SELF EVALUATION REPORT, RAE 2020 @ KTH

MATHEMATICS AND ENGINEERING MECHANICS (PANEL 8)

Self evaluation report for Panel 8: Mathematics and Engineering Mechanics.
RAE 2020 at KTH, changed to internal review.
Panel coordinator: Anna-Karin Tornberg

Introduction

The research panel for Mathematics and Engineering Mechanics comprises two large departments with these respective names. In both departments, the number of faculty is slightly below 60. Counting also PhD students, postdocs, researchers and technical staff, the department of Engineering Mechanics is the largest with about 200 employees in total, compared to a total of about 140 in the Mathematics department.

Description of the research fields of the departments included in the research panel

The department of Mathematics has consolidated much of mathematical sciences within the same department. In addition to subjects in pure and applied mathematics that typically belong to a mathematics department, the department also includes divisions devoted to mathematical statistics, numerical analysis and optimisation and systems theory. Driven by the rapid developments in machine learning and data science and enhanced by new sources of external funding, several recent hires have been made in the field of mathematics for AI and data science. In addition to many important contributions to "pure" mathematics, researchers from the department devote themselves to mathematical challenges in many application areas in engineering and life sciences.

The department of Engineering Mechanics is currently organized in two divisions: *Vehicle Engineering & Solid Mechanics* and *Fluid Mechanics & Engineering Acoustics*, with a further division into units and research groups. The scope of the research performed within the department is broad, both concerning the range from more fundamental research to research performed in close collaboration with industry, as well as the multitude of applications. Research disciplines include: Rail and road vehicle engineering on the ground, naval engineering on and below the water surface, aerospace engineering, solid mechanics, composites and lightweight design, sound and vibrations, fluid mechanics and biomechanics. There are several very important experimental facilities within the department, and at the same time the department is a large user of computational resources that are allocated on a local, national and international level.

Description of the self-evaluation process for the research panel

The department of Mathematics saw a larger organizational change around the time of RAE2012, when the division of Numerical Analysis joined the department (with the actual physical move taking place in August 2013). Professor Sandra di Rocco was the chair of the department 2012-2019. Starting January 2020, the new chair of the Mathematics department is Professor Mats Boij.

The department of Engineering Mechanics is a new department, inaugurated in January 2020 by a merge of three previous departments: *Aeronautical and Vehicle Engineering, Solid Mechanics* and *Mechanics*. The chair of the new department is Professor Fredrik Lundell.

The respective situation for the two departments going into the self-evaluation process were hence quite different. The Numerical Analysis division was well integrated into the Mathematics department, whereas Engineering Mechanics was in the initial phase of effectuating the merge. Both department chairs were however new on their posts.

RAE 2020 is meant to be forward oriented, and as such, the self-evaluation process has the potential to facilitate a discussion that is definitely needed when merging three departments, but obviously also highly useful for a new chair. To allow more time and focus for this discussion than the day to day life at the department offers, the panel coordinator organized a workshop at Högberga gård on Lidingö, at a short distance from KTH. The workshop started in the morning of Wednesday March 4, and ended after lunch on Thursday March 5.

The panel coordinator met with the chairs well before the workshop to plan the writing work in general, and later to work out the program for the workshop. The chairs asked different key persons to provide texts for different sections before the workshop. In this process, these faculty members talked to others around them, in this way involving almost all faculty members at the departments to a varying degree.

At the workshop, there were in total about 20 participants from the two departments. Much of the time was spent for internal work within the departments, but there was also time for discussion and feedback across the departments. Two areas that were in focus for the discussions were section 1a, regarding strengths, weaknesses and development areas, together with 4a and the question where the department aspires to be in 5-10 years. It was necessary to form a common ground through the discussion about strength and weaknesses, leading into development areas, before continuing to formulate visions for the future development of the departments.

The panel coordinator and the chairs met directly after the workshop to plan the continued work, and a week later again to follow up. Due to the Corona virus outbreak, everything then changed completely. RAE 2020 changed to RAE 2021, and this self evaluation is for internal use only. Different adjustments to the new situation, including e.g. moving all the teaching online and arranging for digital examination, left essentially no time for the department chairs and others in the organization to devote to this report. It was not until after April 20 when the re-exam period was finished that work on this report continued. The initial plan was to circulate the report within the departments to get feedback. In reality now, with a deadline of April 30, there was no time to do this.

