Institution: Queen's University Belfast

Unit of Assessment: UoA10 Mathematical Sciences

1. Unit context and structure, research and impact strategy

1.1 Context and key achievements

The Mathematical Sciences UoA at Queen's University Belfast (QUB) is hosted at the Mathematical Sciences Research Centre (MSRC) of the University and is the only research unit in Mathematical Science in Northern Ireland. MSRC is one of six research centres in the School of Mathematics and Physics which, in turn, is one of six schools in the Faculty of Engineering and Physical Sciences, see Figure 1.

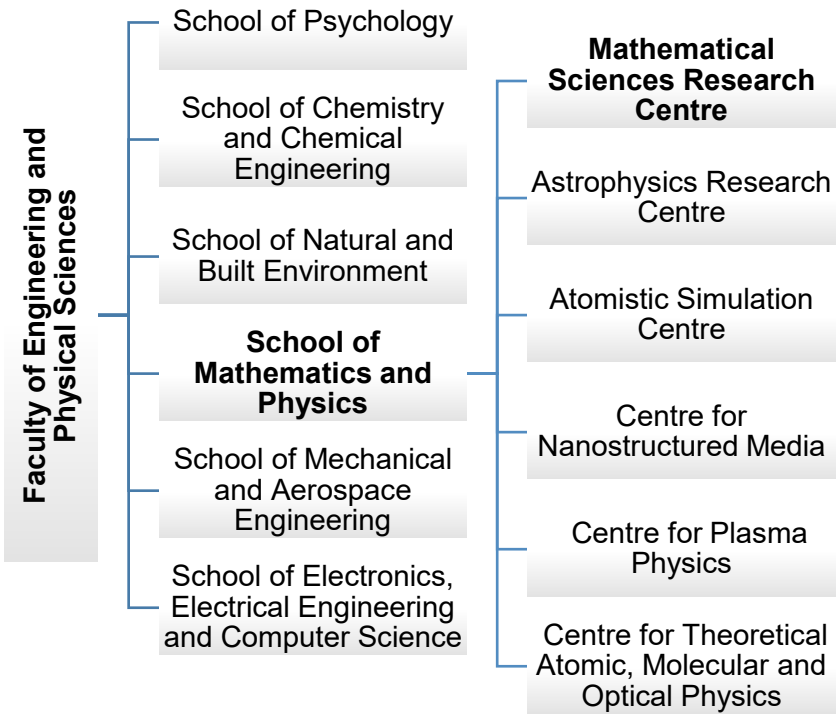
The MSRC was established in 2016 by merging the Pure Mathematics Research Centre and the Centre for Statistical Science and Operational Research and expanding from 12 to 19 staff. This nearly doubled the number of active researchers in the area and created new groups in Applied Mathematics and Data Analytics. The merger and expansion arose from the 2016-2021 Corporate Plan which aims to strengthen *core disciplines* such as the Mathematical Sciences and to create new areas that *encourage interdisciplinarity*.

The recruitment campaign comprised four appointments in Applied Mathematics, four in Data Science and one in Statistics (against one retirement in Pure Mathematics and one long-term absence in Statistics). The majority of the Unit are early-to-mid career researchers (see also Figure 4), with four staff declaring themselves Early Career Researchers, meeting the Corporate Plan aim of creating *new opportunities for inspiring research leaders, both established and emerging*.

The Unit has many notable achievements during the REF period:

- The successful integration of nine new staff into the unit.
- More than double the research income: £0.9M (£81K/FTE) in 2014 against £2.4M (£128K/FTE) in 2021.
- Increased international recognition, evidenced through three prestigious visiting positions at the Isaac Newton Institute and 13 further invited stays at leading international research centres.
- An expanded global network of coauthors and collaborators, covering 22 countries in Europe as well as Australia, Canada, China, Israel, Iran, Japan, Morocco, New Zealand and USA, see Figure 6.
- Increased interdisciplinarity, demonstrated by new collaborations with leading researchers in biology, engineering, computer science and theoretical physics, demonstrating how Mathematical Sciences are a core part of research in a wide range of disciplines.
- Broad links to industry, evidenced by nine Knowledge Transfer Partnerships with a combined total value of more than £1.1M.
- Strong engagement with the NI Executive, most notably Covid-19 modelling guidance to the *Chief Scientific Advisor* of the *Department of Health (NI)* and the nationwide body the *Joint Biosecurity Centre*.
- Renewal of the School Athena SWAN silver status.

Figure 1: Organisational chart of the Faculty of Engineering and Physical Sciences.



1.2 Strategy

The Unit's research strategy is built around the staff expansion that resulted in the MSRC. It consists of three key stages:

- Consolidate and expand the Mathematics and Statistics groups to achieve a critical mass of researchers.
- Embed new appointments into the School and enhance both individual research lines and the overall research environment of the Unit.
- Encourage impactful research with industrial potential to bridge and mutually strengthen the traditional and newly established expertise of the Unit.

The first stage is now complete via the formation of the MSRC (an overview of the hiring strategy is in Sec. 1.3). The second stage is currently ongoing and involves the appointment of a *Director of Research* (appointed October 2020) and the formulation of a new *Mathematics Curriculum* (to provide more quality research time) as detailed in Secs. 2.3 and 3.3. Initial, yet crucial, steps on the third stage have already been taken by the Unit:

- Increased interdisciplinary connections (see Secs. 1.4 and 4.3).
- Establishing greater links to local industry (via Knowledge Transfer Partnerships, see Secs. 1.5.2 and 4.4).
- Widening the staff base of impact-focused research (via the appointment of, and collaboration with, the School's *Director of Impact,* see Sec. 1.5.1).
- Facilitating cross-fertilisation between new and existing research areas (as detailed in Secs. 1.3 and 1.4.3).

This research strategy is a substantial evolution from the REF2014 submission, reflecting the institutional strategy and the new ambitions for research in Mathematical Sciences at QUB. The 2014 strategy focused on development of traditional research strengths in the areas of *Functional Analysis, Algebra* and *Topology* within *Pure Mathematics,* and of *Survival Analysis, Markov Modelling* and *Data Mining* with applications to *Healthcare* and *Traffic Flow* within *Statistics and Operational Research*. These developments took place alongside the expansion, as evidenced by the successes given in Sec. 1.1.

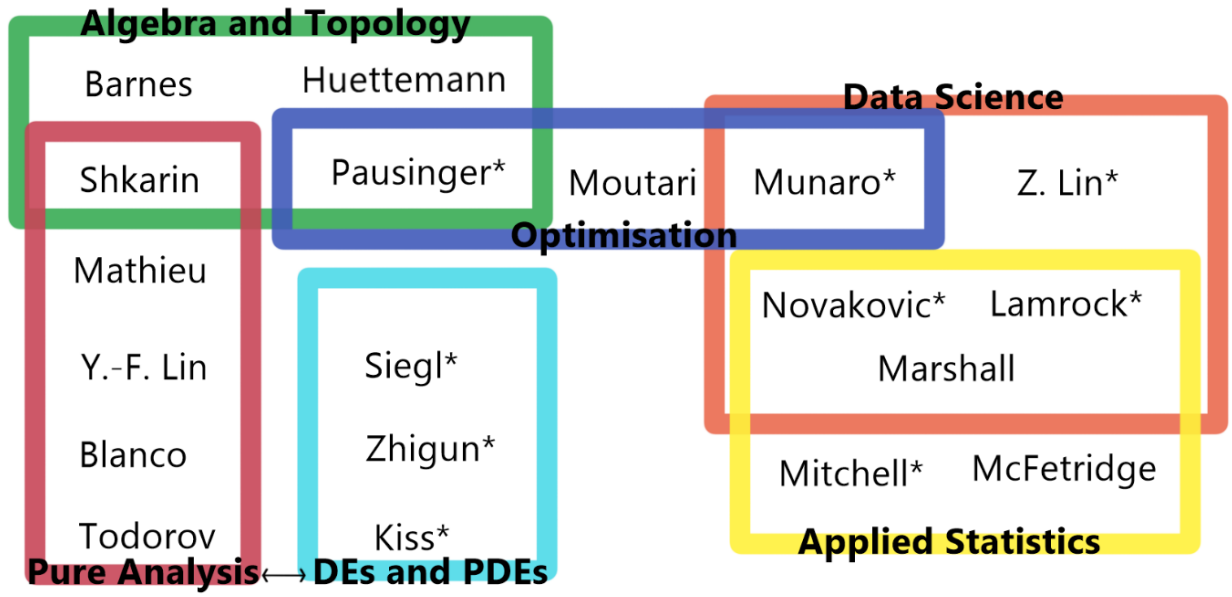
1.3 Structure and Research

The staff may be grouped as follows, with new appointments asterisked.

- **Applied Statistics and Operational Research:** Marshall, McFetridge, Mitchell*, Moutari.
- **Pure Mathematics:** Barnes, Blanco, Huettemann, Y.-F. Lin, Mathieu, Shkarin, Todorov.
- **Applied Mathematics:** Kiss*, Pausinger*, Siegl*, Zhigun*.
- **Data Science:** Lamrock*, Z. Lin*, Munaro*, Novakovic*.

An indicative representation of primary staff interests is presented in Figure 2. This diagram demonstrates the large number of research interconnections within the MSRC and how the new appointments have, as intended, made the Unit itself more cohesive.

Figure 2: Diagram of staff interests.



The thematic interconnections were intentionally enhanced by the new staff investment:

- New expertise in *Spectral Theory*, *Differential Equations, Partial Differential Equations* and *Dynamical Systems* (Kiss, Siegl, Zhigun) naturally aligns with the pre-existing *Pure Analysis* group (Blanco, Y.-F. Lin, Mathieu, Shkarin, Todorov) who work on *Operator Theory* and *Functional Analysis*.
- Three staff members in *Data Analytics* (Lamrock, Z. Lin, Novakovic) connect strongly to current expertise in *Healthcare Statistics* (Lamrock and Novakovic) and will allow for new interactions with business and industry, based on statistical data science (see Sec. 3.2 for current examples of this connection).
- An appointment in *Foundations of Data Science* (Munaro) establishes concrete links with computer science and cyber security research conducted at the *Institute of Electronics, Communication and Information Technologies* at QUB. It has further created graph-theoretic links to the pre-existing *Traffic Flow* theme (Moutari) and the *Zero-error Quantum Information* theme (Todorov).
- A strong appointment in *Topological Data Analysis* (Pausinger) has led to tangible links with staff members from the existing *Algebraic Topology* (Barnes, Huettemann) group.

1.4 Interdisciplinary research

The development of interdisciplinary links is an integral part of the Unit's research activities. The current research landscape benefits from strong interdisciplinary features, as evidenced by published research that makes links between:

- Statistical Science and Healthcare (Lamrock, Marshall, McFetridge, Mitchell, Novakovic).
- Statistical Science and Physics (McFetridge, Marshall).
- Graph Theory and Data Science (Munaro).
- Dynamical Systems and Biology (Zhigun, Kiss).
- Optimization and Traffic Flow (Moutari).
- Functional Analysis and Quantum Information Theory (Todorov).
- Mathematics and Engineering (Barnes, Marshall and Novakovic).
- Data Science and Topology (Pausinger).
- Data Analytics and Computer Science (Z. Lin, Novakovic).

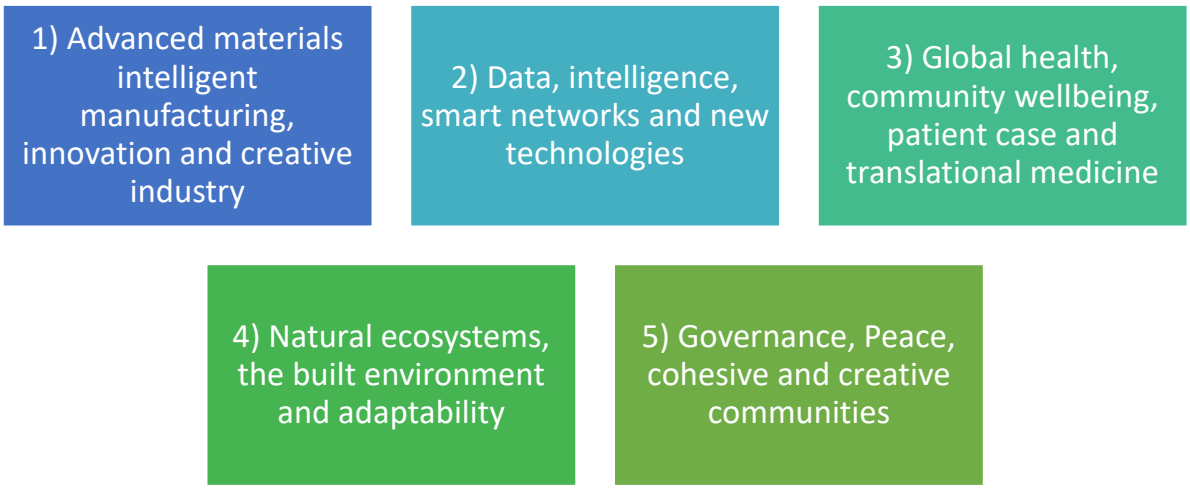
Wider links within the University were enhanced, and mathematics impact encouraged, by an institution-wide *Mathematics Sandpit* in 2015. A headline outcome was the ongoing collaboration between Barnes and the engineering group, leading to four published papers (with more to appear) and a cross-disciplinary funded PhD project with the School of Mechanical and Aerospace Engineering on mathematically optimizing rotational molding.

1.5 Impact Strategy

A vital part of the third stage of the Unit strategy is to encourage wide interaction between the Unit, Industry and the Public Sector, with the aim of enhancing and accelerating societal and economic impact. This has been achieved through the activities of the School-level *Director of Impact,* a focus on Knowledge Transfer Partnerships and the addition of the *Data Science* group to the Unit. This strategy has created a culture of impactful research in the Unit. As the next two subsections detail, there are several projects in various stages of development, which are part of a pipeline of potential Impact Case Studies for the next REF submission.

The Unit's first Impact Case Study is based on the application of statistics and data science to Healthcare (modelling patient flow through hospitals, survival rates and optimizing treatment). The second focuses on monitoring the health of key infrastructure (such as bridges). These two case studies cut across the five strategic themes of the Institutional Statement, reproduced below as Figure 3. The first case study connects themes 2 and 3, the second themes 2 and 4, thus demonstrating how Mathematical Sciences underpin much of the major research activities within QUB.

Figure 3: Five strategic themes summarising existing and future research strengths of QUB.



1.5.1 Director of Impact

The Director of Impact manages the support mechanisms from the School's 2014 Impact Development Strategy, encourages all staff to look for impact potential within their work and advises on how to discover such potential. The support includes mentoring by staff with impact experience, a reduction in teaching load for staff members with substantial impact-focused projects and guiding staff to University-wide support, such as institutional impact grants (worth £5K each). The new appointments have been particularly encouraged to engage with impact activity to broaden the impact pipeline and ensure sustainability of the Unit's impact successes. Examples of headline projects from the new appointments include:

- Lamrock's mathematical modelling of Healthcare. This activity builds on her past role as statistical advisor to the *National Centre for Pharmacoeconomics* and has resulted in an ESRC Impact Acceleration Account on the impact of Covid-19 on cancer screening.
- Pausinger's support and training for researchers at *TWT GmbH* to develop analytical problem-solving skills that will be applied to provide technological solutions to their clients.

1.5.2 Knowledge Transfer Partnerships

Over the REF2021 period, members of the MSRC had nine KTPs with a combined value exceeding £1.1M, see Sec. 4.4. This marks the success of the Institutional Knowledge Exchange Strategy where, for the period 2014-15 to 2019-20, QUB ranked 11th in the UK for total value of Innovate UK grants offered (5th by total value as lead partner). Three of the most impactful KTPs from MSRC are:

- Marshall: real-time data analytics and algorithms for intelligent safety devices (GPS, road condition, air quality) at See.Sense (Limeforge Ltd). This project has seeded new developmental funding for See.Sense through smart city initiatives (the integration of information and communication technology into cities to optimize operations and to connect better with citizens).
- McFetridge: developing artificial intelligence models of felt emotion at Sensum. This work has led to the development of a personalised mobility experience with empathic artificial intelligence and has been awarded an 'Outstanding' classification by Innovate UK.
- Marshall: embedding the use of machine learning and analytic techniques into Ampliphae Ltd products. As a result, Ampliphae can now assess the quality of encryption on a service and highlight to users when they may be using an insecure cloud service.

1.5.3 Data Science

The Unit's two Impact Case Studies are based on *Applied Statistics* and *Healthcare Modelling.* Both research activities connect strongly to the new *Data Science* group. A £220K grant by the *Health Foundation* (20% controlled by the Unit) shows the strength of the connection between the Unit's *Data Science* group and *Healthcare Modelling* by leveraging the combined expertise in sophisticated statistical modelling and big data analytics of the MSRC.

The strong links to industry and the public sector of the *Applied Statistics* group is being leveraged to provide the new *Data Science* group with support and high-quality mentoring in the creation of new links. This will offer new impactful research possibilities in big data, artificial intelligence and data analytics, the focus of the Global Innovation Institute: a £53.4M project to catalyse digital innovation in key sectors within the Belfast region, by creating challenge-led solutions for the data-driven economy. This institute is a core part of the Belfast Region City Deal, a collaborative, cross-sector approach that will deliver economic growth and recovery to the region.

1.6 Open Research Environment

The Unit has a strong culture of open access (OA) publishing, utilizing community repositories (such as arXiv) and the QUB publication repository "PURE". The Unit closely follows the open access policy described in the Institutional Environment Statement, Section 2f. The Unit is supported by the McClay Library on OA matters and consistently shows extremely high rates of compliance. The same is true for our storage of research-related data and its availability to others upon request.

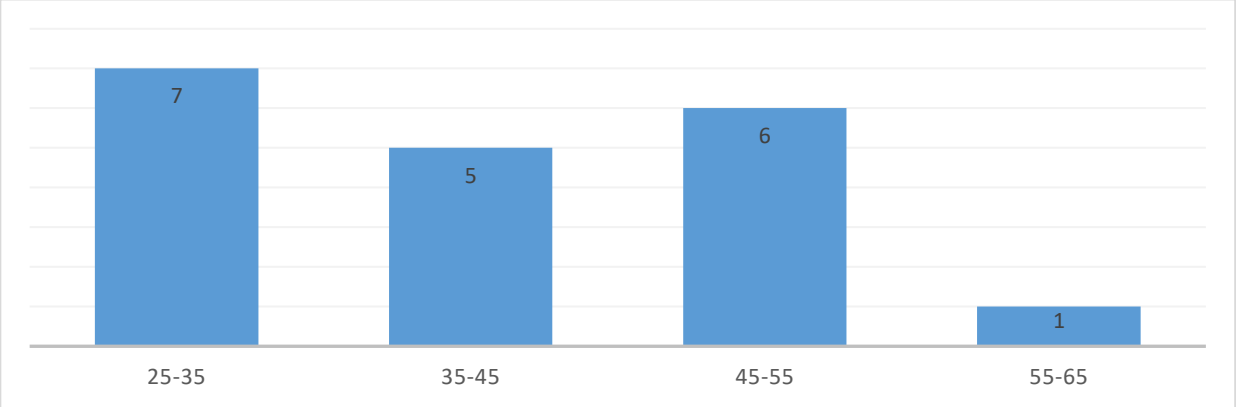
2. People

2.1 Staffing strategy

Staffing in MSRC is directly linked to both the research strategy of Sec. 1.2 and the large scale QUB institutional objectives (such as the aforementioned Global Innovation Institute and Belfast Region City Deal). Having virtually no *Applied Mathematics* research at the time of the REF2014 submission, the Unit has now established, and successfully integrated into the Centre, a vibrant group in this area comprising four permanent academic staff members. Its specific research themes were chosen after careful consideration for coherence and interconnection, as seen in Figure 2. Similarly, the new appointments in *Data Science*, while complementing the existing expertise in *Statistical Data Science*, permit new directions and applications. Mitchell, appointed in 2016, is part of the Q-Step Centre, a multidisciplinary collaboration promoting a step-change in quantitative social science training. The Q-Step Centre is part of a £19.5M UK-wide programme funded by the Nuffield Foundation, ESRC and UKRI.

The new appointments were completed in three rounds spread across the REF2021 period, which allowed for consolidation of new appointments and more responsive growth. Figure 4 shows the impact of hiring many new staff at early stages of their careers.

Figure 4: Graph of staff age distribution.



The MSRC places a significant emphasis on industry links as part of its staffing policy. Both Lamrock and Novakovic were recruited after gaining experience in industry or the public sector. The appointments of Lamrock, Z. Lin and Novakovic were linked with the provision of a flagship MSc programme in Data Analytics, which started in 2017. The programme, developed with substantial industry input, and connecting to the Global Innovation Institute, has attracted hundreds of applicants. All students enjoy an industrial placement as part of the course and the first year of operation saw a 100% employment rate within three months.

2.2 Staff development

2.2.1 Appraisal and Progression

The University has made substantial changes to its staff development policies as detailed in the Institutional Environment Statement, Section 3a. A major outcome of this change has been a dramatic alteration to the appraisal processes, moving away from a measurement-focused task comparing staff to academic profiles, to one directly based on staff development. The new Personal Development Review framework provides the stage for an ongoing, constructive and non-judgemental conversation between reviewer and reviewee. The conversation addresses progress against previously agreed priorities, career aspirations, the co-creation of future priorities and development goals, and support plans.

A second reform was to move away from a numerical Workload Allocation Model to a qualitative review of workload by the Head of the Centre, the Director of Research and the (Associate) Director of Education. Moreover, as part of a revised planning process, each School in the Faculty has been asked to develop a staff strategy that explicitly creates and maintains succession planning, with opportunities for staff to gain management experience through deputy positions. These changes are an important part of the equality and diversity initiatives of the School, detailed in Sec. 2.6.

Over the period, four staff have progressed to Senior Lecturer and one to Professor. The pace of promotions will increase as the new progression scheme embeds into the University. In particular, the new scheme states that progression from Lecturer to Senior Lecturer will be a smooth and expected part of an academic career.

2.2.2 Probation, Sabbaticals and Travel

Newly appointed staff members are given a probationary period of three years. They are assigned a mentor (for both teaching and research issues) who works closely with them on achieving the development goals agreed upon at the commencement of the post. The mentors are taken from current staff, particularly the previous round of academic appointments (who are now taking on leadership roles and more senior positions), giving those staff valuable experience as mentors. A School Probationary Committee (chaired by the Head of School and including the Head of MSRC) annually reviews progress of probationers and runs the confirmation in post process.

Probationers must complete the QUB Postgraduate Certificate in Higher Education Teaching and to attend a one-day training course on PhD supervision. Probationers receive a start-up package of £10K to develop their research, attend relevant conferences and meetings and expand their collaborative network. Since 2016, research projects by new staff members have been prioritized for centrally allocated PhD studentships. This quickly gives new appointments supervision experience and enhances their research career. During the first year of probation, staff members enjoy a reduced teaching load of one module per year (an average equivalent of 45 contact hours) and a reduced administrative workload. These duties are then increased in a tapered manner over the next two years. Over the REF2021 assessment period, six staff members have passed probation. This includes three of the nine new appointments, representing 100% of those eligible to pass probation.

Staff are encouraged to apply for sabbatical leave according to the institutional policies, especially for invited stays at major research institutes. In this context, Barnes was given leave to participate in a semester-long programme in the Isaac Newton Institute for Mathematical Sciences, which is a very prestigious accolade. Conference travel is supported and hosting of research visitors is encouraged by an allowance of approximately £1K per year per staff member from the annual budget of the Centre.

2.3 Staff development: New appointments

To manage the challenge of appointing many new staff in a short period, the Unit implemented a plan to accelerate the embedding and development of the new appointments by establishing prompt connections to suitable activities, as detailed below. This is a core part of the second stage of the overall Unit strategy and will accelerate the promotion of the new appointees and quickly give them deeper connections to Unit and School activities. In all cases, the workload was closely monitored by the Head of MSRC.

The *Applied Mathematics* and *Foundations of Data Science* appointments were involved in the curriculum reform alongside more senior staff from across the School. The reform (completed in 2019, delayed to 2021 due to the shift to online teaching) will reduce teaching loads to an average of about 1.25 modules (63 contact hours) per year per staff member. It will embed the research expertise of the new appointments into the curriculum and align the provision of education in mathematics to the needs of an ever-evolving market through the introduction of modern topics (such as machine learning and topological data analysis).

The *Data Analytics* appointments were either provided greater support in engaging with impact activities (Lamrock) or offered leadership positions in the refinement of the MSc programme in *Data Analytics* (Novakovic, Z. Lin). Such leadership opportunities gave the new appointees a high-level view of the School, greater contact with School staff outside the Unit, experience building consensus for change, and practice communicating such change.

2.4 Postdoctoral Research Assistants

Postdoctoral Researchers in the MSRC are normally given a probationary period of six months, with the project supervisor acting as mentor. The process of confirmation in post is undertaken by a School Committee involving the Head of the MSRC. Research staff are normally supported by externally funded research contracts. During the REF2021 period, the Unit has hosted eight PDRAs. QUB actively supports the Concordat for Training Research Staff and provides training aimed specifically at them. A School-wide Postdoctoral Forum provides a comprehensive context to share career experience with other research staff members, opportunities to receive advice from experienced academics on important aspects of career development, and preparation for undertaking a permanent academic post. The forum offers community-building activities, including well-attended “Coffee&Research” morning sessions. It appoints PDRA representatives who are embedded in the Gender Equality Committee of the School.

2.5 Research students

2.5.1 Studentships and funding

During the REF2021 assessment period, 22 PhD students have started their postgraduate research studies with members of the Centre. Within the same period, 24 students completed their PhD. The MSRC has received an allocation of at least two PhD studentships per year from the School, funded by the Department for the Economy of Northern Ireland or by the EPSRC (in addition to the PhD studentships leveraged to newly appointed staff members). The studentships cover fees and a stipend of approximately £15K per annum. The School allocates part of its budget to provide £700 per annum to each PhD student as a research-and-training allowance (primarily conference expenses).

In addition to the general School allocation, the Centre has had significant success in attracting PhD students funded from the public sector. Among them: two InvestNI bursaries, another two from the Strategic Investment Board (part of a £220K award to the Unit), an award from the Department of Agriculture and Rural Development and one from the Department for Infrastructure. Self-funded PhD students have been attracted by our internationally leading expertise (notably, 25% of the current PhD cohort are self-funded, the largest percentage of such students in any research centre within the School). In addition to the sources already mentioned, the Unit is using funding from the China Scholarship Council to attract outstanding PhD students. This diversity of funding sources adds to the sustainability of the PhD cohort size.

The Centre's strong connections with other disciplines has led to cross-supervised research students with the following QUB schools:

- Medicine, Dentistry and Biomedical Sciences,
- Pharmacy,
- Social Sciences, Education and Social Work,
- Electronics, Electrical Engineering and Computer Science,
- Mechanical and Aerospace Engineering,
- Natural and Built Environment.

Funding for these positions often comes from the public sector (as above) or by leveraging against substantial cross-discipline grants.

2.5.2 Recruitment and support

PhD research projects offered by staff members are advertised widely and the applicants undergo a formal selection interview with a panel of MSRC staff. The usual minimum requirement for admission is a 1st class Honours MSci degree. Quality of applications and field diversification are both factored into the ranking. In case of equal profiles, candidates from underrepresented groups are given priority.

PhD students are supported by their Principal and Secondary Supervisors (with further supervisors in case of inter-disciplinary research). The first is the traditional supervision role and the second acts as an additional point of contact and provides pastoral support. New research students attend a range of induction events and training, organised by both the University and the School. Three months after starting, students complete an Initial Review to confirm the feasibility of the project. Students' progress is monitored annually in a formal manner by a Progress Monitoring Committee, independent of the supervisors. This committee reviews both academic progress and engagement with the research community, as demonstrated by preprints, publications, talks and conference attendance.

2.5.3 PhD Training

Training and education beyond the supervisory team is a key focus of the Centre. Visitors to the Centre (averaging roughly one per month) are encouraged to give mini-courses aimed at postgraduate students during their stays, providing focused introductions to advanced areas. Visiting PhD students through Erasmus programmes have contributed to an enhanced diversity in our PhD cohort, with three such visits over the period.

PhD students regularly attend national and international conferences and present their work, usually attending 2-3 such conferences a year. These talks are practiced at departmental seminars and colloquia, comprising at least 24 meetings annually. The PhD student community is encouraged and supported in running its own seminars, such as a Gong Show format of short introductory talks and the Online Algebraic Topology Seminar. The shift to online seminars will sustainably provide further engagement of the Centre's PhD students with the wider mathematical community and additional learning opportunities.

PhD students undergo a total of 20 days of University-organised generic training and development specifically aimed at enhancing skills which improve their employability.
All PhD students are given the opportunity, after School training, to undertake assignment marking and to conduct tutorials, while a small number may be invited to deliver selected undergraduate lectures, valuable experience for a possible future academic career.

2.6 Equality and diversity

The University is recognised as nationally leading in equality initiatives. Through the Gender Equality Committee, the School is fully engaging with its commitment to promote equal opportunities and to create and sustain an environment that celebrates staff and student diversity. Since September 2013, the School holds an *Athena SWAN* Silver Award (renewed for 5 more years in 2020) and is a supporter of both the *Institute of Physics* Project JUNO and the *London Mathematical Society's* Good Practice Scheme*:*

- All staff have successfully undergone diversity and anti-bias training through centrally administered mandatory QUB training courses.
- All recruitment adverts include a statement of the School's commitment to equality and diversity, and recruitment panels must have female representation.
- A healthy work-life balance is supported by scheduling meetings during central hours of the day, flexible work opportunities and career leave possibilities.
- All members of staff are actively encouraged to apply for promotions and leadership positions by the Unit and School.
- Attending events organized by the EPSRC-funded SENSE Network partnership on 'Inclusion Matters'.

An Athena SWAN Champion oversees all gender initiatives, which include outreach activities such as an annual *Girls in Maths* event whose keynote speaker is female. Maternity and paternity pay and leave are enhanced beyond the statutory minima, with additional support offered for return from maternity leave. Staff members have taken such leave three times during the REF2021 period.

The care for staff wellbeing occupies a primary role at the University. After formal training, four School staff have undertaken a role as a Safe Harbour, a contact point for staff and students in case of work-related stress and anxiety. In the case of reports for work-related stress, a meeting with the relevant Head of Centre is arranged, which produces a formal report with recommendations, whose implementation is monitored by the Head at subsequent meetings. Staff experiencing ill health or taking health-related leave are supported by a University-wide policy and the QUB Occupational Health Service. After an absence, staff discuss their needs and develop a re-integration plan at a formal meeting with the relevant Head of Centre, which may include graduated reductions in both teaching and research duties.

The Unit has a high degree of cultural diversity, with 87% of the new appointments from outside the UK, providing natural collaborative links with research centres in Austria, France, Germany, Greece, Hungary, Italy, Serbia, Switzerland and Taiwan. Six members of the Unit (32%) are female and the School encourages all staff to engage with gender equality activities that occur throughout the year. Three members of the Unit (16%) are from ethnic minority backgrounds.

Outputs for REF were selected following internal and external peer review. Where outputs were close in judged quality, selections were made to better reflect the diversity of research in the Unit and more equitably represent individuals, as per institutional policy.

3. Income, infrastructure and facilities

3.1 Infrastructure and facilities

Since 2015, the MSRC is housed in the newly refurbished historical Lanyon building at the heart of the QUB campus. In addition to staff offices, it comprises offices for PDRAs, PhD students, MSci students and meeting rooms to facilitate discussions and to host group meetings. Its location, next to the Main Physics building and opposite the Mathematics and Physics Teaching Centre (opened in 2016), ensures easy and convenient contact with undergraduate students and quick access to seminar rooms and conference space. The refurbishment was valued at £2.3M and development of the Teaching Centre at £2.7M.

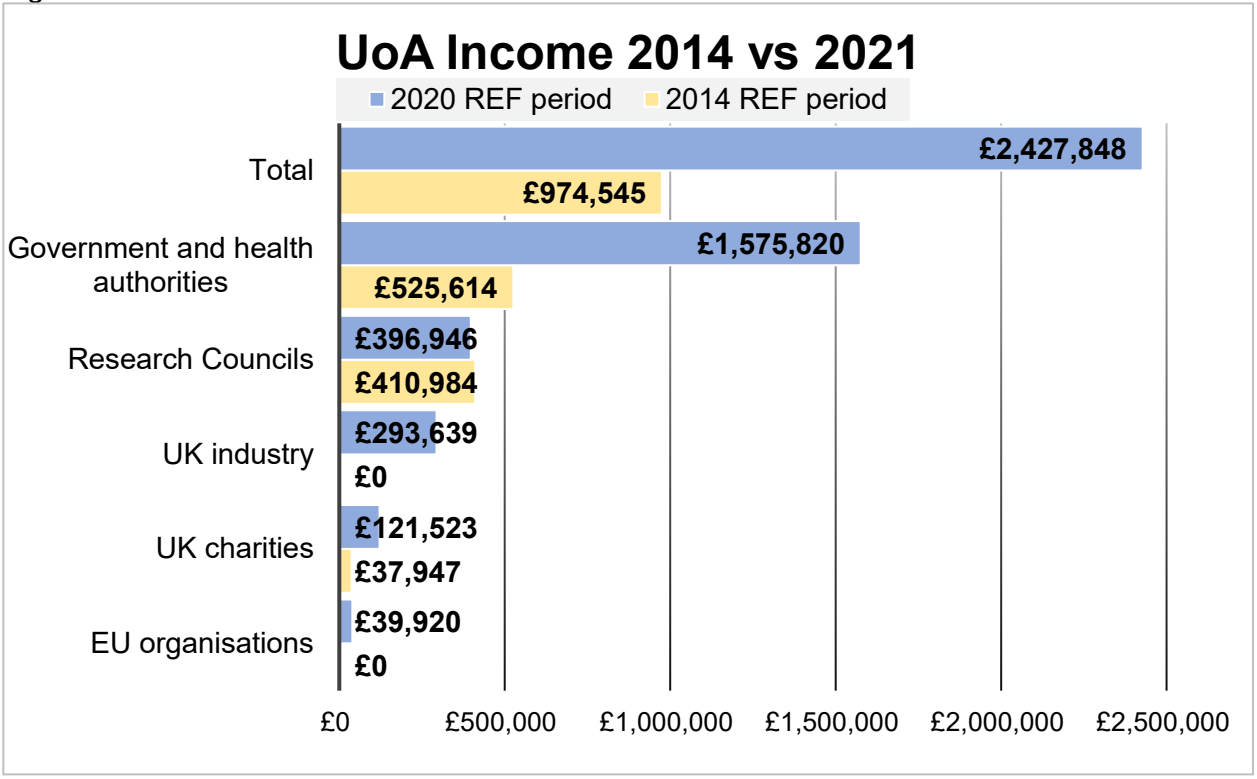
Two minutes' walk from the Lanyon Building are both the state-of-the-art McClay Library and the QUB Graduate School, a hub for PhD training, support and interdisciplinary work. All staff and research students have dedicated computers (replaced every four years) equipped with the software packages Matlab, Mathematica, SAS and SPSS (available both on and off campus).

Computing infrastructure for the needs of research in *Statistics* and *Data Analytics* is available through the £5M University level High Performance Computing (HPC) provision Kelvin-2: one of seven UK Tier-2 HPC Centres and the only one in Northern Ireland. Smaller-scale provision comes from a 2016 investment of £30K by the School for dedicated computing infrastructure.

3.2 Income

The first two stages of the Unit strategy have led to a substantial increase in the external funding attracted by the Unit. The increase in the diversity of funding sources has added to the sustainability of the Unit. A summary of the Unit's REF2021 research income is given as Figure 5.

Figure 5: REF2014 vs REF2021 research income.



With respect to the REF2014 assessment period, the volume of secured research funds has grown by more than £1.4M, increasing from £81K/FTE to £128K/FTE, thus demonstrating the enhanced impact of the research performed by members of the Unit.

The Unit has strong success in attracting funds from UK industrial actors, public corporations, government and local authorities. This is partly the result of a sustained long-term collaboration between *Applied Statistics*, hospitals and healthcare institutions (both local and overseas). A highlight is Marshall acting as Co-Investigator on the £3M Phase 2 of the *Centre of Excellence in Public Health NI*. The strategically appointed experts in *Data Analytics* add to this collaboration and have already produced dividends, as exemplified by the partnership of Marshall and Novakovic, including an award of over £220K by *The Health Foundation* (20% ownership), and a grant of £215K from the *Connected Health Innovation Centre* (an industry-led, interdisciplinary research team) which includes two international PhD studentships on solving healthcare problems through data analytics.

The *Applied Statistics* group has been successful in obtaining other grants from industry and charity; for example, McFetridge has 10% ownership of a £500K award from *Randox Laboratories Ltd* and Mitchell has 10% ownership of a £211K award from *The Dunhill Medical Trust.* As part of the Unit strategy, Knowledge Transfer Partnerships have been a regular route to facilitate interactions with industry, with Marshall, McFetridge and Moutari being actively involved in such collaborations.

During the REF2021 period, the MSRC has had significant successes in attracting EPSRC funding, highlights include:

- Barnes and McFetridge have both secured EPSRC New Investigator Awards of £91K and £100K respectively.
- Moutari has been successful in obtaining a standard EPSRC grant of *circa* £200K.
- Mathieu was awarded a £46K EPSRC standard grant for research bridging Topology and Operator Algebras.
- Todorov has been the PI of a £32K EPSRC interdisciplinary grant, through which he led a team of researchers from Pure Mathematics, Theoretical Physics and Computer Science to make advances in Zero-error Quantum Information Theory.

In addition, Todorov has twice been awarded Heilbronn Institute Focused Research Meetings grants, as well as a Royal Society International Exchanges award for collaborative research with the University of Guelph (Canada).

During the REF2021 period, MSRC staff members have obtained a total of 28 grants from various schemes of the London Mathematical Society, including an LMS-CMI Research School grant, an LMS Workshop grant and a grant to host the 2016 edition of the Young Functional Analysts Workshop. In 2019, the Centre was awarded a £31K LMS grant to host the LMS Undergraduate Summer School in 2021.

3.3 Funding application support

Support for grant applications is a priority, due to the young age-profile of the Unit. The School provides the MSRC with an annual budget to support research activities in accordance with the Centre's priorities and strategy, typically around £25K-£30K. This is more than double the per-annum support received in the REF2014 period. Targeted support is received for hosting current and prospective collaborators or for developing grant applications.

Further support for the applicant comes from advice of their mentor, more senior colleagues and reviews of draft applications by the Centre's Head. This mentoring led to the successful New Investigator Awards and the ESRC Impact Acceleration Account. More direct assistance comes from the *Director of Research,* who can reduce administrative loads for staff preparing large grants (over £150K).

4. Collaboration and contribution to the research base, economy and society

4.1 International leadership and recognition

The Unit has achieved international leadership in research, as evidenced by:

- Prestigious visiting positions at the *Isaac Newton Institute* for Mathematical Sciences held by three of its members in the past three years: Barnes, Y.-F. Lin and Todorov.
- A total of 13 stays during the REF2021 period by members of the MSRC at leading international research centres. The most prominent of which are:
    - *Fields Institute for Research in Mathematical Sciences* (Toronto),
    - *Banff International Research Station* (Banff),
    - *Centre International de Rencontres Mathematique* (Marseille),
    - *International Centre for Mathematical Sciences* (Edinburgh),
    - *Institut Henri Poincaré* (Paris),
    - *Instituto de Ciencias Matemáticas* (Madrid),
    - *Centre de Recerca Matemática* (Barcelona).
- Visiting positions in universities in Austria, Belgium, Canada, China, Germany and Slovenia, as well as a distinguished *Thousand Talents* Visiting Professorship at Nankai University, China.

The MSRC enjoys significant international recognition in a variety of areas, as evidenced by a total of 113 invited or keynote talks at national and international conferences during the REF2021 period. Further to these talks, MSRC members have spoken externally at 124 seminars, at a total of 89 different institutions, including the University of Oxford, Imperial College London, King's College London, Jilin University, Beijing Institute of Technology, Shanghai University, Yale University, the Sorbonne, the Max Planck Institute for Mathematics and the Isaac Newton Institute. Moreover, MSRC staff acted as UKRI funding panel members six times during the period.

Specific examples of high-level research recognitions include, but are not limited to, the following:

- Leadership in *Abstract Harmonic Analysis* has resulted in regular invitations of Y.-F. Lin and Todorov to the major biennial meeting in the area (Halifax, Kaohsiung) and an invitation of Todorov to the Canadian Abstract Harmonic Analysis Symposium (Ottawa).
- Siegl has realised Research in Pairs stays at Institute Henri Poincaré (2018) and Centre International de Rencontres Mathematique (CIRM, 2016).
- Barnes' strength in *Equivariant Homotopy Theory* led to Research in Pairs stays at CIRM (2018) and Oberwolfach (2017).
- Y.-F. Lin has been fully supported by the University of Sydney to participate in a research group meeting in *Operator Algebras* (2019).
- Todorov has been invited to deliver mini-courses at the *Fields Institute* (2014), the Chalmers University of Technology (2014), the Hellenic Summer School of Operator Theory (2014, 2017, 2018) and Nankai University (2017, 2018) while Mathieu and Todorov gave lecture series at IPM Tehran (2014, 2017).

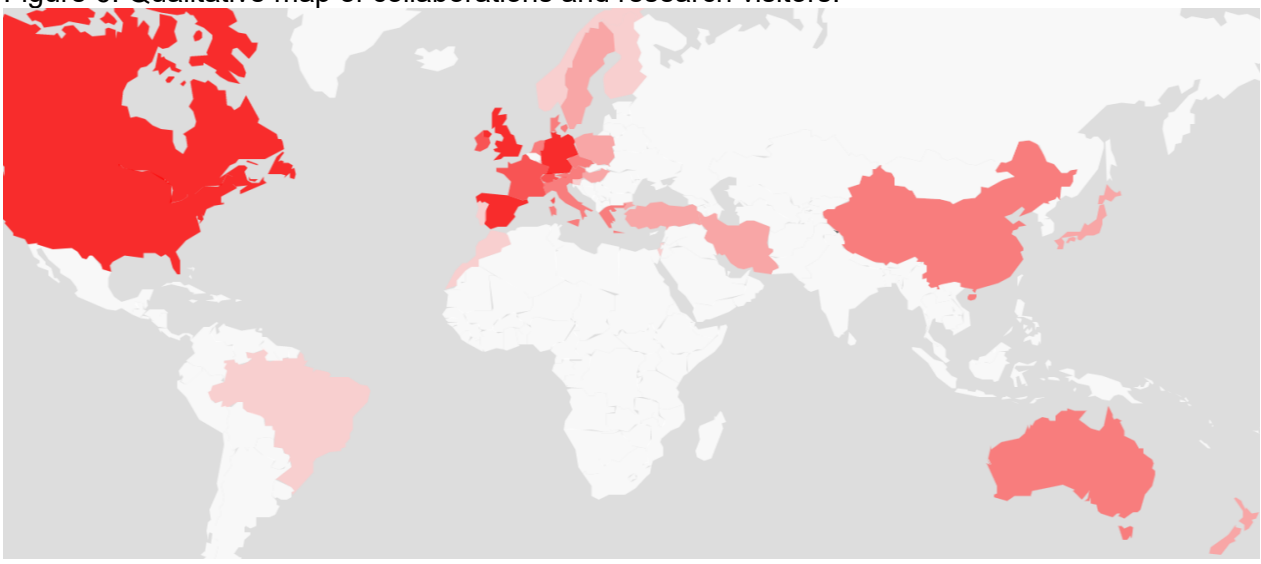
4.2 External collaboration

External collaborations and joint research projects are at the heart of MSRC's research activities. Examples of such activities conducted within the REF2021 period include:

- Todorov's collaboration with Turowska (Gothenburg), which has resulted in nine joint papers since 2014, including one publication in *Advances in Mathematics* and two in the *Journal of Functional Analysis.*
- Siegl's collaboration with Krejcirik (Prague), which has led to seven publications, including ones in the *Transactions of the AMS* and the *Journal of Functional Analysis.*
- Pausinger's work with Edelsbrunner (Klosterneuburg), which has resulted in a publication in *Advances in Mathematics.*
- Barnes' collaboration with Greenlees (Warwick) and Kedziorek (Utrecht), which has led to four publications, including papers in *Mathematische Zeitschrift* and *Algebraic and Geometric Topology.*
- Y.-F. Lin's participation in a joint research project with five other female researchers from Australia, Germany, New Zealand and the USA that originated at a meeting at BIRS (Banff) and has attracted, already in its initial stages, funding from the University of Sydney and the University of Munster.

A qualitative map of collaborations and research visitors is given as Figure 6, with stronger colouring indicating greater interaction. This demonstrates the truly global reach of the Centre's research.

Figure 6: Qualitative map of collaborations and research visitors.



In more detail, members of the Centre have a total of 143 such collaborations, 102 of which are international, with researchers from 22 countries in Europe as well as Australia, Canada, China, Israel, Iran, Japan, Morocco, New Zealand and USA. During the REF2021 period, the Centre has received a total of 59 research visitors. Funding has come from external grants (*EPSRC*, *London Mathematical Society*, the *Royal Society*, the *Heilbronn Institute*, as well as visitors' own funds) and MSRC travel support. The Centre regularly provides full support for week-long visits of promising collaborators. For example, support for visits of Ludwig (Lorraine) led to a series of joint papers with Y.-F. Lin and publications in *Advances in Mathematics* and the *Journal of Fourier Analysis and its Applications*.

Five staff members have been successful in obtaining LMS *Celebrating New Appointments* grants (Kiss, Y.-F. Lin, Pausinger, Siegl, Zhigun) funding workshops at QUB with current and prospective collaborators, each with at least one international speaker. The hosted visitors usually give colloquium and seminar talks, which lead to research interactions with the rest of the staff members.

4.3 Interdisciplinary work

The majority of MSRC engage in interdisciplinary research, with staff from all subareas engaging in high-profile interdisciplinary activity. A major interdisciplinary theme, supported by the Unit strategy, is statistical applications to Healthcare. This work is the basis for the first of the Unit's Impact Case Studies (see Sec. 4.4) and has seen applications in Australia, Canada, Ireland and Italy. Further examples include:

- Mitchell has collaborated with researchers in biology (Davis and Medina, QUB), producing publications on glaucoma and the award of a £211K grant (10% ownership by Mitchell) on vascular ageing.
- Lamrock is involved in joint PhD supervision with the *Centre of Excellence for Public Health* at QUB.
- Mitchell and McFetridge have recent and developing work with Dr Waterfield (*Children's Health Ireland*, Dublin) on Covid-19 antibodies in children that has led to publications in *The Lancet Infectious Diseases* and *BMJ Open*.

A leading example of interdisciplinary work in Pure Mathematics is Todorov's pioneering links between *Functional Analysis* and *Quantum Information Theory*. This research is supported through an EPSRC grant on "Zero-error quantum information and operator theory – emerging links". He is a member of the collective "Quantum computing, information and algebras of operators", among whose activities were the LMS-CMI Research School on "Combinatorics and Operators in Quantum Information Theory", held in 2016 at QUB, and the ICMS Workshop on "Analytical and Combinatorial Methods in Quantum Information Theory" in 2019 in Edinburgh, both co-organised by Todorov.

A selection of other interdisciplinary examples include:

- The work of Siegl which has led to new developments on the border of PDEs and Theoretical Physics. This link is evidenced by five publications and three keynote talk invitations.
- Barnes' joint supervision of a student in the School of Mechanical and Aerospace Engineering has led to the publication of four papers (with more to appear) and several presentations at international engineering conferences on mathematically optimizing rotational molding.
- Zhigun's work in applying ODEs and PDEs to Biology, demonstrated by a successful collaboration with Surulescu *et al* solving problems about cell migration, which has resulted in three publications in this area in the past three years.
- Moutari's continuing work on traffic networks, with two publications in the period. His renown in this area was evidenced by his hosting of the Irish Transport Research Network in 2019.
- L. Zhiwei's in natural language processing, with four publications in 2018-2020 and Munaro's work in graph theory and computation complexity, with three publications in the same period.
- Pausinger's collaboration with Gomez-Perez and Gonzales-Villa on problems in Stereology and recent work with Rosa on Topological Data Analysis applied to changing land use.
- McFetridge's recent work with the Astrophysics Research Centre of QUB, leading to a 2020 publication in *Philosophical Transactions of the Royal Society A*.
- Marshall's and Novakovic's ongoing collaboration with the School of Natural and Built Environment on monitoring the health of essential structures (such as bridges). This work is the basis for the second of the Unit's Impact Case Studies.

4.4 Consultancy and Knowledge Transfer Partnerships

The quality of the Unit's research activity can be further evidenced by major national and international consultancy roles taken on by several staff. Marshall has been providing Covid-19 modelling guidance to the *Chief Scientific Advisor* of the *Department of Health (NI)* and the nationwide body *The Joint Biosecurity Centre*. This vital consultancy work is the pinnacle of a long-term project on the application of statistics (*Survival Analysis*) and data science to Healthcare. Earlier highlights of this project include deep collaborations with hospitals in Northern Ireland and healthcare centres in Australia, Canada, Ireland and Italy. These institutions have implemented the models produced by the MSRC to make measurable savings and improved patient outcomes. As mentioned, this success has been recognised and rewarded via the appointment of new *Data Analytics* experts. Moreover, it is the basis for an Impact Case Study.

Further examples of consultancy work by the Unit are:

- McFetridge's and Mitchell's roles as statistical advisors for the *Statistical and Methodological Support Unit* of *Health and Social Care* (the NHS of Northern Ireland).
- Mitchell's supervision of a joint research student with veterinary epidemiology aimed at modelling and identifying effective actions to reduce the incidence and costs of Bovine TB, a project funded by the *Department of Agriculture, Environment and Rural Affairs* (NI).
- Lamrock's role (and associated publications) as a statistical advisor for the *National Centre for Pharmacoeconomics of Ireland* and advisement of the *Health Service Executive* on drug therapies.
- Pausinger's consultancy role at the German technology transfer company *TWT GmbH.*

These consultancy roles are part of a strategic push by the Unit to deepen connections to industry and the public sector. This encouragement and support by the Unit has led to nine Knowledge Transfer Partnerships during the period, connecting research to industry. The total value of these projects exceeds £1.1M, see Table 1, with funding coming from Innovate UK (IUK), Invest NI, UKRI and the Scottish Funding Council (SFC). Overall, QUB is ranked number one in the UK for Entrepreneurial Impact and has added an estimated gross value of £55M to the economy over the period.

This success is bolstered and sustained by the Unit's engagement with industrial placements. At the start of summer 2020, the School had 44 Data Analytics MSc students and 11 undergraduates taking placements, with more expected to take up placements in the following years. The connections forged by such placements (in public sector bodies and local and national employers) have been leveraged into Knowledge Transfer Partnerships and opportunities for staff to take consultancy and advisory roles, raising the Unit's profile in industry and ensuring responsiveness to industrial needs.

Table 1: Knowledge Transfer Partnerships summary

Company name	Funding	Value	Project Aim Summary
CARD Group Limited	IUK[75%], INVEST NI[25%]	£167,516	Quantifying town centre retail and service potential for local authorities.
Limeforge Limited	IUK[50%], INVEST NI[50%]	£137,493	Real-time modelling of cycling data, for enhanced user experience and municipal planning.
Ampliphae Limited	IUK[50%], INVEST NI[50%]	£140,699	Applying intelligent statistical methods to communications.
Terex GB Limited	IUK[50%], INVEST NI[50%]	£146,788	To develop a predictive maintenance programme for machinery and vehicles using data analytics.
Limitless Digital Solutions Limited	IUK[50%], INVEST NI[50%]	£146,110	Developing a prescriptive analytics platform for location-based marketing.
Aridhia Informatics Limited	SFC[40%], MRC[60%]	£146,966	To develop and validate risk stratification models for diabetics.
Sensumco Limited	ESRC[50%], INVEST NI[50%]	£135,499	A multimodal data investigation to understand contextual emotional biometric response.
Crossbows Optical Limited	IUK[50%], INVEST NI[50%]	£133,558	Improving software for lens design and production.
Wavteq Limited	InterTradeIreland	£23,250	Collaboration with an international investment consultancy (Fusion project)
		£1,177,879	

4.5 Further indicators of esteem and academic citizenship

Indicators of esteem have been accrued by both senior and junior members of MSRC. Mathieu has been an elected member of the Royal Irish Academy since 2010, while Todorov is the recipient of a *Thousand Talents* fellowship, funded by the Chinese Government and allowing a high-profile Visiting Professorship at Nankai University, 2017-2020. Zhigun has received a Postdoctoral Fellowship from the *Wolfgang Pauli Institute* Vienna, and Kiss received the Marie Skłodowska-Curie Actions Seal of Excellence by the *European Commission* both in 2017 and in 2018. Marshall and Novakovic are Adjunct Professors at *Ontario Tech University*. McFetridge is on the council of the *Royal Statistical Society* and Mitchell was Secretary of the *Royal Statistical Society Northern Ireland Local Group* in the period 2016-2019 (currently an ordinary member, starting as Chair in 2021).

4.5.1 Conferences

Members of MSRC have contributed to the discipline's health and growth by (co-)organising a total of 22 conferences and scientific events at QUB, including four international LMS conferences or workshops, one in *Operator Theory* and three cross-disciplinary meetings on *Linear Preservers*, *Finiteness Conditions in Topology and Algebra* and *Operator Methods in Harmonic Analysis*. The Centre hosted the *British Topology Meeting* 2015, the *British and Irish Geometry Meeting* 2018, the *Annual Meeting of the Irish Mathematical Society* 2014 and the *Irish Transport Research Network Conference* 2019. A further strength is McFetridge's substantial and increasing involvement with the organisation of the *International Conference of the Royal Statistical Society* from 2019 onwards. The 2019 meeting, hosted in Belfast, consisted of 555 delegates from 33 countries.

Members of the MSRC have also co-organised 16 conferences at other institutions, among which are two meetings at the *Centre International de Rencontres Mathematique* Marseille, one workshop at the *American Mathematical Institute,* one *ICMS* workshop, a workshop at the *Isaac Newton Institute* and two instances of the *Conference on Applied Statistics in Ireland.*

4.5.2 Editorial and committee roles

Members of the Centre are involved in journal and conference proceedings editorship. Mathieu is an Editor-in-Chief of the *Mathematical Proceedings of the Royal Irish Academy*, an Associate Editor of the *Journal of Mathematical Analysis and Applications* and an editorial board member of *Extracta Mathematicae* and of *Advances in Operator Theory*. Todorov is a member of the editorial board of *Serdica Mathematical Journal* and has co-edited a conference volume on *Algebraic Methods in Functional Analysis*, while Barnes and Moutari are editors of special conference volumes in *Homotopy Theory* and *Transport Networks* respectively.

MSRC staff members have taken membership roles in several national and international committees related to the discipline. Todorov has been representing Northern Ireland Mathematical Sciences in the *Council for Mathematical Sciences* since 2018 and has acted as an INI/ICMS correspondent since 2017. Mathieu is a member of the Council and the Meetings Committee of the *European Mathematical Society*, the Physical, Chemical and Mathematical Sciences Committee of the *Royal Irish Academy* and the Nominating Committee of the *London Mathematical Society*. Y.-F. Lin, McFetridge and Mitchell have been members of the EPSRC Early Career Forum.

MSRC members have contributed to the discipline through active reviewing. During the REF2021 period, they have produced 116 reviews for *ZentralblattMath* and a further 61 reviews for *Mathematical Reviews*. In the same period, they have refereed a total of 262 papers for a large spectrum of journals.

MSRC members have been External Examiners for 13 PhD theses in Belgium, France, Germany, India, Ireland, South Africa, Australia and the UK. They have been External Evaluators for the EPSRC, NSERC, Innovate UK, the Irish Research Council, the Estonian Research Council, the National Research Foundation of South Africa, and the Institut d'Estudis Catalans. Todorov is a member of the Hellenic Register of Academic Reviewers and has reviewed seven applications for promotions in Greek universities during the REF2021 period. Pausinger is a member of the scientific board of the Workshop on Image Analysis and Stereology.

4.5.3 Outreach and Internationalisation

Y.-F. Lin has been actively involved in the QUB internationalisation agenda. She has organised the Mathematics and Physics International Summer School at QUB in 2018 and 2019, part of a Faculty-wide event, which aimed at introducing guest students to mathematics and physics themes beyond the normal university curriculum, informed by the research conducted in the School. These activities have led to international research links for the Unit, particularly for Y.-F. Lin and Kiss.

We have actively engaged with promoting mathematics and associated technologies to local schools through a variety of outreach events, including:

- Hosting the *Julia Robinson Mathematics Festival* (as part of *Mathsweek Ireland*) in 2017 and 2019, with more than 100 attendees from at least 8 different schools in each year.
- Holding the *Girls in Maths* event in 2019, with approximately 50 attendees.
- Co-hosting the *Royal Institution Mathematics Masterclass* with *W5* in 2019, with 52 attendees from 13 schools.
- Organising events at the annual *Northern Ireland Science Festival*, 2014-2019.
- Running a mathematics stall at the *Portrush Airwaves Airshow* in 2017, 2018 and 2019. This was direct outreach to the public who were attending the events as part of the *STEM Village* and reaches at least 500 visitors of ages between 4 and 80 each year.
- Contributing to *MathsQUBe*, an online initiative run at the start of lockdown for younger (primary school aged) children on mathematical topics.