CDT EVALUATION FRAMEWORK

Summary of the CDT's Objectives and Key Achievements to Date (max 1000 words)[1]

STOR-i is an interdisciplinary Centre for Doctoral Training where Lancaster University (LU) works together with a wide range of industrial partners and world-leading academic groups from outside the UK to secure a step change in the quality and ambition of PhD training in statistics and operational research (STOR). While STOR-i benefits from being an existing CDT with considerable momentum and experience, a range of significant developments have been successfully implemented to meet the enhanced vision of the new Centre.

The core objectives of the new Centre are:

(i) Recruit and train 5 cohorts of students of the highest calibre in a programme co-designed and co-delivered with industry, the central goal of which is the development of future STOR leaders. Our aim is that the programme's graduates are highly employable and capable of assuming leadership roles in industry or of taking their experience of, and commitment to, industrial engagement into academic leadership in STOR;

(ii) Produce STOR research of the highest scientific quality;

(iii) Increase the proportion of students undertaking doctoral projects jointly supervised with industry from 50% (in the previous Centre) to 80%, with industrial internships provided for those not following a PhD with industry;

(iv) Benefit the wider STOR community by establishing a national network of STOR PhD students working with industry.

Key achievements of the new Centre toward meeting the above objectives include the following:

Students

- Three great cohorts (32 students) have been recruited to the new CDT from 15 UK universities, Boston (US) and Patras (Greece), with in total 5 non-UK residents. These were typically top at their respective universities, have developed exceptional cohort dynamics and have evolved the vibrant research and social environment of the existing CDT. STOR-i now has 52 students in total;

- The new students feature diverse educational backgrounds (8 new to STOR, with two from Physics) and a healthy gender balance with 38% female (consistent with our long term rate of 41%);

- A new MRes programme has been successfully implemented. A key feature is its staged development of independent learning;

- Evidences of the high quality of our training, research and impact are given throughout this report. These include the career paths of our alumni, the publications of our students and the industrial exploitation of research. Critically, industrial and strategic partners are very keen to continue engaging in new research projects with our students;

[1] This report has to be self-contained document, separate from the original Case for Support

- A National Associates scheme for UK STOR PhD students working with industry has been launched (10 per cohort).

Industry

- The new CDT has students partnering on PhD projects with both new (AIMIA, JBA, Roche, Rolls Royce, Sparx) and existing (ATASS, BT, Shell) companies, with active supervision from and engagement with these companies and an investment of £550K cash to date. Remaining students pursue industrial placements with internships already agreed with Improve Digital, Office for Nuclear Regulation, Sky Bet and Tesco;

- STOR-i has 25 PhD projects (60%) co-funded with industry overall, including 80% in the most recent cohort;

- In total, 25 companies have contributed to the new CDT's programme. Typically companies contribute in multiple ways. Over the two CDTs this number exceeds 60;

- A 0.3FTE Industrial Liaison Officer has been appointed to the new CDT to further strengthen industrial engagement. An example of the impact of this post-holder is a major new partnership with Rolls Royce who now co-fund and co-supervise 3 PhD students.

International

- Strategic academic partners provide STOR-i with outstanding international engagement through co-supervision of students, research exchange and advice. New partnerships with Northwestern and University of Washington complement on-going links with SFI (now Big Insights, Oslo) and the Naval Postgraduate School (Monterey). All four partners are engaged in co-supervision of the new Centre's students;

- Our new international visitor programme has begun, with 20 visits supported to date.

Infrastructure

- STOR-i moved into new purpose-developed dedicated space in February 2016 (cost £300K). The space houses all students and support team and has high quality mixing/meeting space;

- The capital equipment fund award of £85K has provided dedicated high-quality facilities to enable and capture virtual meetings, presentations and training.

Environment

- Our supervisory community has expanded considerably following renewal of STOR-i and outstanding REF2014 results (Mathematics =5th overall, and 3rd in Impact with Management Science 1st in

power) with 2 new professors and 9 lecturers appointed. New groups in statistical learning, networks and OR for transport and logistics have been established;

- LU has invested £2.4M over 5 years in a new Data Science Institute (DSI) with substantial benefit to STOR-i through cross-disciplinary research and partnerships with new industrial sectors. Eckley (co-Director of both STOR-i and DSI) ensures that synergies of these initiatives are fully exploited;

- Over the last two years EPSRC has invested more than £6M in STOR at LU through two Fellowships and two programme grants. The latter are OR-Master and StatScale, and are complemented by LU investment, including additional PhD studentships;

- STOR-i initiated the Mathematics CDT leaders' network to help share best practice.

1. Objectives and general CDT operation:

1.1 To what extent has the CDT met its original strategic objectives? What changes were made from the original proposal, why and how have these improved the CDT? 300 words

We had high confidence in the plans set out in our proposal to EPSRC for the new STOR-i CDT. This reflected our considerable experience from running an existing CDT and the fact that the new Centre built ambitiously, but naturally, on its predecessor. We are therefore happy to report that there has been no significant divergence in the delivery and leadership of the new Centre from that outlined in the proposal. It is on track to meet all of its strategic objectives. Minor divergences from our original plans include:

- In light of the new CDT landscape, and notably the increase in mathematical sciences CDTs, we undertook a review of our recruitment strategy. As a result we decided not to go ahead with our planned roadshow events due to increasing awareness of CDTs in the undergraduate population. Our ability to recruit has not been impaired by this decision. Indeed, if anything we feel that our cohorts are strengthening year on year;
- In our first and second cohorts, 50% and 80% respectively of the projects are co-funded by and co-supervised with industry. Our first set of PhD projects represented a transitional phase between the first and second STOR-i CDTs. We made the tactical decision to use the first cohort portfolio to integrate into STOR-i both our new strategic academic partners and the significant number of new LU academic staff in STOR by allowing a small number of PhD projects at the statistics/OR interface which were industry facing but not explicitly co-funded. This has had the benefit of widening STOR-i's supervisory base. Our second cohort of projects met our ambitious target for the new Centre and we remain committed to delivering the level of industrial engagement set out in the proposal to EPSRC. We are meeting this challenge not least by fostering an exciting range of new partners.

1.2 How has the CDT demonstrated added value (e.g. value for money, comparisons with other doctorates – *see also section 3*), and in what ways has the CDT programme benefited from its larger scale? 300 words

The value for money in the CDT resides in its cost effective use of EPSRC and LU investment to create a programme of ethos, size and quality not achievable under conventional funding. The programme created thereby attracts not only exceptional students but leverages additional investment of time and money from a wide range of academics and industrialists for whom the opportunities of contributing to, and gaining from, the enterprise have great appeal.

Examples of substantial external input over and above EPSRC's critical contribution include:

- LU has provided £626K in cash to date for studentships, management time, interns, strategic academic partnerships and visitors fund in addition to contributing £300K for a new purpose designed and furnished space to house STOR-i;
- Companies are eager to invest directly through collaborative PhD projects, with £550K in cash already provided for doctoral studentships though a combination of part and full funding. Company personnel co-supervise, typically via regular virtual meetings, and host extended student visits;
- Our key industrial partners are strongly committed to the Centre's present and future success. Over and above joint doctoral projects, their engagement with STOR-i extends to training events, joint research fora and participation in recruitment and governance. This level of commitment rarely emerges from the traditional CASE model where the primary contact is with a single student only;
- Four students have already been funded directly or through the university for extended industrial internships (8 over both CDTs);
- World leading academic groups are also very keen to be involved. STOR-i has established major strategic academic partnerships with the Naval Postgraduate School (US) and Big Insights (Oslo, Norway), while the new Centre has fostered new partnerships with the universities of Northwestern and Washington (both US). Academics from these institutes actively co-supervise STOR-i students and contribute to the Centre's scientific agenda;
- STOR-i has attracted an extremely high calibre of international speakers and masterclass presenters. For details see http://www.stor-i.lancs.ac.uk/people/visitors.

1.2.1 In particular comment on the added value of the cohort based approach at your CDT? How have you built a coherent cohort with core and incorporated students? 300 words

We believe that the co-location of our students in our new dedicated space, designed to facilitate cohort building and group work, is essential for nurturing the STOR-i culture, developing a group identity and promoting peer-to-peer learning. We encourage an atmosphere of strong mutual engagement throughout the programme. Examples include:

- Joint training: This starts with a two-day residential team-building event aimed at integration into STOR-i. Group work is integral to the MRes programme. Intra-cohort engagement for all cohorts comes from team working on career skills, industrial problem-solving days and summer team building away days;
- Mentoring: All students act as a mentor to a student in the cohort following;
- Students owning the scheme: All PhD students have an agreed organisational role to support core Centre activities (e.g. careers initiatives, recruitment events, supervising interns). Key student-led activities include the forum (weekly informal research talks), STORC (a student initiated activity for sharing computational skills for STOR research), research kitchens (an informal student-only space where students can seek advice and share ideas). Group run events include two highly-successful UCLID workshops on big data in industry (which the students both conceived and organised) and STOR-i's social programme (including a summer ball). Our industrial funding covers the costs for these group events.

The benefits of our strong cohort engagement are illustrated through:

- Recruitment: Our internship programme advertises STOR-i's outstanding cohort experience to potential new students and achieves a conversion rate into the programme of over 50%;
- Professional collaboration: Our industrial partners comment consistently that our students' ability to engage professionally and collaboratively is noticeably stronger as a consequence of our committed cohort focus;

- Mutual Academic Support: There is excellent inter- and intra- cohort support for new MRes students, especially for those whose first degree is not in mathematics. PhD students actively trade skills, experiences and code and some groups of students jointly develop software packages (https://github.com/STOR-i for Julia packages and the R package: changepoint). Forums lead to excellent discussions, as all students are engaged with each other's work;
- Alumni engagement: Our alumni have already shown a clear commitment to feed back into STOR-i. They continue to support each other professionally through networking and sharing STOR ideas;
- Excellent Mutual Personal Support: Students with significant health issues have been supported to achieve to their potential. Sadly, one of our students died from leukaemia. The students pulled together amazingly for him, his family and each other during his illness. In recognition his family have very generously set up a bursary scheme for the STOR-i students.

1.3 How has the CDT ensured proper management and quality control? How have you solicited advice from partners and from independents? How can you demonstrate responsiveness to that advice? How have you demonstrated effective governance? 300 words

STOR-i has a pro-active leadership team comprising Director (0.5 FTE, Jonathan Tawn), co-Director (0.3 FTE, Idris Eckley) and Chair (0.3 FTE, Kevin Glazebrook). This team delivered the first STOR-i CDT and was commended in its mid–term review. STOR-i's external examiner, external advisory board and numerous visitors have complimented the team for its approachability, effective leadership and committed engagement with the Centre's students.

We have the following support and governance structures which our extensive experience has shown to be effective.

- External Advisory Board: meets annually to engage with the students and to review and evaluate STOR-i's progress. Discussion focusses on a comprehensive annual report produced by the Director. Membership is drawn from leading UK and international academics in STOR, technical leaders from our industrial partners and representatives from our funders. Independents on the Board include Adrian Bowman (Glasgow), Richard Davis (Columbia, USA) and Amedeo Odoni (MIT, USA). We also benefit from the considerable experience of Edmund Burke (QMUL). Advice of the Board is also requested on an ad hoc basis, as the need arises. Additionally, we have a list of international advisors who will each typically visit STOR-i once to offer independent comment;
- Executive Committee: comprises the leadership team, a range of LU academic staff and student representatives and meets termly to reflect on all aspects of the Centre;
- An external examiner (previously Bedford –Strathclyde, now King -Edinburgh) is a member of the external advisory board and through formal exam boards provides feedback on the taught programme and the development of research proposals;
- We have a constant dialogue with our external partners, both industrial and academic. We also have an industrial panel that we consult informally on a regular basis;
- We participate in LU's annual review cycle to reflect on the previous year of operation, to maintain a rolling action plan, and to moderate any changes in the scheme.

We take all advice seriously. Two areas where we have made substantial changes are:

- MRes progression and assessment have been substantially modified following advice from STOR-i's external examiner. Changes have been made to assessment weights over modules, marking criteria for PhD plans, and the use of vivas to inform progression decisions for borderline students;

- Our advisory board has encouraged us to make STOR-i's considerable resources widely available. In response we have developed a very open website explaining our training model and have set up a National Associate scheme to give access to our training events to industrially focussed STOR PhD students across the UK.

1.3.1 For multi-institutional CDTs, how can you demonstrate effective working across institutions? How have you overcome any administrative hurdles? Building on 1.2.1, how have you built an effective cohort across multiple sites? 200 words

STOR-i is a single site CDT with all students and activities co-located.

1.3.2 How have you used student representation and student feedback to shape the running of the CDT? 150 words

STOR-i actively fosters student ownership of all that the Centre is and does. Many aspects of the programme are student run through formally allocated roles. Examples include the organisation of conferences, masterclasses, the visitor programme and career and leadership training.

Student views are highly valued, regularly sought and willingly given and have been the driver of key changes to the programme (see 1.3.3). We have a range of fora with the student body to facilitate information flow (both ways) and to identify and resolve issues as they arise:

- The Staff Student Committee (meets twice termly) and Executive Committee (termly) both include a student representative from each of the MRes and PhD communities. These enable student input to the training, environment, strategic direction and future planning of the Centre;
- The Director has one-to-one meetings with all students at least once a term;
- The Leadership Team has annual group meetings with the MRes and the PhD student communities;
- The timetabled weekly STOR-i coffee sessions enable new ideas for the programme to be raised in an informal setting.

1.3.3 Describe your process for incorporating student feedback into the running of the CDT and any benefits that have been realised? 150 words

Our processes for incorporating student feedback into the running of the CDT are explained in 1.3.2. Student feedback has yielded many specific benefits, but the key result is that the students have joint ownership of the direction of the programme and a clear sense of empowerment to evolve its training. Specific benefits include:

- MRes programme: Key modules STOR601 and STOR604 (40 and 20 credits respectively) have been substantially modified in structure and content. The timing and modes of assessment have been changed and blogs introduced;
- External training for PhD/MRes: As outlined in 1.3.2, students identify external presenters for our visitor programme, masterclasses, and conferences, and help to set priorities in our careers and leadership programmes;
- Environment: When planning our purpose built space the student body was involved in many aspects of its design, including choice of furniture. The result is a space well attuned to their needs and so well used.

1.4 Describe how projects have been allocated (both in terms of mechanism used and spread of supervisors)? How has the supervisor cohort evolved? 150 words

STOR-i has evolved an effective student-centric approach to PhD project allocation. Projects are developed with oversight from the Leadership Team regarding fit to the CDT agenda and balance across supervisors. We aim to integrate new staff into supervisory teams and support them in project creation. In the new CDT 26 staff are (co-) supervisors, 10 of whom were appointed since 2011. Each year we produce a list of about 16-20 projects which reflects our 80% target for projects with industry partners.

Once the approved projects are presented to the students, there follows two months for in-depth discussion with prospective supervisors and external partners, including the opportunity to visit industrial partners to build further understanding. Students then register 5 unordered choices, to include projects with both industrial and academic partners.

The Leadership Team have one-to-one meetings with students to understand interests and motivations, while supervisors are consulted about the suitability of the students for their projects. An interview process for in-demand projects is used as needed. The Leadership Team then proposes a student/project matching, with the allocation only finalised when this is jointly agreed with each student. All students provide feedback on the process with a view to incorporating any suggestions subsequently. Unsurprisingly, almost all industrial projects are selected given the students' motivation for joining STOR-i.

1.5 What training have prospective supervisors been offered, especially for new appointees? In particular, how have you benefitted new academics and early career researchers? 100 words

Centrally within LU there is an excellent programme of staff training and development, including courses on PhD supervision which are mandatory for new supervisors. In STOR-i we require that staff gain experience as co-supervisor in a supervisory team, mentored by a lead supervisor, before assuming project leadership.

We offer considerable support to all new staff, including an induction into STOR-i and help with the development of projects. The co-Director provides tailored support for supervisors new to projects with industry, including help with IP/contract issues. Support for new staff continues as projects proceed through the students' research plan and PhD confirmation (10 months into the PhD). The Director closely oversees all PhD projects, and supports supervisors in resolving issues.

We have three sessions a year for the supervisory community to share 'best practice' and ensure full integration with the STOR-i agenda.

1.6 Explain how the projects are checked for (a) academic quality (b) fit to the theme(s) of the CDT and (c) the relevance to any external end user demand (specific or generic)? 150 words

All projects are developed with oversight from the Leadership Team to ensure that suitable quality control is applied from the outset, including fit to the CDT agenda. Key to this process is the recognition, from all parties, that methodological novelty is core to STOR-i PhD projects. A 1-page summary of all outline proposals is vetted by our Executive Committee prior to inclusion in the project portfolio.

To ensure fit with STOR-i's Industrial Focussed Mathematical Modelling agenda, impact is at the core of all projects. Over 60% of our projects are currently co-funded by industrial partners on a topic of mutual interest, so specific end user demand is unquestionable. The remainder of our projects are joint with strategic academic partners, chosen as world leaders in industrially focussed STOR. Our mutual commitment to application driven research naturally leads to projects with the potential for subsequent direct impact. We look for opportunities to develop industrial applications for these throughout their duration (e.g., a project with Northwestern on radiotherapy treatments now has the NHS involved). In other cases students have undertaken an industrial funded internship that exploits their research (e.g., an extreme values student with Oslo on an Office of Nuclear Regulation internship).