Hence in summary: we have had discussions about the ideas in this report during e.g. the workshop as described above and different people have contributed to the text, but very few people have had the opportunity to see the full text and comment on it. For RAE2021, this text will be the starting point and hence will then be thoroughly discussed and improved upon.

Identified research panel synergies

Within the Engineering Mechanics department, physical experiments as well as numerical simulations are used to learn more and hence drive the knowledge within the specific field forward. When analyzing the experimental data, using a numerical method to perform a simulation or deciding which mathematical model to use to describe the phenomenon under study, different subfields of mathematics is clearly present. In many instances however, one might be satisfied with using standard tools or models that have already been developed, as the focus is on other scientific questions central to the research challenge. In other cases, the mathematical or numerical challenges of the problem are central, and in these cases there is a potential for collaboration with someone from the mathematics department. For a fruitful collaboration, in difference to something of a more consulting character, the mathematical or numerical challenge must be such that it is interesting as a research question for the mathematician.

The question is how to catalyze such collaborations. Research networks or centers can be certainly be one way. Here one example is the Linné FLOW center for fluid mechanics research that started in 2007, which for ten years was funded by the Swedish Research Council (VR) as a center of excellence. Researchers in numerical analysis from the mathematics department have been active in this center together with researcher specializing in fluid mechanics and acoustics. Collaborations have continued within the more recently established center INTERFACE (a VR research environment).

For collaborations to occur, we need to know each other, or at the least know about each other. Centers as above provide platforms for that. There have also been quite extensive discussions across the two departments e.g. when forming the mathematics curriculum for the Vehicle Engineering program, resulting in several mathematics courses combining analytical and numerical methods. At the workshop in March (described above) discussions were held that really highlighted what is said above: real collaboration can only occur when the challenge at hand contain interesting research questions for both parts. Hence, we have not identified any synergies on a large scale, but we do believe that this kind of bottom up initiatives enhance the quality of research within both departments. We believe e.g. that there is a potential for new collaborations in applications where machine learning techniques are starting to be used. We therefore look forward to continuing our discussions on how to encourage and enable such collaborations as we prepare for RAE 2021.

Department of Mathematics

1. Overall analysis and conclusions; strengths and development areas

1a. Limited SWOT-analysis

The department of Mathematics has seen a substantial development since RAE2012. Here we give a brief summary of the current major strength and weaknesses that we have identified, both considering research and organization.

Research - strengths and weaknesses

Strengths

- Excellence of the department. We have many strong individual researchers as exemplified by awards and prizes. Several of our faculty members are members of the Royal Academy of Sciences (KVA). Our researchers are successful in grant applications for VR, ERC and KAW. Several rankings show that our department has an increasing reputation (e.g. no 23 in Shanghai ranking 2019 and No. 38 in QS ranking 2020).

- Consolidated mathematical sciences within the same department. Mathematical statistics, numerical analysis and optimisation and systems theory are represented in the same department unlike at many other universities.

- Genuine willingness to increase collaborations within the department. We have over the last decade had an increase in the collaborations within department and in particular over the division boundaries. As an example, several projects have been launched where supervisors from two divisions collaborate with a PhD student whose project lies between their divisions.

- Recruitments with highly competitive applicants. In our recruitments we have had a high number of highly competitive applicants for each announced position. During the last decade international candidates have filled many of our positions.

- Increase in female faculty. Since RAE 2012 we have hired 25 faculty members among which 11 are female. This has lead to a significant increase in female faculty members.

Weaknesses

- Gender balance. Despite the recent positive development, the total number of female faculty members is still low, especially on the level of full professor.

- Dependence on external funding. In principal all PhD students are financed with external funding and thus the size of our PhD programs strongly depends on external funding.

- PhD students tied to specific project. As a consequence of the dependence on external funding for our PhD programs, each PhD student is tied to a specific project from start.

- Conditions. The starting package that we can offer new faculty is not always competitive. This also applies to conditions over longer time in terms of expected future teaching load etc.

- Internal expertise not used optimally within department. Some systematic factors are short time horizon of result-oriented research, individual research record prioritized and busy agendas.

Organisation – strengths and weaknesses

Strengths

- Division structure that creates belonging. The department is divided into divisions that facilitates staffing and emphasizes subject identities. These traditions have a positive effect on the working environment as they create social belonging among the faculty members.

- Research active faulty. A large proportion of our faculty is research active. This is a positive trend away from the previous bimodal distribution where there was a split between researchers with low involvement in teaching and teachers with low involvement in research.

- Tenure track. We now have a functioning tenure track system and since some time we have an ambition to recruit mainly on the assistant professor level. This should be a form of employment that increases our attractiveness as an employer.

- Efficient local administration**.** Even though some of our administration has been centralized, we still have local key administrative staff in our department. This allows for very efficient administrative support and is highly appreciated by our faculty.

Weaknesses

- Traditions can create cementation. While strong traditions can be good in providing a base for research, they can also create "deadlocks" and become obstacles for development of new cross-disciplinary areas. When a division becomes very small, it will be vulnerable since it will be hard to cover up for other teachers and researchers when needed. When concentrating on our strengths, we are at risk of missing some areas of research all together.

- Slow recruitment processes. Our regulation for hiring has a built-in inertia that can be valuable in order to maintain high standards, but it can also create difficulties in catching opportunities for hiring in a specific field. This puts us at a disadvantage

towards other international competitors for researchers in areas where many universities try to build up their competence.

- Cumbersome promotion processes. According to several of our junior faculty members, the process they have to undergo during their time as assistant professors is cumbersome and is afflicted with unnecessary negative feelings. There are many items that have to be fulfilled and all at the same time. It is also tough to go through the process for promotion when creating a family. This might have gender implications and might counteract our quest to achieve a better gender balance among our faculty.

- 5-year limit for applying for assistant professorships. Our regulations for the tenure track system states that there is a five-year limit after the PhD in order to apply for an assistant professorship. Since there might be several years between announcement of an open position in a subfield (i.e. numerical analysis or mathematical statistics) this might be too tight, and puts us at risk of losing excellent candidates due to non-optimal timing.

Development areas

Based on the strengths and weaknesses discussed above, we have identified the following five development areas to be addressed:

- Increased internal collaboration. Many of our faculty have several international collaborators, which is excellent and encouraged. However, we do also want to promote internal collaboration, since we believe that this is beneficial for the overall quality of research of the department as well as for the working environment. It will also be important to alleviate two of the weaknesses listed: that traditions can create cementation and non-optimal use of internal expertise. One ambition is that this will render us more adept to form different coalitions that can lead to more joint grant applications. Here, we have a great opportunity in Mathematics for AI and Data science. Different initiatives such as study groups have already attracted faculty from all divisions, and it is an excellent opportunity to combine expertise from different subfields of mathematics.

- Build on strength with more research active faculty. In addition to having more research active faculty, the external funding of the department has increased substantially over the recent years, which has e.g. increased the number of postdocs at the department, making the department even more research intensive. While there are many active seminar series at the department, we want to establish more natural meeting places for research discussions. This also connects to the previous point of internal collaborations. We will also look at how we can better support our faculty, and in particular those new to Sweden, in their efforts to apply for grants. As noted as a weakness, almost all our PhD students are funded by external grants. To keep a decent size of the doctoral program, we are hence dependent on external grants. For the richness of the program, it is

essential to have many faculty involved in advising students, and it is also important for younger faculty to gain this experience.

- Further development of recruitment practices. In order to continue recruiting excellent candidates with a significant proportion of females, we will continue to improve on our internal recruitment process. This include the subject profiles that we propose as well as the active search procedures to identify candidates and encourage them to apply. We will also for each position evaluate if it is applicable to utilize a strategy that we have already used at some occasions: to hire two candidates instead of one if the second person on the ranking is female.

- Improve on sub-optimal promotion process as well as faculty development support. To optimize the chance of retaining successful hires, we will work to influence how the promotion process is handled across KTH. In parallel to that, we will look over how we better can support our faculty overall, and specifically assistant professors through the promotion process. For the latter, a mentor system will be developed with the input from those who have recently been promoted.

- Recruitments within the area Mathematics for AI and Data science. With financial support from the recently initiated Wallenberg AI, Autonomous Systems and Software Program (WASP), four assistant professors have recently been hired. The department needs to work out a recruitment strategy for this field, in order to also optimally leverage the expertise within the department. This includes to decide if one should aim to recruit a well-established professor with a strong international standing.

There are some weaknesses that have not been addressed with these development areas. These mainly have to do with regulations or resources that are not under our control. The slow recruitment process and the 5-year limit after PhD for applicants to assistant professorships are determined by regulations or procedures outside of the department. To the resource questions belong the fact that the PhD students are almost all paid by external grants, and that PhD students, unlike at many other mathematics departments internationally, therefore are tied to a specific project from the start. It also concerns the initial and long term conditions that we can provide for faculty.

An attractive working place provides good working conditions, including sufficient time for research. We have prioritized to use internal research funding for faculty salaries to provide as stable a situation that we can. Despite this, the research time for the tenured faculty will vary depending on the external funds available for each faculty member, as the base level that can be offered from the department is on the low side. The size of the faculty is dimensioned given the education mission. This insecurity regarding long term conditions is a disadvantage in the recruitment process, especially when it comes to high-profile international candidates.

1b. Summary statement on contributions of department on impact, infrastructure and sustainable development

Since there will not be any cross panels in the internal assessment and since we have had time pressure to finish the report as it is, we leave this to be written at a later stage after the internal assessment.

An extensive discussion about impact is provided in section 6, “Impact and engagement in society”.

2. Research profile

2a. General information of the department

The Department of Mathematics has five divisions, one that has just been started and will not be described in the following. The four divisions that have had during the period 2012-2019 are

- *Division of Mathematics*
- *Division of Mathematical Statistics*
- *Division of Numerical Analysis*
- *Division of Optimization and Systems Theory*

The Division of Mathematics is the largest and it corresponds to about half of the department. The Divisions of Mathematical Statistics and Numerical Analysis are of similar sizes and the size of the Division of Optimization and Systems theory about half of that. Since 2020 we have a new division, Mathematics for Data and AI, where we gather the faculty associated with the Wallenberg AI, Autonomous Systems and Software Program (WASP). Since 2017 we have the Brummer & Partners MathDataLab as a centre on the department level.

The Department of Mathematics is one of the four departments in the School of Engineering Sciences, where the remaining departments are the *Department of Applied Physics*, *the Department of Engineering Mechanics* and the *Department of Physics*.

2b. Central research questions and themes, knowledge gaps addressed, main research activities and composition of research team(s)

We describe the research themes present in the department according to the organization into divisions.

Division of Mathematics

Mathematics is an essential and ever present part of our attempts to understand the world around us. Increasingly, research and development require sophisticated mathematics. Our vision is to be a research unit that works to actively strengthen this

central role of mathematics, both at KTH and in society, and that makes fundamental contributions to the subject.

The research at the Division of Mathematics covers broad areas of modern mathematics. There is no formal division of the research activities into different research groups. With the growth and development of the division as a research centre it is not meaningful, or even possible, to keep up borders between research areas. There is an informal division into different areas in that there are seminars, some joint with Stockholm University, that cover different parts of mathematics. Based on this, the research activity within the Division can be split into the following themes.

- Algebra and Geometry. (Tilman Bauer, Mats Boij, Wojciech Chachólski, Sandra Di Rocco, David Rydh, Roy Skjelnes). Algebra and geometry are basic areas of mathematics that often interact with each other in the form of Algebraic geometry and Algebraic topology, where methods from algebra are used to study geometric objects and topological properties. The group incorporates a broad spectrum of research topics in these two fields and also in Commutative Algebra. Research in algebraic geometry is focused on moduli spaces and moduli stacks, Hilbert schemes, modular forms, moduli spaces and their cohomology, toric geometry, and tropical geometry; homotopy theory and applied topology; Gorenstein and level algebras and Betti diagrams of Cohen-Macaulay modules.

- Combinatorics and complexity theory. (Petter Brändén, Johan Håstad, Svante Linusson) Combinatorics is an area of mathematics that deals with counting problems and discrete structures like graphs often using methods from other areas like algebra, topology and analysis. Complexity theory is a relatively recent area of mathematics dealing with the problem of understanding how difficult it is to solve problems algorithmically. Research in complexity theory is a recent addition to the Department. The combinatorics group is active in research on a broad front, including enumerative, algebraic, probabilistic and topological aspects of discrete mathematics. Within the group there is also expertise in cryptographic and error-correcting codes, combinatorial algorithms, and connections with biology (phylogenetic trees, mutation distance) and social sciences (election systems).

- Differential Geometry and Mathematical Physics. (Mattias Dahl, Hans Ringström). Differential geometry lies at the interface between geometry and analysis and is an important area of modern geometry with strong connections to non-linear partial differential equations. Research in the group is done on mathematical problems arising in general relativity with connections to nonlinear partial differential equations, Riemannian geometry and also dynamical aspects.

- Dynamical Systems. (Kristian Bjerklöv, Danijela Damjanovic, Maria Saprykina). Dynamical systems is the study of the time evolution of systems in particular through non-linear models. Research interests of the members of the group cover

several central areas of modern dynamical systems, with a focus on low-dimensional dynamics and Hamiltonian systems.

- Number Theory. (Pär Kurlberg, Lilian Matthiesen). Number theory is a central part of mathematics with connections to almost all other parts of mathematics. Research in number theory is done in problems related to dynamics, mathematical physics and probabilistic aspects, as well as in combinatorial and analytical number theory.

- Harmonic Analysis and PDE. (John Andersson, Tomas Ekholm, Håkan Hedenmalm, Jonatan Lenells, Henrik Shahgholian, Ozan Öktem) Analysis is a broad and basic area of mathematics with strong ties to applications and modelling. The research of the group ranges from harmonic and complex analysis to partial differential equations (PDE), free boundary problems, and potential theory, applications to imaging and also connections to random models. Another direction is towards integrable PDE:s.

- Random matrix theory and stochastic models. (Maurice Duits, Håkan Hedenmalm, Kurt Johansson, Kevin Schnelli, Fredrik Viklund). A growing area of mathematics is the interface between probability, analysis and combinatorics often motivated by problems originating in physics, statistics and other applications. The research in the group is focused on statistical properties of various random matrix ensembles, and connections between random matrix theory and models originating in statistical mechanics. Another research area is the study of critical lattice models and conformal invariance.

Division of Mathematical Statistics

As a subject, mathematical statistics analyses and describes random phenomena using mathematics. The research-active faculty members of the Mathematical Statistics division conduct research in a wide range of topics; these topics can, broadly speaking, be divided into the following areas.

- Probability theory (Boualem Djehiche, Anja Janssen, Sigrid Källblad, Pierre Nyquist, Kevin Schnelli, Thomas Önskog) Probability theory provides mathematical tools for modelling and analysing random phenomena and describing the random nature of data. The division conducts research in mean-field theory, in which interactions of a many-body system are modelled using stochastic differential equations. Further research in stochastic analysis and control is oriented towards reflected stochastic differential equations and the emerging field of martingale optimal transport. Another classical research area in probability covered by the division is random matrices, and the focus is on spectral statistics of high-dimensional random matrices in mathematical statistics and random networks. Finally, on-going studies in extreme value theory concern distributional properties of extreme values in random vectors and time series as well as the statistical dependence between such extremes.

- Stochastic simulation (Henrik Hult, Pierre Nyquist, Jimmy Olsson) In a broad and widely used class of computational algorithms, numerical results are obtained by means of repeated random sampling. The division conducts active research in this area; especially regarding importance sampling, sequential Monte Carlo (SMC), and Markov chain Monte Carlo (MCMC) methods. In addition to gaining general theoretical understanding of such techniques and developing novel methodology, the focus is also on tailoring algorithms for applications to rare-event analysis, population-genetics simulation, restricted Boltzmann-machine learning, and high-energy physics simulations for the CERN large hadron collider.

- Statistical learning and data science (Henrik Hult, Pierre Nyquist, Jimmy Olsson, Tatjana Pavlenko) In generative models (GM), which are paramount in artificial intelligence and unsupervised machine learning, latent data—to be inferred on the basis of observed data—are modelled as random variables. General hidden Markov models form a class of GM allowing latent-state and parameter learning to be carried through online for streaming data, and ongoing research develops SMC-based methodology for this purpose. Further research concerns variational auto encoders, a class of deep learning techniques allowing complex GM to be fitted to high-dimensional data such as images and texts. