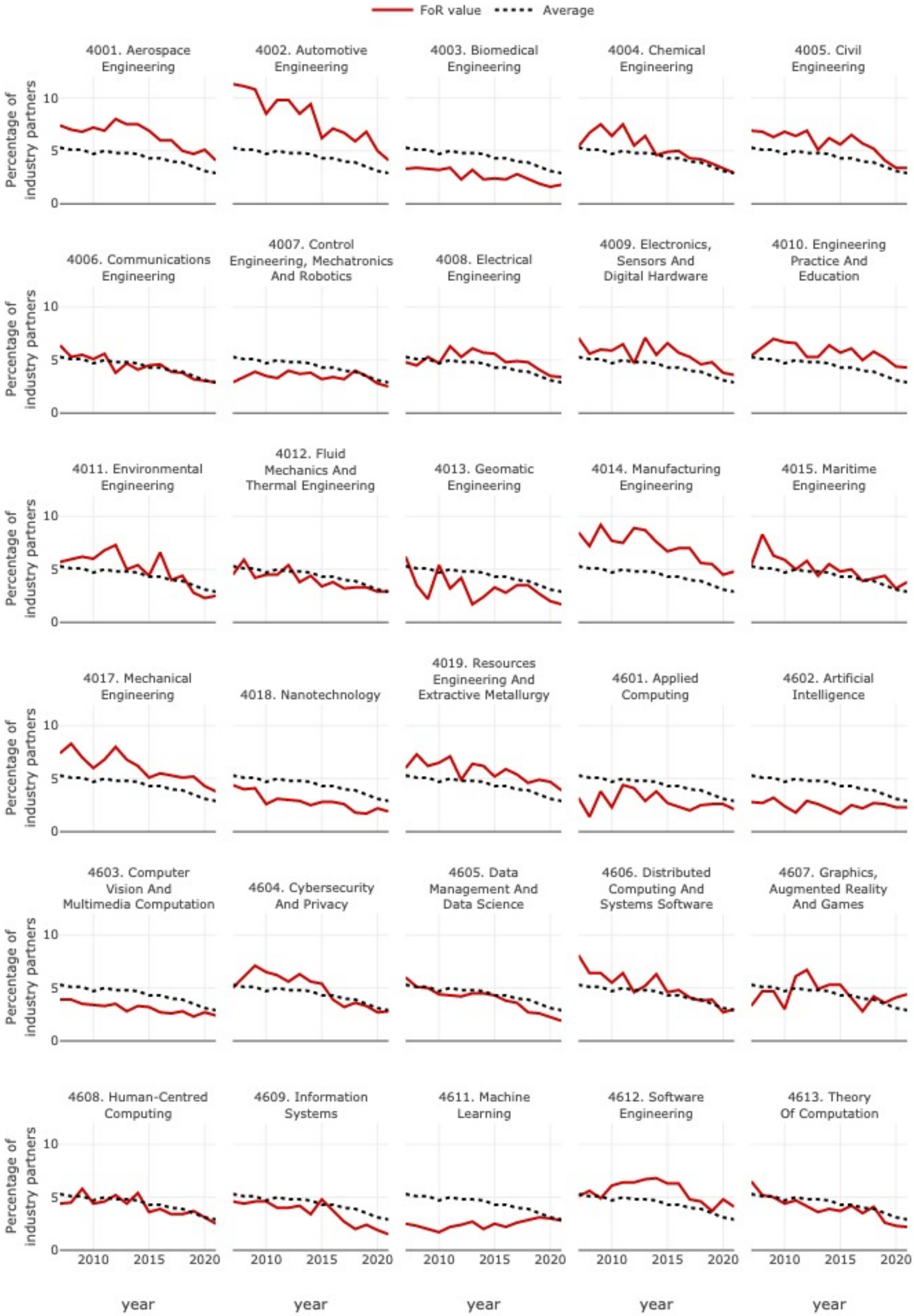


Figure 35: Percentage of industry partners in collaborative UK engineering publications.

Collaboration with disciplines outside of engineering

There are strong links with disciplines outside of engineering in the production of scientific research papers. In particular, we note that Engineering disciplines have collaborations with Physical, Chemical and Mathematical Sciences, and also Environment and Design, Commerce and Biomedical Sciences.

Methodological note. We explored the extent to which Engineering researchers collaborate with researchers in disciplines other than Engineering.

This analysis used published research from 2007 to 2021 which included at least one author with an affiliation in the UK, and at least one field of research in either FoR 40 Engineering or FoR 46 Information and Computing Sciences (please note the two fields have been combined for the purposes of this work).

Most collaborative research publications in engineering (59.4%, 359,452 out of 605,138) include a subdiscipline outside engineering. For the remaining 245,686 research publications (40.6%), the majority of the collaborations occurred in subjects aligned within engineering.

Among the top 20 collaborations with engineering researchers are disciplines outside the field, including Chemical Sciences (FoR 34), Physical Sciences (FoR 51), and Built Environment and Design (FoR 33) (see Table 15). The top 20 collaborations within engineering are visualised in Figure 36. The figure provides a visual representation how the subdisciplines interconnect.

Table 15: Top 20 pairs of Fields of Research associated with engineering, based on co-occurrence in publications from 2007 to 2021.

Field of Research 1	Field of Research 2	Number of publications
4008. Electrical Engineering	4009. Electronics, Sensors And Digital Hardware	14,682
4006. Communications Engineering	4613. Theory Of Computation	11,216
4009. Electronics, Sensors And Digital Hardware	4006. Communications Engineering	11,017
4016. Materials Engineering	3403. Macromolecular And Materials Chemistry	7,843
5102. Atomic, Molecular And Optical Physics	4009. Electronics, Sensors And Digital Hardware	7,319
4602. Artificial Intelligence	4605. Data Management And Data Science	7,164
4010. Engineering Practice And Education	4007. Control Engineering, Mechatronics And Robotics	6,679
4606. Distributed Computing And Systems Software	4605. Data Management And Data Science	6,628
5102. Atomic, Molecular And Optical Physics	4006. Communications Engineering	6,597
4006. Communications Engineering	4008. Electrical Engineering	6,250
4016. Materials Engineering	3406. Physical Chemistry	5,773
4002. Automotive Engineering	4017. Mechanical Engineering	5,064
4005. Civil Engineering	3302. Building	4,429
4603. Computer Vision And Multimedia Computation	4006. Communications Engineering	4,142
4606. Distributed Computing And Systems Software	4006. Communications Engineering	3,879
4016. Materials Engineering	4001. Aerospace Engineering	3,634
4016. Materials Engineering	4018. Nanotechnology	3,590
4602. Artificial Intelligence	4611. Machine Learning	3,372
4604. Cybersecurity And Privacy	4606. Distributed Computing And Systems Software	3,242
4019. Resources Engineering And Extractive Metallurgy	4005. Civil Engineering	3,209

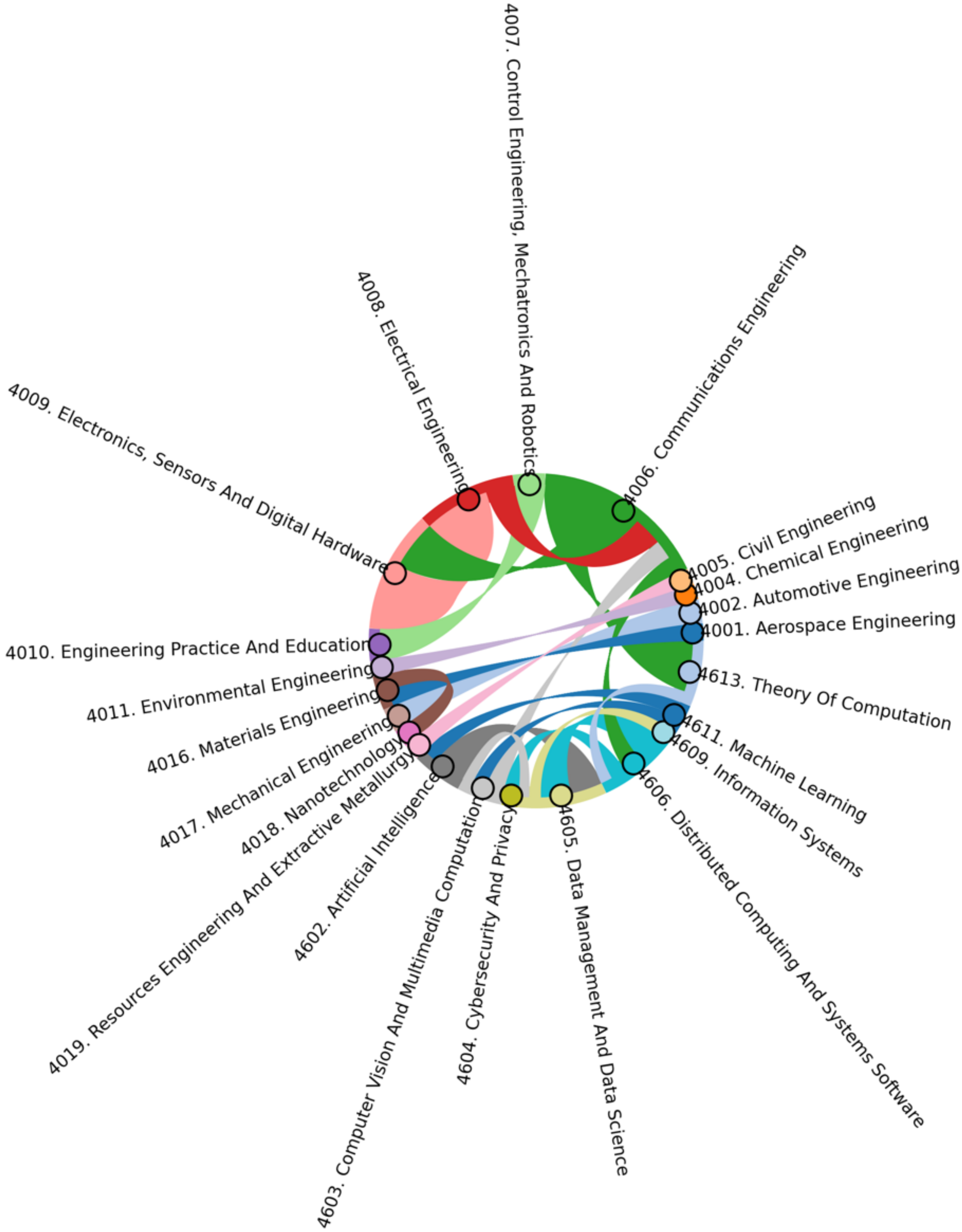


Figure 36: Frequency of Engineering (incl. Computer Science) Fields of Research appearing together on research publications (Top 20 Fields of Research).

Looking at engineering collaborations with fields of research outside of the discipline (see Table 16) we note that a number of research partnerships are evident, in particular with subdisciplines in Physical Sciences (FoRs 5102 and 5103), in Chemical Sciences (FoRs 3403 and 3406), in Mathematical Sciences (FoR 4901), in Built Environment and Design (FoR

3302), Commerce, Management and Tourism Services (FoR 3509) and Biomedical and Clinical Sciences (FoRs 3206 and 3209). Table 17 outlines the subject areas in which research collaborations have been conducted with engineering subjects.

Tables 16 and 17 demonstrate the interdisciplinarity of research outside the fields of Engineering and Computing Sciences. This has already been observed in the UK REF2021 submission where engineering (and computer science) research, mapped onto REF Units of Assessment outside of these UoAs for example in Architecture, Built Environment and Planning (UoA13) and Business and Management Studies (UoA17) amongst others, as seen also in the next section on societal and industrial impact.

Table 16 shows strong links of Engineering research with Physics and Chemistry (top three of the list).

Table 16: Top 10 Fields of Research (non-40 Engineering and non-46 Information and Computing Sciences) associated with engineering research in 2007-2021.

Field of Research	Number of publications
5102. Atomic, Molecular And Optical Physics	14,500
3403. Macromolecular And Materials Chemistry	11,642
3406. Physical Chemistry	9,400
4901. Applied Mathematics	5,855
3302. Building	5,155
5104. Condensed Matter Physics	4,664
3509. Transportation, Logistics And Supply Chains	4,265
3503. Business Systems In Context	2,502
3507. Strategy, Management And Organisational Behaviour	2,276
3206. Medical Biotechnology	2,152
5108. Quantum Physics	2,142
3301. Architecture	1,846
3303. Design	1,821
3101. Biochemistry And Cell Biology	1,723
4203. Health Services And Systems	1,629
5103. Classical Physics	1,505
3705. Geology	1,383
3209. Neurosciences	1,300
3006. Food Sciences	1,236
3709. Physical Geography And Environmental Geoscience	1,234

Table 17 shows where these links exist within the fields of Engineering; the strongest links are in Materials Engineering (4016), Electronics, Sensors and Digital Hardware (4009) and Communications Engineering (4007).

Table 17: Top 10 pairs of Fields of Research (non-40 Engineering and non-46 Information and Computing Sciences) in publications 2007-2021.

Field of Research 1	Field of Research 2	Number of publications
4016. Materials Engineering	3403. Macromolecular And Materials Chemistry	7,843
4009. Electronics, Sensors And Digital Hardware	5102. Atomic, Molecular And Optical Physics	7,319
4006. Communications Engineering	5102. Atomic, Molecular And Optical Physics	6,597
4016. Materials Engineering	3406. Physical Chemistry	5,773
4005. Civil Engineering	3302. Building	4,429
4007. Control Engineering, Mechatronics And Robotics	4901. Applied Mathematics	2,598
4018. Nanotechnology	5104. Condensed Matter Physics	2,553
4609. Information Systems	3503. Business Systems In Context	1,886
4005. Civil Engineering	3509. Transportation, Logistics And Supply Chains	1,857
4018. Nanotechnology	3406. Physical Chemistry	1,601
4016. Materials Engineering	5104. Condensed Matter Physics	1,592
4609. Information Systems	3507. Strategy, Management And Organisational Behaviour	1,552
4018. Nanotechnology	3403. Macromolecular And Materials Chemistry	1,523
4004. Chemical Engineering	3406. Physical Chemistry	1,490
4609. Information Systems	3,509. Transportation, Logistics And Supply Chains	1,226
4003. Biomedical Engineering	3206. Medical Biotechnology	1,204
4004. Chemical Engineering	3006. Food Sciences	1,085
4611. Machine Learning	3209. Neurosciences	986
4016. Materials Engineering	3101. Biochemistry And Cell Biology	910
4009. Electronics, Sensors And Digital Hardware	5108. Quantum Physics	896

Societal and industrial impact

Increasingly, UK engineering research publications are associated with the United Nations Sustainable Development Goals (SDGs), in particular those related to environmental issues.

We examined the impact of engineering research beyond academia, using patent citations of engineering publications as a proxy. Notably, specific research publications in the Computer Science disciplines, such as Human-Centred Computing (4608) and Machine Learning (4611), as well as in Chemical Engineering (4004) within the Engineering disciplines, were influential.

This section looks at patent citations to explore industry's adoption of engineering research. We did find that the number of patent citations has declined across the time period, with exceptions of subjects aligned to computer sciences.

10.1 Uptake of UK engineering research

The focus in this section is on engineering research that is associated with the UN SDGs along with research that moves beyond academia (including policy, innovations, and society).

10.1.1 Citations in research related to SDGs

Methodological note. We explored the extent to which engineering research is cited in publications that relate to Sustainable Development Goals (SDGs). Classification of SDGs is based on Dimensions.

To facilitate the presentation of the analysis, we have grouped 16 SDGs into three groups as set out below. It is important to note here that publications can be associated with more than one SDG and classified as such.

Societal

- 1 No Poverty
- 2 Zero Hunger
- 3 Good Health and Wellbeing
- 4 Quality Education
- 5 Gender Equality
- 6 Clean Water and Sanitation
- 11 Sustainable Cities and Communities
- 16 Peace, Justice and Strong Institutions

Economic

- 8 Decent Work
- 9 Infrastructure and Innovation
- 10 Removing Inequalities
- 12 Responsible Consumption and Production

Environmental

- 7 Renewable Energy
- 13 Climate Action
- 14 Life below Water
- 15 Life on Land

SDG 17, Partnerships for the Goals, was not included in the groups, although it is part of the SDG classification system available in Dimensions.

Engagement with the societal, environmental, and economic aspects of impact emerging from this analysis reveals the commitment that engineering makes in areas such as climate change, innovation (including supply chains), and responsible consumption.

Societal SDG grouping

In the 19 Engineering subdisciplines, publications have been cited by research in the Societal SDG grouping. The subdisciplines that have received the most citations include Biomedical Engineering (4003) - focusing on SDG 3: Good Health and Wellbeing related research - and Environmental Engineering (4011) - most likely addressing issues on SDG 6: Clean Water and Sanitation.

In the 12 Computer Science subdisciplines, with the exception of Computer Vision and Multimedia Computation (4603) and Theory of Computing (4613), the percentage of publications cited either increases in line with the average (of the entire corpus) or increase at a higher rate throughout the time frame (see Figure 37).

Environmental SDG grouping

Engineering research that is associated with the Environmental SDG grouping (and thus goes some way to addressing environmental issues), includes Environmental Engineering (4011) which has the most publications cited with a focus on the environment, increasing twofold to 80% across the time frame 2007 to 2021 (see Figure 38).

Geomatic Engineering (4013), had most publications early on in the time frame but was surpassed more recently by Environmental Engineering (4011) and Automotive Engineering (4002). Regarding Automotive Engineering (4002), research categorised as environmentally associated research in this subdiscipline, is perhaps more likely, in part, to address aspects of improvement in engine performance thus reducing carbon emissions, etc. This research tends to focus on the type of fuels (biofuels, mixtures) that could help to improve engine performance in minimising waste or exhausts.

Table 18: Top 10 publications in FCR in Automotive Engineering and Environmental SDGs.

Title	DOI	FCR
Progress and future challenges in controlling automotive exhaust gas emissions	10.1016/j.apcatb.2006.02.029	118.05
Methanol as a fuel for internal combustion engines	10.1016/j.pecs.2018.10.001	104.73
Natural-gas fueled spark-ignition (SI) and compression-ignition (CI) engine performance and emissions	10.1016/j.pecs.2010.04.002	88.22
Impacts and mitigation of excess diesel-related NOx emissions in 11 major vehicle markets	10.1038/nature22086	70.77
Advances in reforming and partial oxidation of hydrocarbons for hydrogen production and fuel cell applications	10.1016/j.rser.2017.09.071	59.23
The scope for improving the efficiency and environmental impact of internal combustion engines	10.1016/j.treng.2020.100005	54.13
Engine performance and emissions of a diesel engine operating on diesel-RME (rapeseed methyl ester) blends with EGR (exhaust gas recirculation)	10.1016/j.energy.2007.05.016	48.24
Syngas production in downdraft biomass gasifiers and its application using internal combustion engines	10.1016/j.renene.2011.07.035	47.31
Advancements of combustion technologies in the ammonia-fuelled engines	10.1016/j.enconman.2021.114460	42.69
Catalytic control of emissions from cars	10.1016/j.cattod.2010.12.044	42.67

Looking at Computer Science disciplines, publications across the subdisciplines, excluding Data Management and Data Science (4605), Distributed Computing and Systems Software (4606), and Theory of Computing (4613), fall below the average for publications cited that are associated with Environmental SDGs.

Table 19: Top 10 publications in FCR in Information Systems and Environmental SDGs.

Title	DOI	FCR
Design, modelling, simulation and integration of cyber physical systems: Methods and applications	10.1016/j.compind.2016.05.006	75.07
Decision Support Frameworks and Tools for Conservation	10.1111/conl.12385	48.88
An AHP-based multi-criteria model for sustainable supply chain development in the renewable energy sector	10.1016/j.eswa.2020.113321	48.59

Continued on next page

Table 19: Top 10 publications in FCR in Information Systems and Environmental SDGs.

Title	DOI	FCR
An overview on fault diagnosis and nature-inspired optimal control of industrial process applications	10.1016/j.compind.2015.03.001	47.12
Optimisation of the resource efficiency of food manufacturing via the Internet of Things	10.1016/j.compind.2021.103397	32.43
Applications of agent-based modelling and simulation in the agri-food supply chains	10.1016/j.ejor.2017.10.041	31.28
Barriers and enablers to the use of seasonal climate forecasts amongst organisations in Europe	10.1007/s10584-016-1671-8	27.72
Tibidabo: Making the case for an ARM-based HPC system	10.1016/j.future.2013.07.013	22.32
Impacts of low citizen awareness and usage in smart city services: the case of London's smart parking system	10.1007/s10257-016-0333-8	22.18
Decision support systems for forest management: A comparative analysis and assessment	10.1016/j.compag.2013.12.005	20.33

Economic SDG grouping

The Engineering subdisciplines contribution to publications related to the Economic SDG grouping (using shares of cited publications as a measure) is notable with the exception of Aerospace Engineering (4001) as seen in Figure 39.

Materials Engineering (4016), which is the largest discipline based on publication numbers, has one of the lowest share of cited publications related to the Economic SGDs despite its relevance in SDG 12 Responsible Consumption and Production.

In contrast, Computer Science publications cited in research related to Economic SDGs have increased sharply over the period of time of the analysis. Linking this increase with an association of research with SDG 9 Innovation and infrastructure is worthy of further investigation, but is outside the scope of this report.

"The share of Computer Science publications cited in research related to the Economic SDG grouping has increased sharply over the time period of analysis."

Looking at research publications related to the Economic SDG grouping, the upward trajectory seen for Environmental Engineering (4011), with its research focus on industrial innovation (process orientated) and responsible consumption (including recycling), and removal and avoidance of waste is notable. One other engineering subdiscipline, where the percentage of publications cited in the Economic SDG grouping is noteworthy, is Manufacturing Engineering (4014). Of further interest is Information Systems (4609) which performs strongly (see Figure 39) which has a research focus in the management of global supply chains in the broadest sense, e.g., smart cities, water resource management and food security.

Table 20: Top 10 publications in FCR in Environmental Engineering and Economic SDGs.

Title	DOI	FCR
Recent progress towards the electrosynthesis of ammonia from sustainable resources	10.1016/j.cattod.2016.05.008	59.8
Evaluating challenges to Industry 4.0 initiatives for supply chain sustainability in emerging economies	10.1016/j.psep.2018.04.018	57.0
Recycling of Bioplastics: Routes and Benefits	10.1007/s10924-020-01795-8	22.3
International comparative study of 3R and waste management policy developments	10.1007/s10163-011-0009-x	20.6
Bioconversion of food waste to volatile fatty acids: Impact of microbial community, pH and retention time	10.1016/j.chemosphere.2021.129981	14.0
The carbon footprint of bread	10.1007/s11367-011-0271-0	13.8

Continued on next page

Table 20: Top 10 publications in FCR in Environmental engineering and Economic SDGs.

Title	DOI	FCR
The contribution of PAS 2050 to the evolution of international greenhouse gas emission standards	10.1007/s11367-009-0079-3	13.2
An Overview of Solid Waste Management and Plastic Recycling in Qatar	10.1007/s10924-011-0332-2	13.0
A Methodology for Sustainable Management of Food Waste	10.1007/s12649-016-9720-0	12.8
Model predictive control of an activated sludge process: A case study	10.1016/j.conengprac.2010.09.001	11.4

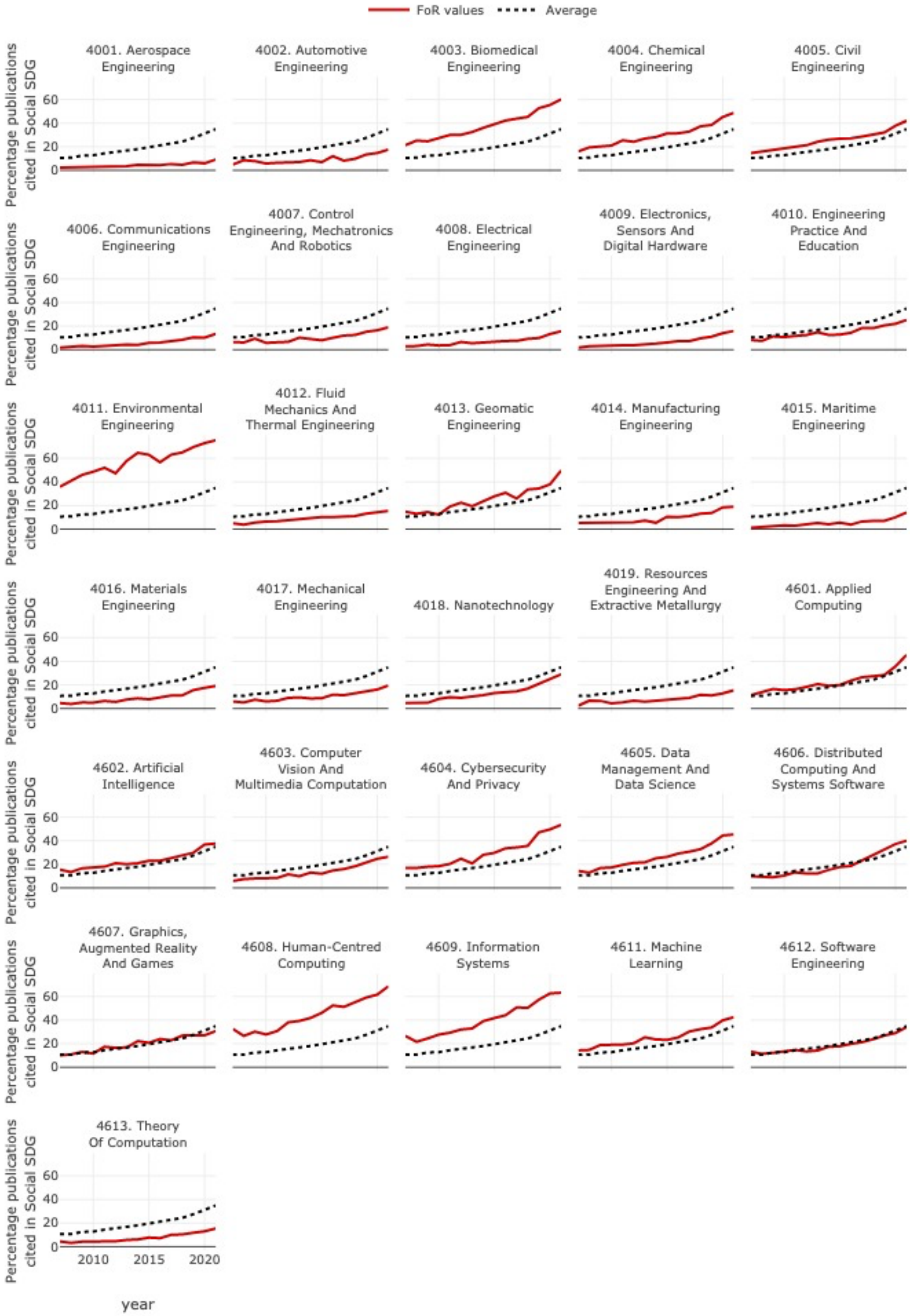


Figure 37: Percentage of Engineering publications cited in the Societal grouping of SDGs.

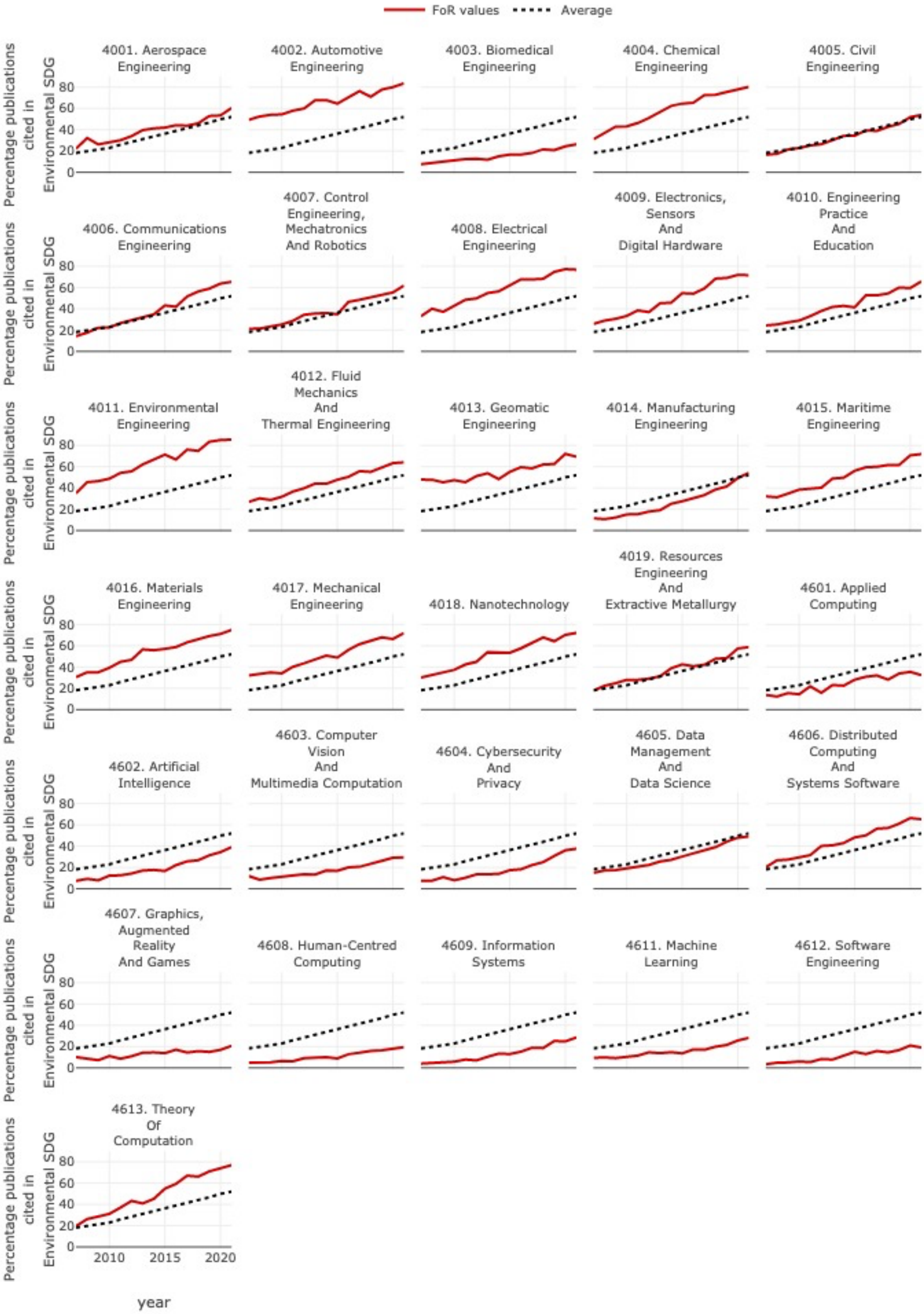


Figure 38: Percentage of Engineering publications cited in the Environmental grouping of SDGs.

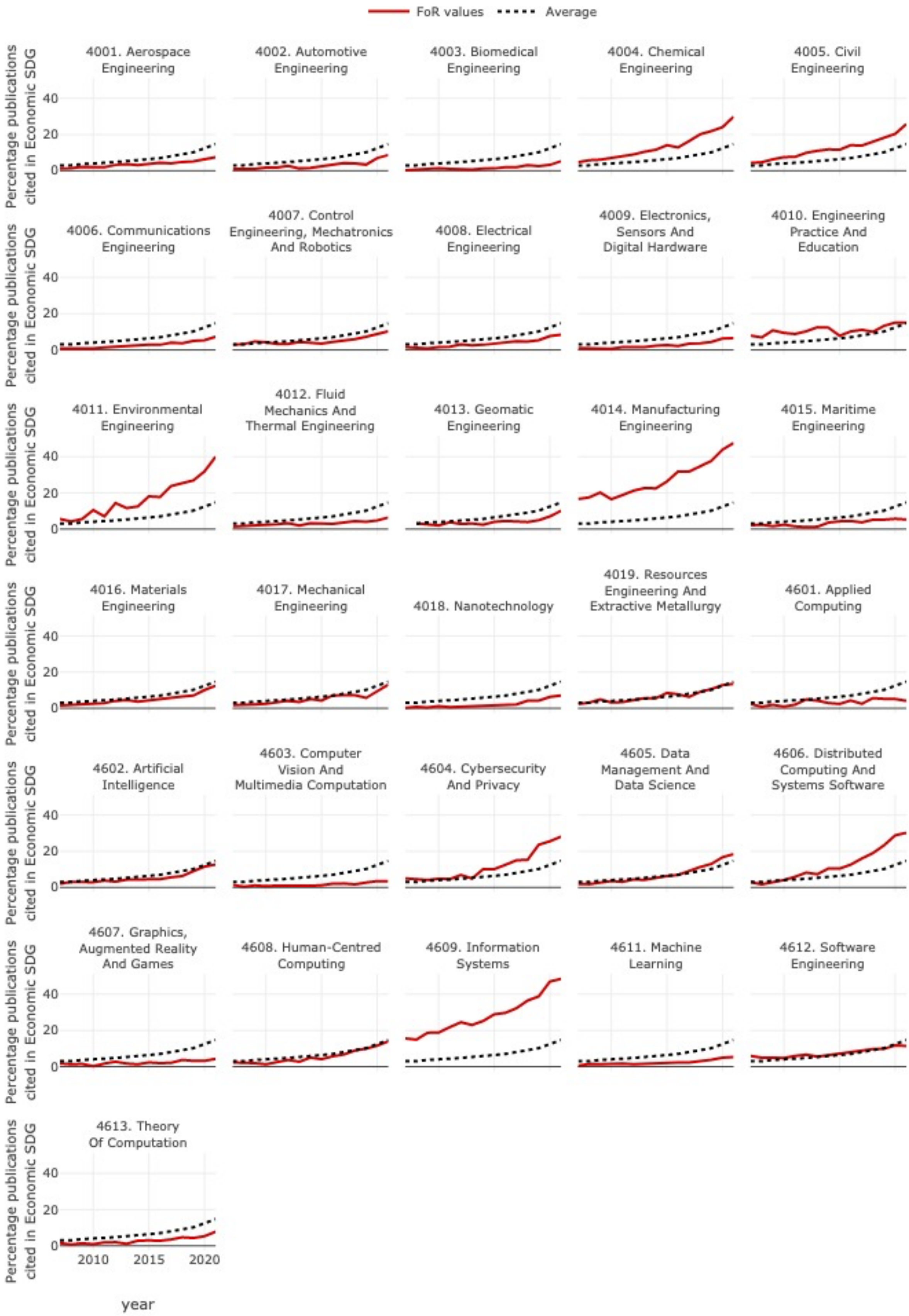


Figure 39: Percentage of Engineering publications cited in the Economic grouping of SDGs.

10.1.2 Citations in policy documents

Using Dimensions, we explored the extent to which the 2007-2021 corpus of UK engineering research is cited in documents published by governments and nongovernmental organisations (e.g., WHO, World Bank, etc.). There is no clear upward or downward trend in the citation behaviour in all subdisciplines, and the citation patterns do not show a fixed trajectory (see Figure 40). Although outside the scope of this report, looking at the citation trajectories might be interesting to see why different subdisciplines peak sharply at different times.

Publications in the Computer Sciences subdisciplines are better cited in policy documents than those from Engineering subdisciplines. Most notably, Chemical Engineering (4004) has a significant percentage of publications over a number of years that are cited by policy documents. In most recent years in particular, publications in engineering are not well cited in policy documents in comparison to computer science led by Artificial Intelligence (4602), Machine Learning (4611) and Human-Centred Computing (4608).

"Chemical Engineering (4004) has a significant percentage of publications over a number of years that are cited by policy documents."

Examples of influential papers cited in policy documents are presented in Table 21.

Table 21: Top 10 influential papers cited in policy documents.

Title	DOI	Number of policy documents citing it
The FAIR Guiding Principles for scientific data management and stewardship	10.1038/sdata.2016.18	23
Semantics derived automatically from language corpora contain human-like biases	10.1126/science.aal4230	9
Dynamic population mapping using mobile phone data	10.1073/pnas.1408439111	9
Computer-based personality judgments are more accurate than those made by humans	10.1073/pnas.1418680112	6
Mastering the game of Go with deep neural networks and tree search	10.1038/nature16961	6
Overview of current development in electrical energy storage technologies and the application potential in power system operation	10.1016/j.apenergy.2014.09.081	5
Mastering the game of Go without human knowledge	10.1038/nature24270	5
Toxicology of nanoparticles: A historical perspective	10.1080/17435390701314761	5
The implications of projected climate change for freshwater resources and their management	10.1623/hysj.53.1.3	5
Overview of current development in electrical energy storage technologies and the application potential in power system operation	10.1016/j.apenergy.2014.09.081	5

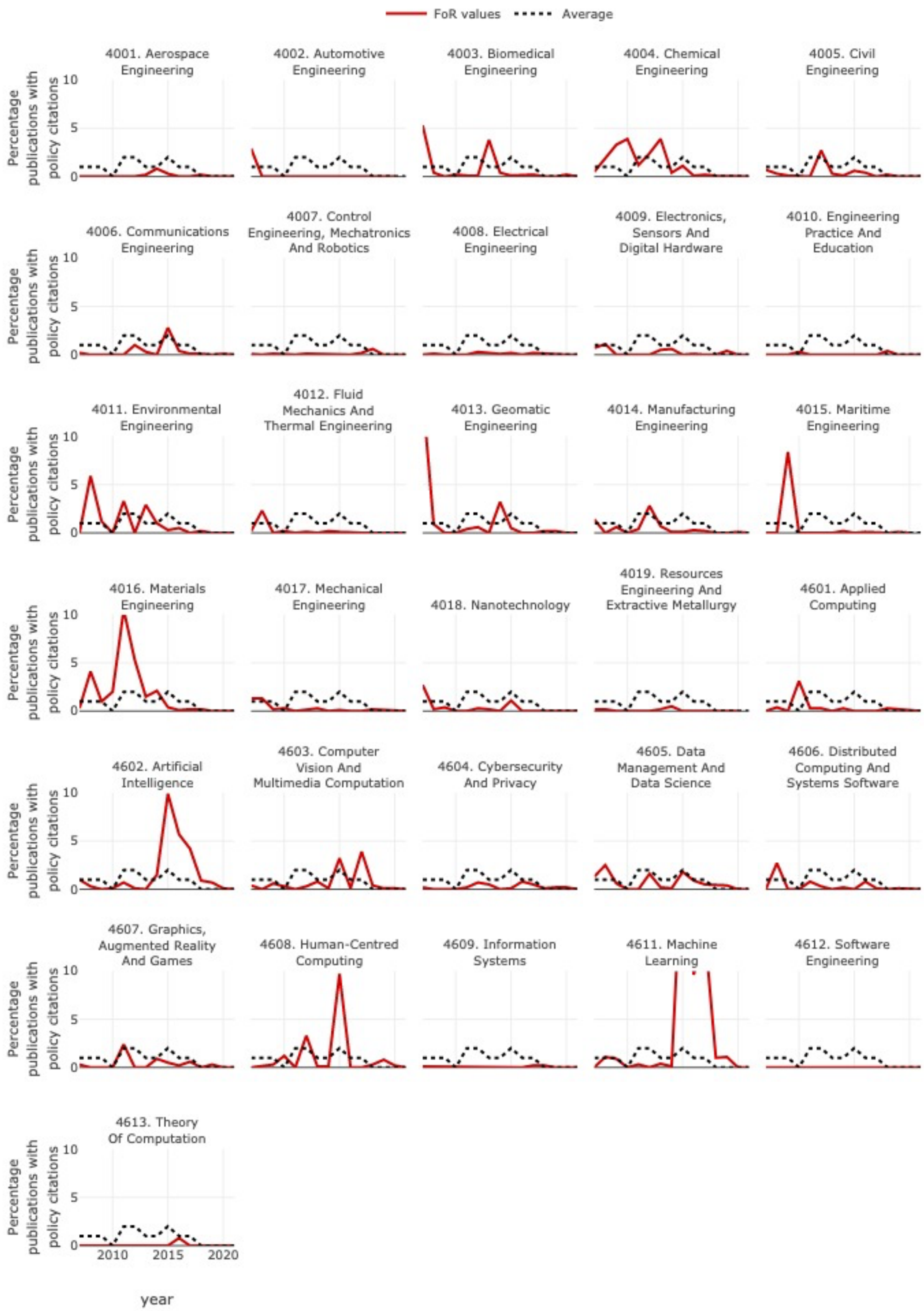


Figure 40: Percentage of UK Engineering publications with policy citations. Publications from 2007 to 2021. (Graph for Machine Learning is significantly bigger than the others and so was cut to be able to see the variability of the other Fields of Research).

10.1.3 Citations in patents

Using Dimensions, we explored the extent to which UK engineering research from 2007 to 2021 is cited in patent applications, independent of the patent's status (e.g., filed, granted) and jurisdiction (e.g., US, Japan, or European Patent Office). Overall, a decline in the percentage of papers cited in patents is evident and likely to be a reflection, in part, of the time lag for citations to start to accrue.

A number of engineering subdisciplines perform well, particularly in the earlier years of the time frame: Biomedical (4003), Communications (4006), Electrical and Electronics and Materials Engineering (4016), as shown in Figure 41.

In the computer science related disciplines, the number of publications cited in patents reveals that for the majority of subdisciplines the decline since 2007 is marked. A number of publications in Computer Vision And Multimedia Computation (4603), Graphics, Augmented Reality And Games (4607) started well but lost momentum. However, Machine Learning (4611) performed well in the latter half of the time frame, with Machine Learning (4611) outperforming Artificial Intelligence (4602) in the percentage of patent citations (see Figure 41).

"A number of engineering subdisciplines perform well, particularly in the earlier years of the time frame: Biomedical (4003), Communications (4006), Electrical (4008) and Electronics, Sensors and Digital Hardware (4009) and Materials Engineering (4016)."

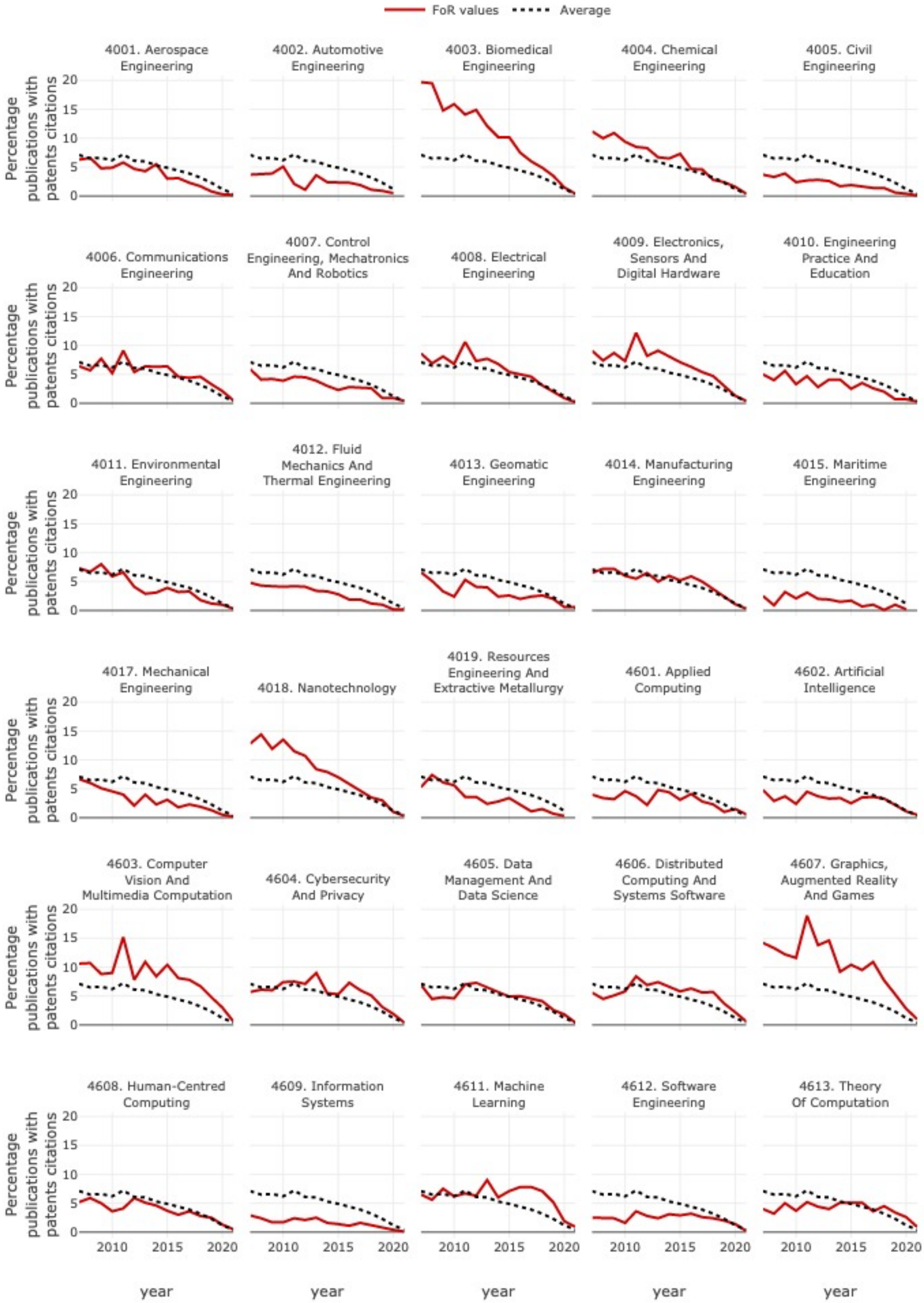


Figure 41: Percentage of publications cited in patents across Engineering.

10.1.4 International comparisons

Comparing the percentage of engineering publications in the UK cited in policy documents, we note that the UK exceeds other countries (although, percentages are small, so any comparisons should be made with caution) - see Figure 42.

The UK citation rate remained higher than other countries, particularly Asian countries, and although declining slightly, they remained higher overall. This indicates that engineering research in the UK is influential by proxy of policy document citations in an international context.

China and the US differ markedly in the number of publications cited in policy documents: China's share of engineering citations in policy documents is the lowest among the comparator countries[13]. The number of policy documents by country is the likely explanation for this. All other Asian comparator countries (India, Japan, and South Korea) show a similar, below-average percentage of citations in policy documents. However, it should be noted that the number of policy documents in Dimensions from East Asian countries is small and is likely to contribute to these findings.

[13] Chinese policy documents are either not publicly available or not citing research literature.

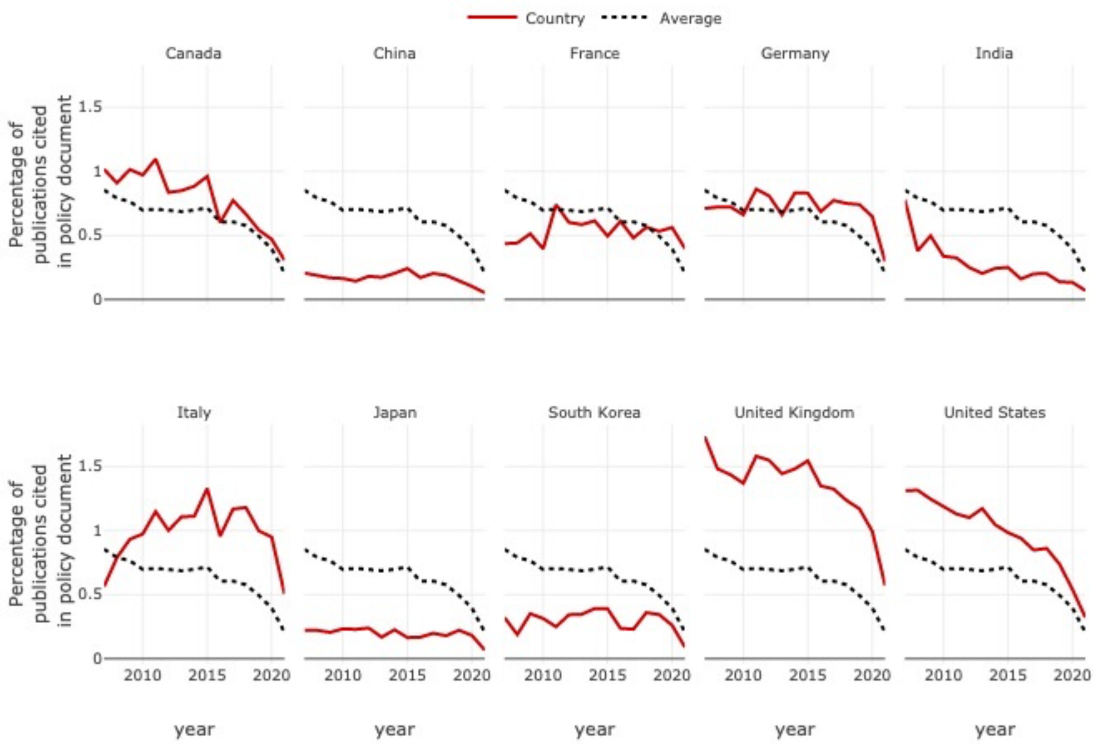
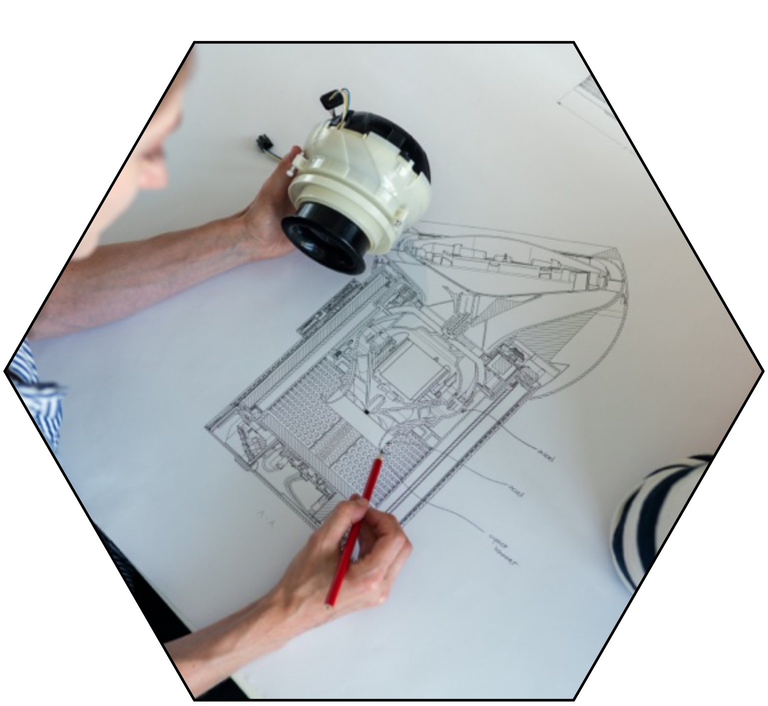


Figure 42: Percentage of UK Engineering publications cited in policy documents.

Conclusions



This report provides a comprehensive analysis of the subdisciplines that make up Engineering and Computer Science, two strong performing disciplines in the research sector. Examining the subdisciplines in relation to comparator countries, the analysis provides an overview that allows significant comparisons to be made.

The key findings of the report are:

Trends

Materials Engineering (4016), Data Management And Data Science (4605), and Civil Engineering (4005) are the three strongest areas of UK research based on publication volume. China, the US, and India are the strongest international competitors in these areas.

Strength

The UK strongest subdisciplines based on FCR are Applied Computing (4601), Graphics, Augmented Reality And Games (4607), and Machine Learning (4611). The UK is second behind the US for top cited engineering publications overall.

Major funders

The majority of funders acknowledged in engineering research are UK-based, with EPSRC being the top funder. The top non-UK funders / co-funders are the European Commission and the National Natural Science Foundation China. Four of the ten biggest funders are Chinese.

Research integrity and reproducibility

Compared to the international average, the UK compliance on research integrity such as data availability and code availability is generally good, particularly in Biomedical Engineering (4003).

National and international collaborations

The majority of engineering research is collaborative, either nationally or internationally. However, national collaborations and collaborations with industry have declined across engineering subdisciplines.

Societal and industrial impact

An increasing share of UK engineering research is related to the SDGs, particularly in relation to environmental issues. The influence of engineering research outside academia measured by patent citations was notable in the computer science disciplines, namely Human-Centred Computing (4608) and Machine Learning (4611), and Chemical Engineering (4004).

Although the range of engineering subdisciplines presented challenges, it also created avenues in specific areas that may warrant further exploration for the Academy. For example, a dedicated in-depth report (or series of short reports) exploring those subdisciplines where the data show an interesting picture worthy of more analysis.

During the analysis work, we discovered areas that were out of the scope of the report, but we think it would be useful to look at more detail in a potential follow-up. For example, the interdisciplinary aspects of Engineering and Computer Science, and the centrality of research at the core of science and technology in the UK.

Further analyses

The findings outlined in the report revealed that the ability to drill deeper into the data in a number of engineering areas would be advantageous and would allow for a greater understanding and additional inferences to be made.

Our analysis revealed a paucity of US funding in UK engineering research. With the US unsurpassed in the academic impact of its research outputs and funding in general, a more thorough investigation on why this is may be of interest. In particular, in the case of increased international collaboration, this may be an untapped potential for UK research to improve future prospects.

Moreover, in the workshops conducted as part of this study, it became evident that certain themes, such as Design and Nature-Based Engineering, generated significant interest. In response, conducting further investigations using concept-level analysis, bibliometric coupling, or other combined analytical approaches could prove valuable in specific areas of interest.

Finally, it should be noted that certain aspects of our work for this analysis were not included in the final report. We tried to map the Technological Challenges identified in the TERC report[14] to the publications held in Dimensions using a previously tested methodology, however, this was not successful. As a fallback, we used more traditional methodologies, such as Boolean searches and Dimensions' classifications, which fit better with the timeline for the report. However, given more time, it would be worth applying new AI-based methodologies to provide a more comprehensive understanding of the TERC Technological Challenges. This would make a valuable addition given that the UK ranked at the top among the countries compared for most of the Technological Challenges.

In conclusion, our analysis highlights the notable contributions of UK Engineering (including Computer Science), while also emphasising the need for further exploration and methodologies to fully understand and align with emerging research priorities and international trends.

[14] Tomorrow's Engineering Research Challenges. Visions from the UK Research Community.

Appendix

12.1 ANZSRC 2020 FoR - structure and definitions

Table 22: ANZSRC 2020 Field of Research classification, definition and exclusions – Only 40 Engineering and 46 Information and Computer Sciences

Field of Research	Definition	Exclusions
4001. Aerospace Engineering	This group covers aerospace engineering including avionics and aeronautical and astronomical engineering.	a) Space sciences are included in Group 5109 Space Sciences. b) Transport engineering other than aerospace engineering is included in Group 4005 Civil Engineering. c) Remote sensing is included in Group 4013 Geomatic Engineering. d) Heat and mass transfer operations, fluidisation, fluid mechanics and turbulent flows are included in Group 4012 Fluid Mechanics and Thermal Engineering. e) Satellite communications are included in Group 4006 Communications Engineering. f) Aerodynamics is included in 4012 Fluid Mechanics and Thermal Engineering.
4002. Automotive Engineering	This group covers automotive engineering.	a) Combustion and fuel engineering without automotive applications is included in Group 4004 Chemical Engineering. b) Transport engineering other than automotive engineering is included in Group 4005 Civil Engineering. c) Mechatronics without automotive applications is included in Group 4007 Control Engineering, Mechatronics and Robotics. d) Materials engineering without automotive applications is included in Group 4016 Materials Engineering. e) Heat and mass transfer operations, fluidisation, fluid mechanics and turbulent flows are included in Group 4012 Fluid Mechanics and Thermal Engineering. f) Electrical energy generation and storage are included in 4008 Electrical Engineering.
4003. Biomedical Engineering	This group covers biomedical engineering.	a) Regenerative medicine and medical biotechnology is included in Group 3206 Medical biotechnology. b) Other material sciences are included in Groups 5104 Condensed Matter Physics, 3402 Inorganic Chemistry, 3403 Macromolecular and Materials Chemistry, 4016 Materials Engineering, and 4019 Resources Engineering and Extractive Metallurgy. c) Materials used in dentistry are included in Group 3203 Dentistry. d) Medical robotics and biomechatronics are included in Group 4007 Control Engineering, Mechatronics and Robotics.
4004. Chemical Engineering	This group covers chemical engineering including process technologies.	a) Chemistry is included in Division 34 Chemical sciences. b) Carbon sequestration science and modelling are included in Group 4101 Climate Change Impacts and Adaptation. c) Combustion and fuel engineering for automotive applications is included in Group 4002 Automotive Engineering. d) Water resources and quality engineering are included in Group 4005 Civil Engineering. e) Process control and simulation associated with control engineering is included in Group 4007 Control Engineering, Mechatronics and Robotics. f) Fluidisation, fluid mechanics and heat and mass transfer operations are included in Group 4012 Fluid Mechanics and Thermal Engineering. g) Biocatalysis is included in Group 3106 Industrial biotechnology. h) Non-Newtonian fluid flows including rheology are included in Group 4012 Fluid Mechanics and Thermal Engineering.
4005. Civil Engineering	This group covers civil engineering.	a) Hydrology other than agricultural hydrology is included in Group 3707 Hydrology. b) Agricultural hydrology is included in Group 3002 Agriculture, Land and Farm Management. c) Aerospace engineering is included in Group 4001 Aerospace Engineering. d) Automotive engineering is included in Group 4002 Automotive Engineering. e) Water treatment processes are included in Group 4004 Chemical Engineering. f) Surveying is included in Group 4013 Geomatic Engineering. g) Maritime engineering is included in Group 4015 Maritime Engineering. h) Materials engineering without civil engineering applications is included in Group 4016 Materials Engineering. i) Geotechnical engineering associated with mining and mineral extraction is included in Group 4019 Resources Engineering and Extractive Metallurgy. j) Agricultural engineering is included in Group 4099 Other engineering. k) Building science and techniques including acoustics, lighting, structure, thermal and moisture are included in Group 3302 Building. l) Building science, construction management and quantity surveying are included in Group 3302 Building. m) Transport planning is included in Group 3304 Urban and regional planning. n) Mechanical engineering asset management is included in Group 4017 Mechanical engineering.

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Table 22: ANZSRC 2020 Field of Research classification, definition and exclusions

Field of Research	Definition	Exclusions
4006. Communications Engineering	This group covers communications engineering.	a) Electronic devices and digital hardware for communication engineering is included in Group 4009 Electronics, Sensors and Digital Hardware. b) Molecular and biological materials are included in Group 4016 Materials Engineering.
4007. Control Engineering, Mechatronics and Robotics	This group covers control engineering, mechatronics and robotics.	a) Automotive mechatronics and autonomous systems are included in Field 400203 Automotive mechatronics and autonomous systems. b) Control Theory is included in Group 4901 Applied mathematics.
4008. Electrical Engineering	This group covers electrical engineering including electrical circuits and systems and electromagnetics, but excluding electronics, communications and control engineering	a) Electronic circuits and systems are included in Group 4009 Electronics, Sensors and Digital Hardware.b) Electromagnetics of antennas and propagation is included in Group 4006 Communications Engineering.
4009. Electronics, Sensors and Digital Hardware	This group covers electronics, sensors and digital hardware.	a) Semiconductor materials are included in Group 4016 Materials Engineering. b) Quantum device science is included in Group 5108 Quantum physics.
4010. Engineering practice and education	This group covers engineering practice and education.	a) Risk engineering associated with vehicle safety, fire safety and manufacturing safety, is included in Group 4002 Automotive Engineering, Group 4005 Civil Engineering, and Group 4014 Manufacturing Engineering, respectively. b) Systems engineering associated with the single disciplines of aerospace engineering, civil engineering, communication systems, electronics and electrical engineering is included in Group 4001 Aerospace Engineering, Group 4005 Civil Engineering, Group 4006 Communications Engineering, Group 4009 Electronics, Sensors and Digital Hardware and Group 4008 Electrical Engineering, respectively. c) Education theory and practice in areas not principally focussed on engineering is included in Group 3901 Curriculum and Pedagogy.
4011. Environmental Engineering	This group covers environmental engineering.	a) Hydrology other than agricultural hydrology is included in Group 3707 Hydrology. b) Environmental sciences is included in Division 41 Environmental sciences. c) Agricultural hydrology is included in Group 3002 Agriculture, Land and Farm Management. d) Protection of infrastructure from climate change and other environmental factors is included in Group 4005 Civil Engineering. e) Environmental biotechnology, including bioremediation, is included in Group 4103 Environmental Biotechnology.
4012. Fluid Mechanics and Thermal Engineering	This group covers fluid mechanics and thermal engineering.	a) Hypersonic aerothermodynamics is included in Group 4001 Aerospace Engineering. b) Hydrodynamics in maritime engineering applications is included in Group 4015 Maritime Engineering. c) Thermal processes in chemical energy transformation and combustion is included in Group 4004 Chemical Engineering.
4013. Geomatic Engineering	This group covers geomatic engineering.	a) Geophysics and Geodesy are included in Group 3706 Geophysics. b) Antennas for use in remote sensing are included in Group 4006 Communication Engineering.
4014. Manufacturing Engineering	This group covers manufacturing engineering.	a) Post-harvest packaging, transportation and storage of agricultural products are included in Division 30 Agricultural, Veterinary and Food Sciences. b) Automotive engineering and automotive mechatronics are included in Group 4002 Automotive Engineering. c) Membrane and separation technologies are included in Group 4004 Chemical Engineering. d) Manufacturing robotics is included in Group 4007 Control Engineering, Mechatronics and Robotics. e) Food packaging, preservation and safety are included in Group 3006 Food Sciences. f) Heat and mass transfer operations, fluidisation and fluid mechanics and turbulent flows are included in Group 4012 Fluid Mechanics and Thermal Engineering. g) Applications of biosensors to manufacturing are included in Group 3106 Industrial biotechnology. h) Manufacturing robotics and mechatronics, other than their automotive applications are included in Group 4007 Control Engineering, Mechatronics and Robotics.
4015. Maritime Engineering	This group covers maritime engineering.	a) Transport engineering other than aerospace engineering is included in Group 4005 Civil Engineering. b) Fluidisation, fluid mechanics and turbulent flows are included in Group 4012 Fluid Mechanics and Thermal Engineering.

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Table 22: ANZSRC 2020 Field of Research classification, definition and exclusions

Field of Research	Definition	Exclusions
4016. Materials Engineering	This group covers materials engineering.It includes: ceramics science, technologies and engineering; polymer and textiles engineering; composite and hybrid materials; physical metallurgy and alloy materials; functional materials; and semiconductor materials science and technologies.	a) Materials physics is included in Group 5104 Condensed Matter Physics. b) Materials chemistry, including the theory and design of materials, is included in Group 3403 Macromolecular and Materials chemistry. c) Engineering of materials for automotive applications is included in Group 4002 Automotive Engineering. d) Biomaterials are included in Group 4003 Biomedical Engineering. e) Powder and particle technology is included in Group 4004 Chemical Engineering. f) Construction materials are included in Group 4005 Civil Engineering. g) Extractive metallurgy is included in Group 4019 Resource Engineering and Extractive Metallurgy. h) Nanomaterials, molecular and organic electronics, and nanotechnology are included in Group 4018 Nanotechnology. i) Electro-optical, photonic and photovoltaic devices are included in Group 4009 Electronics, Sensors and Digital Hardware.
4017. Mechanical Engineering	This group covers mechanical engineering.	a) Control theory is included in Group 4901 Applied mathematics. b) Energy generation from photovoltaic devices (solar cells) is included in Group 4009 Electronics, Sensors and Digital Hardware. c) Heat and mass transfer operations, fluidisation and fluidMechanics and Thermal Engineering. d) Nanoelectromechanical Systems (NEMS) are included in Group 4018 Nanotechnology. e) Architectural acoustics is included in Group 3301 Architecture. f) Automation, control engineering and autonomous vehicles are included in Group 4007 Control Engineering, Mechatronics and Robotics. g) Electrical energy generation and storage is included in Group 4008 Electrical Engineering. h) Chemical energy generation and storage is included in Group 4004 Chemical Engineering. i) Automotive combustion and fuel engineering is included in Group 4002 Automotive Engineering.j) Control engineering, mechatronics and robotics is included in Group 4007 Control Engineering, Mechatronics and Robotics.
4018. Nanotechnology	This group covers nanotechnology.	a) Nanobiotechnology is included in Group 3106 Industrial biotechnology. b) Medical biotechnology is included in Group 3206 Medical biotechnology.
4019. Resources Engineering and Extractive Metallurgy	This group covers resources engineering and extractive metallurgy.	a) Earth sciences are included in Division 37 Earth sciences. b) Geotechnical engineering associated with civil engineering is included in Group 4005 Civil Engineering. c) Physical metallurgy is included in Group 4016 Materials Engineering.
4099. Other Engineering	This group covers engineering not elsewhere classified. It includes: agricultural engineering; engineering instrumentation; granular mechanics.	-
4601. Applied Computing	This group covers computing techniques specific to particular application domains and also topics which combine techniques from different sub-disciplines of computing.	a) Hardware oriented applications in Health or life sciences are included in Group 4003 Biomedical engineering. b) Applications where primary focus is the field of application, rather than the application and evaluation of computing technology are included in the appropriate application codes.
4602. Artificial Intelligence	This group covers artificial intelligence other than Machine learning and computer vision.	a) Machine learning is included in Group 4611 Machine learning. b) Vision and imaging are included in Group 4603 Computer vision and multimedia computation. c) Robotics hardware is included in Group 4007 Control Engineering, Mechatronics and Robotics. d) Signal processing is included in Group 4006 Communications Engineering. e) Fairness, accountability, transparency, trust and ethics of AI systems is included in Group 4608 Human-centred computing.
4603. Computer Vision and Multimedia Computation	This group covers computer vision, and methods, systems and technologies for dealing with images, video data, audio and combinations of these.	a) Sound and music processing is included in Group 4607 Graphics, augmented reality and games. b) Signal processing is included in Group 4006 Communications Engineering.
4604. Cybersecurity and Privacy	This group covers the technology that supports cybersecurity and privacy.	a) Legal aspects of cybersecurity and privacy are included in Group 4604 Cybersecurity and privacy. b) Cybercrime is included in Group 4402 Criminology.

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Table 22: ANZSRC 2020 Field of Research classification, definition and exclusions

Field of Research	Definition	Exclusions
4605. Data Management and Data Science	This group covers methods and computing systems for working with data sets.	a) Mathematical transformations and techniques used in the querying of audio, images, or video are included in Group 4603 Computer vision and multimedia computation. b) The management of or administration strategies for database systems are included in Group 4609 Information systems. c) Cryptography, privacy, or security aspects of database systems are included in Group 4604 Cybersecurity and privacy. d) The graphical visualization or visual presentations of data is included in Group 4608 Human-centred computing. e) Machine learning techniques for analysis of large data sets is included in Group 4611 Machine Learning.
4606. Distributed Computing and Systems Software	This group covers methods and systems for supporting the efficient execution of application software, including those which use multiple computation units.	a) The engineering processes that produce these software components are included in Group 4612 Software engineering.
4607. Graphics, Augmented Reality and Games	This group covers algorithms, methods and systems that generate convincing synthetic imagery and sound, amongst other things to allow user interaction in virtual, augmented and simulated environments (including, but not limited to games, online virtual worlds, real-time military, industrial or medical simulators).	a) CAD/CAM systems for manufacturing are included in Group 4014 Manufacturing Engineering. b) Storage and querying of graphics data is included in Group 4605 Data management and data science. c) Human interaction focus in media or games is included in Group 4608 Human-centred computing.
4608. Human-Centred Computing	This group covers methods and technologies which relate to how people and computer systems function together.	a) Use of computing for education other than in the computer sciences and information systems disciplines is included in Division 39 Education. b) Use of computing for information systems education is included in Group 4609 Information Systems. c) Intelligent robotics not focussing primarily on the social aspects of interactions between human and robot is included in Group 4602 Artificial intelligence. d) Hardware aspects of social robotics is included in Group 4007 Control Engineering, Mechatronics and Robotics. e) Design of interfaces for, and experience with, business information systems is included in Group 4906 Information Systems.
4609. Information Systems	This group covers systems that manage information for organisational purposes.	a) Organisation of information and knowledge resources is included in Group 4610 Library and information studies. b) Information retrieval and web search/querying are included in Group 4605 Data management and data science. b) Geospatial Information Systems are included in Group 4013 Geomatic Engineering. c) Development of computer hardware is included in Group 4009 Electronics, Sensors and Digital Hardware. d) Health information systems, including surveillance, where the focus is not on computer science are included in Group 4203 Health services and systems. e) Health information systems with a focus on computer sciences are included in Group 4601 Applied Computing. f) Business information systems are included in Group 3503 Business Systems in context. g) Data science for earth science and geospatial data visualisation is included in Group 3704 Geoinformatics and Geospatial Information Systems and geospatial data modelling is included in 4013 Geomatic Engineering.
4611. Machine Learning	This group covers machine learning and the techniques used by machine learning.	a) Machine learning that is specific to a particular application domain is included in the corresponding code for that domain. b) Systems software to support efficient execution of machine learning is included in Group 4606 Distributed Computing and Systems Software.
4612. Software Engineering	This group covers software engineering and technologies and processes associated with the development of computer software.	a) Descriptions of software applications that are not focussed on the structure or development of the software are included in the appropriate codes for the application domain or type of software.

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Table 22: ANZSRC 2020 Field of Research classification, definition and exclusions

Field of Research	Definition	Exclusions
4613. Theory of Computation	This group covers the theory of computation.	a) Logic not relating to computation is included in Group 4904 Pure mathematics. b) Engineering of quantum computing systems is included in Group 4009 Electronics, Sensors and Digital Hardware. c) Physics of quantum computing is included in Group 5108 Quantum physics. d) Numerical computation and mathematical software that is not in a particular domain and not relating to computer algorithms is included in Division 49 Mathematical Sciences. e) Numerical computation relating to a particular domain is covered in that domain (e.g. computational chemistry is included in Group 3407 Theoretical and computational chemistry).
4699. Other Information and Computing Sciences	This group covers other information and computing sciences not elsewhere classified.	-

12.2 Abbreviations

FCR	Field Citation Ratio
TERC	Tomorrow's Engineering Research Challenge
RAEng	Royal Academy of Engineering
FoR	Field of Research
EPSRC	Engineering and Physical Sciences Research Council
UN	United Nations
SDG	Sustainable Development Goals
REF2021	Research Excellence Framework 2021
CAGR	Compound Annual Growth Rate

12.3 TERC Boolean searches.

Robotics	("Robots" OR "Robot" OR "Robotics" OR "Robotic" OR "Swarm" OR "Swarms" OR "Autonomous" OR "Unmanned" OR "UAV" OR "UAVs" OR "CAV" OR "Automated Functions" OR "Automated Driving" OR "Drive Assist" OR "Multi-Agent Systems" OR "Multi-Agent System" OR "Driverless" OR "Self-Driving" OR "ADAS") AND ("Testing" OR "Validation" OR "Verification" OR "Verifying" OR "Verifiably" OR "Assurance" OR "Assuring" OR "Safety Case Analysis" OR "Runtime Monitoring" OR "Metaheuristics" OR "Simulation" OR "SMT Solving" OR "SAT Solving" OR "Constraint Solving" OR "Model Checking" OR "Search-Based") OR ("Responsible AI" OR "responsible Artificial intelligence") OR ("Explainable AI" OR "explainable artificial intelligence") OR (Explainability) OR ("Human-Machine Teaming" AND Trust) OR ("Human-AI interaction" AND Trust) OR ("Interpretable Machine Learning" OR "Interpretable ML") OR ("Adjustable Autonomy" OR "Flexible Autonomy") OR ("Human-Agent Interaction" AND Trust) OR ("Trust models") OR ("Human-Robot Interaction" AND Trust) OR ("Smart Homes" AND ("Artificial Intelligence" OR AI OR Agents) AND Trust) OR ("Smart cities" AND ("Artificial Intelligence" OR AI OR "Machine Learning" OR ML) AND Trust) OR (automated AND Trust AND Human) OR ("coalition formation" AND Trust) OR ("Agent-based Modelling" AND (Human OR Society) AND Trust) OR ("Smart Grids" AND ("Machine Learning" OR Human OR "Artificial Intelligence" OR AI OR ML) AND Trust) OR ("Smart cities" AND ("Artificial Intelligence" OR "Machine Learning" OR AI OR ML) AND Trust) OR (Auctions AND Trust) OR ("Game Theory" AND (Trust OR Reputation)) OR (("Human Computer Interaction" OR HCI) AND Trust) OR (fair OR fairness OR accountable OR accountability OR ethical OR ethics OR transparent OR transparency OR explainable OR intelligible OR interpretable OR legible OR unbiased OR debiased OR Trust OR Trustworthy OR responsible OR mixed-initiative OR human-in-the-loop) AND (Interaction OR "AI-driven system" OR "AI-infused system" OR "decision-making" OR "interactive system" OR "recommender system" OR "Autonomous system" OR "intelligent system" OR "Virtual Agent" OR "Software Agent" OR "multi-agent system" OR "human-robot interaction" OR "human-machine interaction" OR "human-machine teaming" OR "human-AI interaction" OR "human-computer interaction" OR "personal assistant" OR "autonomous vehicle" OR drone OR UAV OR "smart home" OR "machine learning" OR automation OR algorithm OR "connected devices" OR IOT OR "Internet of Things" OR "smart speaker")
Nature-Based engineering	("Nature inspired" OR "nature based" OR "bio inspired" OR "bio based" OR bioprocessing OR "bio processing" OR bioinspired OR biomimicry OR "bio-mimicry")

Digital Science Solutions

Altmetric

Dimensions

DIGITALscience Consultancy

ifi CLAIMS

figshare

ReadCube

Overleaf

scismic

SYMPLECTIC

writefull

digital-science.com