1.7 How are you aligning with excellence in the wider research field (e.g. other research groups, consortia, working groups etc.)? 150 words

We have strategic partnerships with four key cross-disciplinary centres (Big Insights, the Naval Postgraduate School and Northwestern and Washington universities), all with world leading research reputations and strong alignment to STOR-i's agenda. Our engagement with these groups through co-supervision, student visits and staff exchanges brings to the Centre broadening international research engagement at the highest level.

International visitors (20 to date), workshops (3) and extended student visits overseas (e.g. EPFL, Austin, Paris) supported by industrial income provide additional streams of regular external engagement with international STOR leaders. We are supported in developing best practice in running the Centre by our interactions with other leading centres. External Advisory Board members have included individuals with substantial experience of leading research/doctoral training centres at Columbia, Duke, Eindhoven and MIT. Members of STOR-i's leadership team are external advisors to other CDTs.

We benefit locally from close association with the extensive networks surrounding two EPSRC programme grants (OR-Master and StatScale - £5.75M investment) and the new £2.4M LU Data Science Institute.

2. Students attracted and student outcomes:

2.1 Describe what is different about the student experience in your CDT compared with other doctorates in your department(s) and institution(s)? 250 words

The student experience in STOR-i is radically different from other doctorates.

- The Centre's strong focus on research impact is reflected in the fact that all STOR-i students spend time in industry. Most students are seeking industrial careers. The time that they all spend away from LU gives experience of industrial engagement and an invaluable opportunity to build networks and to develop highly professional collaborative skills to complement their outstanding research abilities;
- The students appreciate and exploit the value-added skills training and opportunities STOR-i offers rather than focussing exclusively on PhD thesis delivery. They make proactive use of industry funds and bursaries to gain external experience (e.g., international research visits and short term projects with Vegan Society, Mercy Corps and Coeliac UK) and show their entrepreneurship inter alia through conference organisation;
- Our research focus at the interface between statistics and operational research has often been espoused (including in NSF reports) but we believe STOR-i's industry facing approach to cohering the subjects to be world leading;
- Our strategic academic partnerships bring a high degree of international research engagement at the highest level.

Other features unique to the STOR-i experience include: highly developed career training, student ownership of the programme, strong mutual personal and academic support within the student body and considerable alumni engagement via a range of contributions to training including industrial co-supervision.

Collectively our students are unlike any we have encountered before with each one driving others on to be proactive in their development.

2.2 Outline your recruitment processes, including the strength of approaches for recruiting and supporting a diverse population of high quality students. Where applicable, how have you managed recruitment of students across multi-site CDTs? 150 words

Our approach to recruitment has been vindicated by an outstanding and diverse student body in an area of national shortage. We constantly refine our strategy in light of experience and stakeholder input. Non-standard highlights include:

- Research internships: an 8-week scheme (10-12 interns p.a.) providing mathematically able UGs with an experience of cohort-based doctoral study in STOR. This is critical to our success in recruitment of female students (70% of whom were interns), from outside maths (2 from Physics), and from 14 other UK universities (only 6 from LU);
- Enhanced stipends: Industry funds enable us to offer stipends to all PhD STOR-i students on a par with average starting salaries for maths graduates;
- Careers fairs: We capitalise on our training in public engagement by using the students as ambassadors at careers fairs.

All recruits have undertaken an UG course with substantial maths content. We interview all strong candidates to assess their suitability for the totality of the programme. Our usual requirement is a first class degree. Applicants that had been really impressive STOR-i interns, in both research motivation and

performance, are considered if they just miss a first. The vast majority of recruits hold a top grade at masters' level.

We have a range of student support mechanisms, including: termly meetings with the Director, student mentors, pastoral support (using staff of each gender), and offer personalised training as required.

2.3 What is the disciplinary background experience of students recruited by the CDT and where have they come from?

Disciplines	**2014-15**	**2015-16**	**2016-17**
	Mathematics (10)	Mathematics (8)	Mathematics (8)
	Statistical Modelling (1)	Theoretical Physics and Applied Mathematics (1)	Statistics (1)
	Maths with a Modern Language (1)	Theoretical Physics with Mathematics (1)	Mathematics and Statistics (Study Abroad) (1)
Origin	**2014-15**	**2015-16**	**2016-17**
Home Institution(s)	2	3	1
Other UK Institution	10	7	7
Industry	0	0	0
Overseas	0	0	2

2.3.1 What is the diversity of your cohort against the four protected characteristics? How do these patterns compare to the 'typical' for the subject at your institution? How does this compare to the HESA-reported research population for the area(s)? (We are seeking aggregate information and not data on individuals). How much of the "student demand" have you fulfilled? 200 words

For the protected characteristics of age, disability and ethnicity there are no clear differences. Our previous CDT had a greater proportion (15%) of students recruited from industry, and hence slightly older. There are positive key differences for gender with 38% female in the new CDT (41% overall), up 10% (respectively 20%) on statistics (OR) PhD norms at Lancaster, with the intern programme the primary cause (see 2.2). At the 2015 LMS event on women in CDTs we were able to share our experiences to help others improve their gender balance.

Interpreting diversity more broadly, STOR-i benefits from core students with non-mathematics or non-STOR backgrounds. Our broader aligned, visiting and national associate student community is diverse in academic background and STOR philosophy.

Regarding demand, we recruit in an area with a historically small pool but large national and strategic demand for PhD graduates (see 2.5) and a priority area for EPSRC. STOR PhD students have been historically under-represented in the EPSRC Mathematics PhD portfolio (11% of 414 in 2009). STOR-i has more than doubled this pool through our unique industrially engaged programme. To achieve this substantial increase in the national pool of STOR PhD students we have been proactive in recruiting students with diverse backgrounds. Appointees exhibit a different demographic from LU's typical statistics PhD intake, where all applicants come direct from an UG degree programme with over half recruited locally. The vast majority of LU's PhD students in OR are from overseas with UK students typically from a mathematics degree.

We believe that we are significantly increasing the pool of postgraduate STOR research students rather than just recruiting those who would have done a non-CDT PhD. We aim to continue this in the future.

		2014/15		2015/16		2016/17	
		No.	%age	No.	%age	No.	%age
Gender	**Female**	6	50%	3	30%	3	30%
	Male	6	50%	7	70%	7	70%
	Not disclosed						
	Unknown						
	Total	12	100%	10	100%	10	100%
Age Range	**0-29**	12	100%	10	100%	10	100%
	30-39						
	40-49						
	50-59						
	60+						
	Unknown						
	Total	12	100%	10	100%	10	100%
Disability status	**Known Disability**					1	10%
	No known disability	12	100%	10	100%	9	90%
	Undisclosed						
	Unknown						
	Total	12	100%	10	100%	10	100%

Ethnicity	**Asian**			1	10%		
	Black						
	Chinese					1	10%
	Mixed						
	Not Disclosed						
	Other						
	Unknown						
	White	12	100%	9	90%	9	90%
	Total	12	100%	10	100%	10	100%

2.4 What is the educational background of students recruited by the CDT? How many have previous industrial employment?

Degrees	**2014-15**	**2015-16**	**2016-17**
1st	11	9	6
2.1	1	1	4
Masters	7	8	7
Other	5	2	3
Origin	**2014-15**	**2015-16**	**2016-17**
UK	11	9	5
EU	1	1	4
Overseas	0	0	1
	2014-15	**2015-16**	**2016-17**
Number with industrial employment	0	0	0

2.5 To what extent is the CDT fulfilling the national need in its area (for example, with reference to the number of serious applications[2] received)? 150 words

In our proposal to EPSRC for funding we made a powerful case for larger numbers of STOR PhD students based on national need. The case has since become yet stronger with the continuing emergence of data science, the need for data-informed decision making and the well understood shortages of those with the associated STOR skills and knowledge at doctoral level. Successive international reviews have opined on the shortage of STOR PhDs, with excellent pre-PhD opportunities in STOR diminishing the pre-doctoral pipeline.

STOR-i's radical industrial-facing approach to research training has meant that we have increased very considerably the national pool of STOR PhD students in part by recruiting students who would not have pursued STOR PhD training but for STOR-i; see 2.3.1 for further details. That the national need in the area is still not being adequately met is beyond argument.

2.6 In what ways has the CDT programme enhanced students' expertise and enabled them to apply it to broader research programmes as applicable outside traditional research fields? How effective is your process for monitoring student progress? What are your processes for managing conflict or under-performance, and facilitating flexible working (e.g. maternity, paternity leave, part-time working etc.)? 200 words

All students gain experience of research in an industrial environment while a number experience working with charities through our bursary scheme. A number of students benefit from engagement with major EPSRC programme grants (OR-Master and StatScale). STOR-i's focus on industrial problems immediately

[2] Please count only applications that completed your official application form/process; do not count speculative emails

takes research beyond traditional fields, transcending disciplinary boundaries. Students learn to research efficiently with industrial and scientific collaborators.

STOR-i alumni provide the key evidence of our success. The overwhelming majority have taken up leadership roles in industry which explicitly use both STOR research skills developed through the PhD and broader skills developed at STOR-i. In addition, the STOR-i Fellowship programme provides a bridge to academic career paths, with all fellows proceeding to academic posts to date.

We have a well-established and effective monitoring process, featuring rigorous requirements for progression from MRes to PhD and for the subsequent confirmation of PhD status. Every term the Director reviews each student's progress. At identified time points all students are required to complete a purpose-developed self-review which encourages reflection on their total experience, including supervision. It also invites supervisors to identify areas for student improvement. LU's PGR management team have been so impressed that STOR-i's monitoring process is being rolled out for all students.

Over both STOR-i CDTs we have successfully managed (i) periods of extended absence for sickness of students/family, (ii) a student not adequately engaging, and (iii) a student request to change supervisor. All were carefully managed and satisfactory conclusions for students were obtained in all cases.

2.7 Where relevant, what benefits are students experiencing as a result of working with industry (or other non-academic partners, e.g. internships etc.)? 200 words

End user engagement is embedded in all aspects of our programme: from design, through delivery, to ensuring that the research has impact. Our diverse community of industrial partners ranges from SMEs to multinationals and covers a wide range of sectors. 25 companies contribute to the new CDT, with 60 contributing overall. Our programme provides regular opportunities to engage with STOR stakeholders:

- Industrial problem solving days develop students' broader problem solving and team working skills (with core partner ATASS hosting such an event at their Exeter headquarters giving the students experience of their unique working environment);
- 60% currently (80% ultimately) of our PhD projects come from industrial partners who provide co-supervision and host regular student visits (students spend ~3 months at the partner during the PhD);
- Industrial internships are provided for those not on industrial PhD projects (e.g., Improve Digital, Office for Nuclear Regulation, Sky Bet, and Tesco);
- Further opportunities to present research ideas to, and network with, industrial representatives include posters and talks at STOR-i's annual conference;
- Shell's statistics team visits for 2 days a month;
- Industrial experts lead sessions on impact, leadership, project challenge and careers.

The added benefits from such interactions are enormous. Students gain from exposure to different organisations and the variety of STOR research being undertaken by them. They have abundant opportunity to consider the wider implications of their work, to transfer their research to real problems and to identify possible pathways to future careers. Those pursuing industrial careers are ideally prepared to make good choices and for rapid career development. Those entering academia have rich industrial networks to support research agendas and to provide funding.

2.8 How are students better equipped to be the future leaders in their field and / or act as 'agents for change' in their organisations? 200 words

We only recruit students with strong potential to be agents for change. We then proactively develop their skills through our training programme. STOR-i students are exposed to a wide range of training and self-development opportunities, including internationally leading research areas and major industrial

challenges. All students experience 1-3 months working away from LU at industrial and/or academic strategic partners.

They are completely unlike standard PhD students as a result. They are highly confident, engaged, proactive, entrepreneurial and strong at debating STOR approaches. They have extensive experience of working in teams and with stakeholders. They have assumed leadership in a number of ways, from taking a role in shaping STOR-i through to developing and supervising an 8-week UG intern project.

A key indicator of the students' preparation to lead comes from the informal feedback we have received from our academic and industrial collaborators (see 1.2.1). They report that our students display considerably more effective communication skills and are better able to articulate the power of their work than is the norm. This is further evidenced by the overwhelming majority of our alumni taking industry positions (including at Dunnhumby, EDF Energy, FeatureSpace, JBA, Lubrizol, and Shell) which explicitly use research area specific skills developed in the PhD, together with broader generic STOR and career skills developed throughout STOR-i training. Furthermore two STOR-i fellows have subsequently been appointed to lectureships and are already using their industrial contacts to develop their research agendas.

2.9 What are the relative completion/submission rates for students funded via the CDT versus the wider Department / University? Please explain any major variations (*see also section 6*). 150 words

For the new STOR-i CDT no students have yet completed their PhD. Of the 22 students who have completed the MRes, 90% achieved a distinction.

Of the first two cohorts from the first STOR-i CDT, 17/18 (94%) submitted within 4-years, and all passed. Many of the third cohort have already submitted and all are due to submit within 3.25 years from the start of their PhD. STOR-i's 4-year completion rate comfortably exceeds department norms of 80-85%.

This improved rate of submission is achieved notwithstanding the extensive additional training undertaken by STOR-i students relative to standard PhD students. We believe that stronger PhD preparation (from the MRes), increased individual and cohort drive from the students, and closer monitoring all play a key role.

2.10 How many students left their studies without completing per cohort? Please give reasons and how have you managed this process? 150 words

In the new Centre we have recruited 32 students and have a 100% retention rate.

Of the Centre's 72 students overall, 8% left early: 1 left after a term and 5 after the MRes. These students were from the earliest cohorts. Additionally one student (Gwern Owain) died in the first year of his PhD.

Our judgement is that the MRes helped clarify to students that undertaking a PhD was not the right path for them. By now, as the nature of STOR-i has become clearer and more evident on our web pages, we believe that we are now attracting better informed applicants. This belief appears to be borne out by the 100% retention rate in the current CDT.

One key lesson we have learnt from students leaving, is the need for strong cohort support. Students (and staff) invest very strongly in their relationships with the cohort and there is a clear sense of loss and even mutual failure when one of the cohort decides to take another career path. In these cases the cohort has met to talk through reactions and to learn lessons. This particular strength was particularly needed as we came to terms with Gwern's death in 2015.

3 Evidence of Value for money

3.1 How has the CDT leveraged additional direct or in-kind funding? Have the original leverage values in the application been achieved? If not, why not? Explain how any physical space promised in the application been realised? Comment on how any other investments and commitments from the host institution(s) has/have been realised. 300 words

We are on track with the scheduled leveraging of additional funds from LU and from industry outlined in the proposal to EPSRC. To date we have received £626K from LU (which is itemised below) in addition to a purpose designed and furnished space valued at £300K. Some LU commitments including Fellowships arise later. We have received £550K in cash from industry with industrial in-kind contributions received to date valued at £497K. We are particularly pleased to report that industrial funding is on schedule despite some of the partners not yet delivering. We have achieved our strong position by proactively seeking new partners. These include Rolls Royce who now co-fund 3 projects. See 3.2 for more details of industry contributions.

Principal contributions from LU are:

- Studentships: 3 studentships and associated costs; underwriting 2 others per cohort. Cost to date: £373K;
- Core Staff Time: Total of 0.7FTE for academic staff managing the Centre; 0.3FTE industrial liaison officer. Cost to date: £145K;
- Strategic Links: The costs of regular trips by students and supervisors to our 4 strategic partners. Cost to date: £30K;
- International Visitor Programme and Workshops: Funding for a series of specialist STOR workshops and a visitor programme. To date 20 visitors and 3 workshops. Cost to date: £45K;
- Summer Internships: Funding for a programme of summer vacation research internships (10-12 p.a.). Cost to date: £33K.

In February 2016 STOR-i moved into new purpose-developed and furnished space adjacent to its two contributing departments. The space includes offices for 60 MRes/PhD students and Fellows (from the old and new CDTs) and for STOR-i's support team with interaction space for group work, a kitchen, and a meeting room containing state-of-the-art video conferencing facilities. The space has been designed to enhance group work, cohort building, and engagement with industry partners. Evidence to date suggests this new environment is delivering a tangible positive impact for all stakeholders.

3.1.1 What contributions has the CDT attracted from other funders, including University studentships? Highlight significant changes from the original bid.

	Cash	In-kind contributions	Details
University	£626K	£300K building	See 3.1
Industry	£550K	£497K	See 3.1 and 3.2
Charity	£0K	£20K	See 5.2 for how we are engaging with charities.
Of b & c, how many are new partners	£240K	£271K	Sparx, Aimia, Rolls Royce, JBA, Roche
Of b & c, how many partners show repeat activity	£310K	£226K	5 are projects with repeat partners, Shell, BT, ATASS
Of b, how many are SMEs	£120K	£157K	4 projects with SMEs, Sparx, JBA*2, ATASS
Other	£10K	£0K	Bursary from student's parents

3.1.2 Give the number of additional students to be aligned to, or benefit from, the CDT (and their funding sources). Highlight significant changes from the original bid.

	Cash	In-kind contributions	Other	Details
University	0	0	0	
Industry	0	0	0	
Charity	0	0	0	
RCUK	Unknown	0	0	2 LU students (ESRC, EPSRC) and National Associate Scheme members.
Other		0	0	3 EU/overseas students

3.2 What other user (e.g. employers, industrial, clinical, government etc.) involvement has the CDT attracted? 100 words

We have 25 industrial partners currently engaged in all aspects of the programme. These range from SMEs to multinationals and cover a wide range of sectors. 60 companies have contributed to the CDT overall.

- The new CDT has PhD projects with new (AIMIA, JBA*2, Roche, Rolls Royce*3, Sparx) and existing (ATASS, BT*2, Shell*2) partners. These contribute co-supervision with investment to date of £550K cash. All other students, 8 to date, have 3-6 month industrial internships (e.g., with Improve Digital, Office for Nuclear Regulation, Sky Bet and Tesco) not costed above;
- Overall we have 25 PhD projects (60%) co-funded with industry, 80% in the latest cohort;
- We provide regular opportunities for students to engage with STOR stakeholders (see 2.7). Estimated in-kind contributions from industry to date total £432K from supervision and £65K from training;
- STOR-i helps LU engage with other users, such as ONS and NAG, who now are funding PhD students that benefit from the CDT.

3.3 How has the CDT managed the requirements of multiple partners? How have you managed changes of partners? 100 words

Management of partners has been a critical part of STOR-i's success. From the outset we have been transparent and consistent in our approach with all parties. The Centre also benefits from a strategy of working with partners from non-competing sectors. In so doing we have been able to develop sustainable relationships which transcend individual academics, resulting in the sponsorship of multiple projects involving a variety of supervisors. Within such a large multi-year endeavour, changes in partners are inevitable, e.g., due to reorganisation, economic instability etc. This has happened and in these cases we have simply sought new partners from different sectors. The emergence of Rolls Royce as a new partner in 2016-17 is a perfect example of this.

3.4 What progress has been made in making the CDT more sustainable within the host research organisation(s)? What are the likely sources of (non EPSRC) funding to maintain the resilience of the CDT beyond the initial five year funding period? Is there a process for succession planning? 200 words

STOR-i has an extensive network of company partnerships in place, together with substantial financial support from LU. Experience from running various PhD-funding models suggests that the level of industrial leverage now sought for STOR-i projects has been set at a level which we believe is (a) sustainable for the longer-term; (b) encourages organisations to make substantial time commitments to projects and (c) ensures that outputs are of a high quality, rather than being dominated by commercial timescales and pressures.

It is still our belief that the underlying cost of offering such a programme is such that, for STOR-i to be sustainable, we will continue to need ongoing research council investment. It is this core funding that enables us to leverage the substantial levels of cash and in-kind contributions across a range of UK business sectors. Based on our track record, and the ever growing demands for highly trained STOR research leaders across all sectors, we can confidently assert that we will continue to leverage substantial industrial and institutional support in the future. Indeed several of our strategic industrial partners are sufficiently concerned about STOR-i's long-term viability that they have already indicated to us that they will offer substantial support to our activities to ensure the renewal of the CDT.

4. Taught component of CDT training:

4.1 Please give brief details of the taught courses offered, (e.g. topic, method of delivery, how many students have attended each one, sharing of courses etc.)? Highlight significant changes from the original bid. 250 words

The MRes curriculum, co-designed with industrial partners, prepares students high in mathematical ability but diverse in mathematical background for the full variety of research opportunities STOR-i offers. Please see http://www.stor-i.lancs.ac.uk/training/mres-content for full details. There have been no significant changes from the proposal to EPSRC.

The training is delivered in four elements, taught broadly consecutively, designed to support student development toward independent working:

- Taught STOR masters modules: a grounding in STOR's mathematical core and its computational implementation. The material is taught in lectures, labs and workshops alongside different MSc programmes, with tailored assessment for STOR-i students. The diverse background of the students on these modules enriches class discussion, with classes containing 30-50 students;
- Skills development: students gain experience of end-to-end modelling strategies for scientific and industrial applications. Core skills including contemporary computational and presentational approaches (e.g., posters, a blog, website development) are developed through a series of assessed assignments. Team-working skills under high pressure are developed in industrial problem solving days (4 p.a. with 20-30 students attending each, students in later years attend a reduced number per year) in which MRes and PhD students team together to solve substantive problems presented by industrial partners;
- Structured exploration of research topics: overviews of thriving research areas within STOR methodology and applications are presented by ~30 staff and extended masterclasses given by 4

international research leaders (attended by all students). Two self-selected individual mini-research projects and group projects with talks and posters build experience of literature reviews and identifying open research problems.

- Selection of a PhD topic and the development of an associated formal plan of research.

Team-working and peer-to-peer learning are central throughout.

4.2 What transferable skills programmes have you used or developed, and what careers training do you provide? 100 words

LU's Graduate School provides generic skills training for all students. STOR-i training develops a broad skills base for modern STOR research leadership:

- Leadership Training: co-delivered with industrial partners and management specialists (Active Training);
- Communications training: Michael Blastland (BBC journalist and broadcaster), Emily Grossman (science communicator), VOX Coaching (academic training specialists) and LU Press Office on working with non-specialists, networking, and press engagement;
- Computational horizon workshops: delivered by external experts;
- Career Training: advice on roles, negotiation and target salary; interview training (VOX); sessions with alumni.

Training is reinforced through its application to the development and management of a competitively awarded proposal, the supervision of an UG intern, team working events and the delivery of an administrative role.

4.3 Describe how the CDT has taken an innovative approach to delivering student cohort training 100 words

We encourage an atmosphere of strong mutual engagement throughout the programme. Our approach to cohort development and training has the following strands:

- Joint training: We plan events whose principal aims include cohort development and team working. These include a two-day residential induction event, industrial problem-solving days, career skills, and summer team building away days;
- Student ownership of the scheme: Our students influence the environment in which they work and develop a strong sense of ownership thereby. High commitment and strong mutual engagement result. All PhD students have an organisational role to support core Centre activities;
- Key student-led activities: We encourage the students to come together to propose, organise and lead research and social activities. These include regular events such as the forum, STORC and research kitchens as well as one-off workshops and conferences and the STOR-i social programme. These are described in 1.2.1.

4.4 How has performance in these taught courses been assessed internally and externally, including input from potential employers and partners? 100 words

A range of assessment methods are used for the taught course elements of 4.1. Assessments are all independently double marked. All work and feedback are seen by the External Examiner (Bedford/King)

- Taught modules: Assessment comprises exercises, group projects and written examinations. All are internally marked, with exam papers externally scrutinised;
- Skills development: Performance on problem solving days (including teamwork) is assessed by internal and industry staff. Core skills used in blogs, talks, websites, programming and posters are assessed internally;
- Research topics: These are assessed internally, but for the masterclasses the external presenter also contributes;
- PhD plan: All students have an external supervisor (industrial or academic) who contributes to the supervisory team's assessment both of the plan and of the student's professionalism and aptitude for research. All plans are double marked by the leadership team to ensure consistency.

4.5 How has the CDT exposed its students to a broad range of environments including for example experience of other universities and or industry in the UK and internationally. 100 words

All students experience at least 3 months away from LU, including:

- All students work away at industry, either on industrially co-supervised PhDs or industrial internships. There is no specific model for visits, with students attending for prolonged periods or making regular short visits;
- All attend a two-day problem solving event at the Exeter headquarters of ATASS and experience their unique working environment;
- 20-40% of students have external academic supervisors at our international strategic partners, with 1-2 week annual visits and regular virtual meetings;
- Students apply for funding from our Bursary Scheme (awards £1K), Research Fund (awards ~£2-4K), or for a place on our new Schools Outreach scheme. These schemes have benefitted 18 students to date, with the Bursary scheme funding work at charities (see 5.2) and the Research Fund enabling long-term visits to leading overseas academics;
- All students attend a mix of NATCOR/APTS external training courses.

4.6 How has training prepared students for their Doctorate projects, and what metrics and information have you used to reach these conclusions? What is the balance between compulsory & optional courses (and why?) How do you create a balance between research & training (including mini research projects)? 150 words

- A 30 hour programme delivered by around 30 staff exposes the students to a wide range of topical STOR research areas to inform their PhD topic choice. This is supplemented by our masterclass programme;
- Students explore their choice of four research topics in mini-projects, developing skills in literature reviews and identifying open problems;
- Students develop a research plan for their selected PhD topic. This includes a literature review, preliminary study, an outline of open problems and the proposed strategy for addressing these problems, as appropriate.

Evidence of PhD preparedness comes from assessment of these elements. In particular, we assess how the students demonstrate initiative, technical skills, focus, communication and professionalism in the development of their PhD plan. Evidence from both CDTs suggests that students who perform well at the MRes progress to the PhD with strong momentum and very clear short- and long-term plans.

All modules of the MRes programme are compulsory to give all students core STOR skills and to provide for the structured progression to research outlined in 4.1. The training: research split evolves from 90%:10% at the outset to 10%:90% at the conclusion. Within the later programme elements there is considerable

choice within all modules to reflect developing research interests. We also provide personalised training for students with different backgrounds.

4.7 What have you been doing to help your students to explore, discuss and reflect on the wider ethical issues around their work (e.g. Responsible Innovation training)? 100 words

Ethics features significantly in STOR-i's agenda.

- The OR element of STOR is concerned with decision support tools. Through a range of material the students learn that their work can change power bases in companies and hence lives, so that their innovation must be responsible;
- We have a growing number of industrial co-funded PhD projects working with personal data. Data security is paramount and training on the associated ethics of data privacy is a priority;
- Students are encouraged to articulate their personal ethical constraints. The PhD allocation needs to reflect these given our diverse range of industrial partners.

All students receive on-going ethics training. This includes a workshop run by LU's Ethics Officer, sessions with STOR staff members and industrial partners discussing the ethical challenges posed by their work and ethics questionnaires for industrial projects.

4.8 How do you encourage your students to engage with the public and to understand the value of this engagement? 100 words

Public engagement is strongly encouraged and actively supported. We lead by example, with the Chair being the 2015 Maths President of the British Science Association and the Director undertaking public lectures on extreme events.

We provide the students with the confidence and skills to undertake public engagement. We provide communication training sessions for presenting to a range of audiences (see 4.2). For example, the Blastland session emphasises how lateral thinking and novel graphical tools are required to communicate effectively with the public, media and non-specialists. The students learn that for their work to have full impact, they need to approach dissemination in a way that goes considerably beyond standard academic approaches. These messages are also invaluable for effective working in multidisciplinary teams and so fundamental for STOR researchers working on substantive applications.

For extensive examples of public engagement see 6.6.

5. Impact in the wider community

5.1 How has the CDT addressed the Priority Areas it originally bid against? 100 words

Our proposal to EPSRC for the new CDT addressed the priority area of Industrially-Focussed Mathematical Modelling. Within that theme we specifically targeted Statistics (itself a priority area) and Operational Research (OR). Our approach has been to develop students toward research leadership in an environment in which scientific excellence in statistics and OR is achieved in response to real world challenge. To achieve this we have developed rich networks of industrial and international academic partnership in support of a programme which combines the development of broadly based state-of-the-art technical skills and knowledge along with the additional capabilities required to translate research into impact.

5.2 What impact and interaction has the CDT had in the wider community, including other research organisations, industry, business, the public and society? 100 words

Our programme is rooted in high quality external engagement and impact. Highlights include:

- Research Organisations: In the new CDT, 7 projects with strategic partners (Oslo, Monterey, Northwestern, Washington) are yielding high quality co-authored papers. Our unique approach to the STOR interface is leading to agenda changes in some of these institutions;
- Industry and Business: 25 students have industry co-funded projects with an intense level of industrial engagement. Industry involvement also occurs in other PhD projects (e.g., Preston Hospital, ABB and BT) and through industrial internships (8 to date). See Annex for further details of impact and pathways to impact;
- Public and Society: We have recently established a Schools Outreach programme with students leading interactive sessions with pupils based on their research. A bursary scheme funds short term projects with charities (e.g., Vegan Society, Mercy Corps and Coeliac UK).

5.2.1 Have there been any wider policy, strategic or social impacts arising from or influencing the direction of CDT activities? 100 words

Examples of the wider policy impact of our work include changes in the Met Office approach to quantifying the risk of heatwaves under climate change and new approaches to workforce planning and work scheduling at BT in response to new Government performance targets, see Annex.

The direction of the CDT's PhD projects and training has been influenced by industry's big data/data science agenda. A related issue is an increased focus on efficient intelligence gathering, given that data acquisition so easily overwhelms analytical capabilities.

Our status in setting the global agenda for STOR industrial engagement is confirmed by John Birge (Chicago), former President of INFORMS, who writes "the STOR-i Centre for Doctoral Training,. . [is]. . the most innovative and comprehensive collaboration between industry and academia that I have seen in any doctoral program. . [LU has] the broadest and most industry integrated OR curricula anywhere in the world."

5.3 How does this CDT coordinate with the wider training of people in this subject (e.g. is this CDT the main provider of students, does the CDT provide access to resources to other students)? How does the CDT network with other CDTs (e.g. subject, regionally etc)? 100 words

We are acutely aware of our strategic position as the UK's principal provider of industrially focused STOR training and make our training events accessible to others:

- Our National Associates scheme funds travel and subsistence to attend STOR-i training events. This has attracted over 10 students, including from other CDTs;
- LU leads in STOR CPD training for the UK, running NATCOR and delivering training on both APTS and NATCOR.

STOR-i has a strong track record of collaborating with other CDTs, including:

- funding MASDOC students to attend training at STOR-i;
- students participating in a data science workshop at Edinburgh CDT;
- initiating the Mathematics CDT leaders' network in the belief that our experience as an existing CDT could help in supporting and sharing best practice;
- supporting other CDTs via roles on the SAT, external advisory board (Newcastle), and programme review (Bath).

5.4 How does the CDT contribute to the students' understanding and capabilities to engage with inter- or multi-disciplinary issues? 75 words

STOR-i brings together statistics, OR and industry. At its core, STOR-i is interdisciplinary. Statistics and OR have grown as separate disciplines and their coming together to form a multi-disciplinary approach is at the heart of all our training. Furthermore, all the applications our students deal with arise from other disciplines and yield direct engagement with researchers from other backgrounds. The students gain understanding of, and capacity for, multi-disciplinary work through experience of and engagement with this rich environment and through structured discussion sessions (e.g., on leadership and team-working) which promote reflection and sharing of experience.

5.5 How has the CDT helped to bring about new collaborations in other research organisations, industry, business and society, including internationally? 100 words

STOR-i has brought about a step change in international and industrial collaboration, with major engagement in doctoral training focussed on co-supervision within our portfolio of PhD projects. Drivers for this change include:

- a critical mass of highly engaged students;
- our novel partnership scheme which encourages broad and deep collaboration;
- our unique STOR interface research agenda;
- leveraging LU investment into our strategic academic partnerships;
- the freeing of leadership team time to create an ideal environment to network with industry.

Our problem solving days have been an especially effective way of introducing new industrial partners to STOR-i. They provide a great environment for organisations to see the technical and inter-personal skills of our students. This encourages them to pursue further collaborative opportunities, including funded projects.

5.6 What wider initiatives have been set up as a result of the presence of the CDT, including those with other research organisations, industry, business and society? How have partners influenced the training content? 100 words

Central to the CDT have been our four international strategic academic partnerships, characterised by longer-term research collaborations and extended visits by staff and students. In addition:

- STOR-i has underpinned successful bids for £5.75M EPSRC investment in the form of two LU led programme grants: OR-Master (with QMUL); and StatScale (with Cambridge);
- Our experiences of manifold industrial opportunities in big data have led to LU's £2.4M investment in a Data Science Institute;
- Work on changepoints has contributed to the development of Newton Institute programmes in 2014 (1 month) and 2018 (6 months);
- Our track-record and strategic partnership with BT are the key foundations for a Prosperity Partnership proposal [confidentiality prohibits further details at this stage].

We have massive involvement from partners in both training and research co-supervision. The MRes was co-designed with industry. See 2.1, 2.7 and Section 4.

5.7 What prominent visitors/speakers and events, from other research organisations, industry, business and society has the CDT been able to attract (e.g. as speakers, supervisors, attending CDT conferences etc)? What international interactions has the CDT benefitted from? 100 words

The new CDT holds an annual conference along with a programme of regular workshops (2-3 p.a), masterclasses (4 p.a.) and industrially-led training events. It also hosts international visitors, usually staying a week and giving seminars (20 in the last 2 years). We have attracted leading international academics and outstanding contributors from industry and society. Details are on our website. Highlights include:

- Academic: Agrawal (Columbia), Crama (Liege), Davison (EPFL), Katehakis (Rutgers), Kolaczyk (Boston), Koole (Amsterdam), Munk (Göttingen), Shaby (Penn State), Stoffer (Pittsburgh), von Sachs (Louvain), Wakefield (Washington);
- Industry: Scott (Google), Jonathan (Shell), Nauck (BT), King (Rolls Royce), Stock-Williams (Eon), Ragnoli, (IBM), Mansson, (DSTL), Pavey (Dunnhumby), Hofmann (Microsoft);
- Masterclasses/Society: Grünwald (CWI), Mirchandani (Arizona), Blastland (BBC journalist and broadcaster), Emily Grossman (Science communicator).

5.8 Have you any evidence that sponsoring companies / sectors have been changed as a result of the activities / training provided via the CDT, especially amongst SMEs? 150 words

Corporate change is a positive consequence of STOR-i's work.

To date 7 PhD projects have been with SMEs, including 4 already in the new CDT (JBA*2, ATASS, Sparx). Change in the SMEs and the value they place on their engagement with STOR-i are evidenced by:

- repeat business (JBA and ATASS);
- ATASS have used our approach to problem solving days and internship scheme in recruitment;
- JBA have appointed 3 STOR-i (including affiliated) students.

Larger companies (including multinationals) have been changed. The Shell Statistics Team so value their engagement with STOR-i that team members base themselves in STOR-i for 2 days every month to work with us on improving their oil-rig risk assessment methods. This certainly helps to facilitate engagement with the students they co-fund but also provides exposure to the full student body, including research group meetings. Further, BT's approach to workforce training and work scheduling have been transformed by the work of a STOR-i student (Ross, see Annex).

5.9 Describe any further impact/benefits on users 100 words

A principal reason for industry's eagerness to work with us is the opportunity our partnership model gives of engagement with a large student body rather than with a single student, as would be typical in the standard CASE model. This gives access to a rich supply of potential recruits.

It is particularly pleasing to see our alumni going to work with our industry partners (e.g., Shell, JBA, Dunnhumby) or companies with whom they have had internships (e.g., Lubrizol). The overwhelming majority of STOR-i alumni are taking up industry positions that explicitly use the research knowledge and skills developed in their PhDs. Many examples include a PhD detecting fraud in sports now being applied to the banking sector at Featurespace.

Such is the demand for them, some of our students are hired a year before they complete.

5.10 What wider impact has the CDT had in the host research organisation(s)? 150 words

LU sees STOR-i CDTs as a flagship of quality and impact. It has looked to learn from us in the expectation that STOR-i innovations can benefit the whole institution. In support of this, Eckley and Glazebrook have served on an LU wide working group on PhD training. Impacts to date include:

- LU is basing a new PhD monitoring process for all students on our purpose built system which encourages greater student reflection on progress and appears to improve completion rates;
- Establishment of a new Data Science Institute and a new Centre for Transport and Logistics (CENTRAL) at LU;
- Thomas Jaki (in Math & Stats) used the STOR-i model in a €3.6M scheme (ITN) which brings together leading European Universities, pharmaceutical companies and clinical experts to conduct joint research and the training of medical statisticians;
- STOR-i has yielded major improvements in the local research environment for statistics and OR. These include our visitor programme and engagement with internationally leading partners. Our critical mass of students strengthens research groups. Non-STOR-i students gain access to training events;
- LU MSc programmes make use of STOR-i's new modules.

5.10.1 How has the CDT become integrated within the host research organisation(s)? How is the CDT working with other EPSRC investments? 100 words

At the time of the new award STOR-i had been running successfully for 4 years and was already integrated into LU. LU's strong support for what is a joint venture between two major departments within different faculties has been critical. In the new CDT, LU is a considerably bigger partner than previously, with a total £3.5M investment. STOR-i is core to LU's interests. See also 5.10.

Our Leadership Team use their experience to advise other groups developing bids. Our Administrative Team help new CDT support staff better understand the complexities of their role. We also have very close links at scientific, leadership and administrative levels with two EPSRC programme grants (OR-Master and StatScale) and are starting to share training events.

5.10.2 Has the CDT facilitated new academic collaborations (give examples)? 100 words

The new CDT builds on the first CDT's step change in collaboration between statistics and OR. All PhD students have supervisory teams from at least two of the Centre's constituencies: statistics, OR and industry. This provides a range of perspectives as well as methodological breadth. For the

majority of our industry projects joint supervision from different STOR areas is essential, as rarely do problems fit within a single established academic research area. In the current CDT new collaborations are:

- Internal: Boyaci-Tawn, Boylan-Kourentzes, Glazebrook-Epitropakis, Glazebrook-Leslie, Grunewalder-Leslie, Jacko-Jaki, Kirkbride-Tawn, Leslie-Pavlidis, Lulli-Zografos, Nunes-Fearnhead, Sherlock-Tawn, Worthington-Onggo, Zografos-Nunes.
- International: Ehrgott-Nohadani (Northwestern), Fearnhead-Fox (Washington) Leslie-Szechtman (Naval Postgraduate School), Nemeth-McCormick (Washington), Titman-Nelson (Northwestern), Wadsworth-Frigessi (Olso).

5.10.2.1 How have any new academic posts (or promotions) been created as a result of the presence of the CDT? How many? 100 words

The first CDT award led directly to 2 new statistics posts and indirectly to 3 further in STOR. All appointees are now active in STOR-i. Following the new CDT award and outstanding REF2014 results (Mathematics =5th and Management Science 1st in power) our supervisory community has further expanded with a net gain of 11 staff (2 new professors and 9 lecturers). This has resulted in new groups in statistical learning, networks and OR for transportation and logistics.

STOR-i has made a major contribution to the quality as well as the quantity of LU's new appointees in STOR. Staff are attracted by its research culture and vibrant atmosphere and by the opportunities it creates for industrially engaged research and PhD supervision.

5.10.2.2 How has the CDT been linked to career progress of academics? 100 words

STOR-i has led to rapid promotions and major awards:

- In 2013 Eckley (co-Director) was promoted to a Chair. His career route is non-standard having worked for 6 years in industry prior to starting as a lecturer in 2007. His skills and experience were critical in developing STOR-i's industrial agenda. His rapid promotion is a highly justified response to his research and STOR-i co-leadership. He now also co-leads LU's Data Science Institute;
- STOR-i Chair Glazebrook was awarded the Beale Medal of the OR Society (2013) and elected an INFORMS Fellow (2016). The citations reference his pioneering contributions to doctoral training, including his leading role in NATCOR and STOR-i;
- The promotion cases of early career staff (Killick, Kirkbride, Wadsworth) have benefitted from STOR-i's support in obtaining industrial funding and our mentored PhD supervision experience.

5.10.2.3 Has the CDT's approach to skills training been followed in other parts of the host institution(s)? How? 100 words

An LU-led internal review identified the STOR-i intern programme and industrial engagement as best practice to be replicated elsewhere in the institution. Our international engagement was seen as exemplary.

As reported in 5.10, Eckley and Glazebrook have contributed to an LU wide working group on doctoral training so that STOR-i's innovative approaches are more widely adopted in LU. Changes to date include:

- Institution-wide adoption of STOR-i's approach to PhD monitoring, including skills training;
- All students in LU's Management School now undertake an agreed scheme of training;
- Internship schemes adopted by other departments.

6. Outputs from CDTs

Some of these questions will be especially relevant at the final reporting point but will need addressing towards the mid-term review point to ensure that information is being collected at the CDTs. CDTs that have been identified as continuations of previous CDTs have the opportunity to input data here.

6.1 Please give details of the first destinations (and beyond if known) of CDT students who have completed to date (for renewed CDTs, include {up to} the last 4 years data):

	Cohort 1	Cohort 2	Cohort 3	Cohort 4
Students continued in academia	2	2	1	-
Students in Relevant Industry (to CDT)	6	6	2	-
Of these, who many employed by Project Partners	1	2	1	-
Other employment	1	0	0	-
Of these, please provide details	PGCE Secondary			

6.1.1 Diversity outcomes

		Year 1		Year 2		Year 3		Year 4	
		No.	%age	No.	%age	No.	%age	No.	%age
Gender	**Female**	3	27%	3	30%	4	40%		
	Male	8	73%	7	70%	6	60%		
	Not disclosed								
	Unknown								
	Total	11	100%	10	100%	10	100%		
Age Range	**0-29**	10	91%	9	90%	10	100%		
	30-39	1	9%	1	10%				
	40-49								
	50-59								
	60+								
	Unknown								
	Total	11	100%	10	100%	10	100%		
Disability status	**Known Disability**								
	No known disability	11	100%	10	100%	10	100%		
	Undisclosed								
	Unknown								
	Total	11	100%	10	100%	10	100%		
Ethnicity	**Asian**	1	9%						
	Black								
	Chinese	1	9%						
	Mixed								
	Not Disclosed	1	9%			4	40%		
	Other	1	9%						
	Unknown								
	White	7	64%	10	100%	6	60%		
	Total	11	100%	10	100%	10	100%		

6.2 How & what is the outcome of the CDT tracking the careers of its alumni network? 250 words

Our alumni are a valued resource for STOR-i. They act as ambassadors, bring new industry links and contribute high quality industry-led training. It is therefore very important to us to maintain strong links with them. We have found it helpful to develop a formal process for maintaining contact with our alumni body (~30 to date).

- At exit interviews with two of the Leadership Team, students review their experiences of STOR-i and the mutual benefits of further engagement are discussed;
- We have established STOR-i's Alumni Network through a closed LinkedIn group for CDT graduates to communicate with peers, keep updated of new STOR-i developments, and identify new ways in which they can contribute to the evolving programme. Alumni are also in regular contact with current students via social media;
- We invite our alumni back on a regular basis and will continue to do so. We have funded slots in our annual conference for two alumni to speak about their latest work. All alumni are invited to attend this conference and give posters if they wish. Evidence to date suggests that they do come if they possibly can;
- Alumni are given open access to our research reading groups.

It is heartening that our STOR-i alumni are keen both to remain engaged with each other and to contribute to new generations of STOR-i students. This approach is already paying dividends. Ten of our alumni (including former STOR-i associates) have returned to give careers talks, lead problem solving days and to give seminars on their industrial research. We are particularly excited to have three of our alumni already involved in the co-supervision of current STOR-i PhD projects, namely Tim Park (Shell), Hugo Winter (EDF) and Chris Nemeth (LU) with more in this year's project pipeline.

6.3 What Intellectual Property, e.g., patents secured, spin-out companies, other commercialisation etc., has been generated to date and what has been the impact of these outputs? 200 words

We have an IP model which has served over 30 industry co-funded projects to date over both rounds of STOR-i funding. It is well established and successful. As companies only co-fund PhD projects, they understand that they do not have full rights to all IP. In every case LU retains the right to publish open source generic code implementing methods (to ensure reproducible research) and to publish research findings in the scientific literature. This is all set in place at the start of each industrial project in a contract that agrees IP and other arrangements. While we recognise that different companies have different requirements (and negotiating on a case-by-case basis is important), the fundamental position, stated above, is not compromised.

In STOR-i we do not seek to secure patents and leave our industrial partners to realise the commercial value arising from the methodological developments we lead. This may be considerable (see Annex: case studies). Our model is one that both industry and LU are comfortable with, given the level of repeat business and that the work this is already generating strong Impact Case Studies for the next REF.

6.4 Any other outputs (e.g. patents) that you wish to report? (e.g. i. how has the CDT supported business needs? ii. what return on investment are they estimating from their involvement in the CDT? iii. Have there been any unexpected benefits from their involvement in the CDT, for example? iv. Details of any Business Processes changed for industrial partners? v. Are there examples of job creation? vi. Details of any benefits in time-to-market?) 200 words

Given the acknowledged difficulty in patenting STOR research, our philosophy has been to work with our partners to drive novel theoretical and methodological research that can make an impact. In so doing, we

are taking a long-term view that seeks to embed STOR thinking across numerous industrial sectors, where arguably STOR research has not been previously prominent. Beginning to quantify the return on investment is a very difficult task, and we have not invited our industrial partners to do so. Our experience of the Edelman prize competition (the most prestigious international prize in OR) tells us that this is invariably a challenging and time-consuming undertaking if it were to be done at all accurately.

The volume of repeat business we secure and the breadth of industrial engagement in STOR-i activities we enjoy is powerful evidence that our industrial partners see the co-funding of STOR-i PhD students as excellent value for their investment. This is further supported by our partners employing our graduates (JBA*3 and Shell*2).

Some examples which illustrate that STOR-i projects are having a direct influence on business practice commercial benefit are set out in the Annex (such as Emma Ross' work for BT, Hugo Winter's work with the Met Office and Tim Park's work with Unilever) and how over a series of 4 projects with Shell our extremes values work is influencing their offshore met-ocean risk work, with a strong REF Impact Case Study emerging.

6.5 What follow-on funding from EPSRC, other Research Councils, industry, business and research charities would you ascribe directly and indirectly to the CDT? 100 words

Colleagues have leveraged the quality and impact of STOR-i's programme to enhance LU research council bids in STOR. Major EPSRC examples include:

- Eckley: £657k Mathematics underpinning digital economy and energy grant LETS (with Nason, Bristol);
- Zografos and Glazebrook: £3M OR-Master programme grant (with Burke, QMUL);
- Eckley and Fearnhead: £2.75M StatScale programme grant (with Samworth and Aston, Cambridge);
- Postdoctoral Fellowships for Maher (£265K) and Wadsworth (£239K).

All cross-reference STOR-i (and its industrially engaged agenda) for either shared activities, training or a strong environment for PhD supervision and impact generation.

Industry cash funding in the new CDT is £550K, of which £310K is follow-on from partners in the first CDT (Shell, BT, ATASS), with similar levels expected subsequently. These long-term relationships have enabled us to develop major, transformational research programmes with their input and support.

6.6 What highlights of public engagement/media coverage can the CDT provide? (other than 4.7) 100 words

- Charities: STOR-i's bursary scheme funds short term projects (e.g., with Vegan Society, Mercy Corps, Coeliac UK) where students work with the charity for up to a month exploiting their STOR skills;
- Schools: We have established a Schools Outreach programme with 4 students leading interactive sessions with pupils based on their research. Previously, 3 students shared their research skills with sixth formers from Cumbria. Further, 2 students are involved in the Brilliant Club and as STEM ambassadors;
- Fund raising: In 2015 the student body undertook the Yorkshire Three Peaks Challenge to raise £2.8K for the Liverpool hospital facility treating a fellow STOR-i student who was terminally ill;
- Learned Societies: Our students have been active volunteers at RSS, ORS conferences and careers days; members of the RSS local group, and section members of RSS, YSS and IMA.

6.7 What other steps have been taken to publicise the outcomes of CDT outputs, including 'branding' the CDT model? How have you been advocates of the CDT model? 100 words

STOR-i reports, software and full details of the training programme are available on our website.

With the experience of two generations of STOR-i and having seen a massive step-change in research quality, agenda and environment, we are very strong advocates for the CDT model to whomever will listen!

Examples include:

- Research Councils: Glazebrook has served on the EPSRC SAT for the Mathematical Sciences where he has been a strong advocate for the CDT model, particularly in areas of the EPSRC portfolio which thrive with a strong user interface and/or are priorities for growth;
- Recruiting Students: Our intern scheme for UGs showcases the benefits of the CDT cohort experience; 2/3 of STOR-i interns subsequently undertake a PhD at a CDT;
- We set up the Mathematics CDT network to help others learn about running a CDT;
- International advice: The Australia-wide ATN Industry DTC in Maths & Stats, and French and Irish universities have sought us out to learn from our experience.

6.7.1 Do partners reciprocate by mentioning the CDT on their publicity? 100 words

Our partners are proud of their links with STOR-i. The most obvious evidences of this comes from substantial repeat industry funding, employment of our graduates by industrial partners and long-term strategic academic partnerships (with co-supervision given free). These collaborations are publicised through joint papers that specifically mention the CDT and EPSRC funding and in some cases via websites (e.g. Big Insight, ATASS, Kognitio).

The value to our academic partners is illustrated through the following quote from Pat Jacobs (Head of the Operations Research Department, NPS, Monterey) 'In the case of NPS, the STOR-i faculty and students have worked with faculty and students in the NPS OR department on important and timely problems in military operations research resulting in publications in first-rate journals.'

At the Maths CDT Director's network meetings that we instigated, we all agreed to link to each other's CDT webpage.

7. Other issues & Annexes:

If there is anything else you would like to report on the CDT which is not covered elsewhere, please include it in this section: 200 words

Website: Our website is open and professional. It has helped encourage industry's involvement and makes clear that we are much more than a standard academic unit. We have been told by colleagues that the openness of our website has helped them understand our successful training model and that they have used this when constructing plans for their own CDTs.

Mixed Author Papers (Industry): Although many of our projects are joint with industry partners, many prefer not to be directly involved in the publication of the work for commercial reasons. This helps them separate the IP issues, of commercial value from the core methodological developments. Despite this approach, for some of our industry partners the publication of joint papers is encouraged with papers with Shell (Annals of Applied Stats, Environmetrics, Ocean Engineering*2, Electronic Journal of Statistics) and Met Office (Annals of Applied Stats, Dynamics and Statistics of the Climate System).

Mixed Author Papers (International): We have a number of papers of this type currently under review and in conference proceedings with staff at all four of our strategic partners and with other international authors. In terms of published journal papers with international co-authors we have papers with Lin (Naval Postgraduate School) in INFORMS Journal of Computing, Ombao (California, Irvine) in IEEE Transactions on Signal Processing, Hocking (McGill) and Rigaill (Paris) in Stats and Computing.

Notes:
Examples could include;

(a) the results from ongoing internal student and alumni surveys,

(b) impacts on (or of) the wider higher education sector

(c) How has your web presence enabled smooth running of the CDT?

(d) Do you have mixed authorship publications with international authors?

(e) Do you have mixed authorship publications with industrial authors?

Annex 1 Case Studies

CDTs are invited to submit a maximum of 6 Case Studies from the following categories;

- 0-3 Science case studies
- 0-3 User case studies
- 0-3 Student case studies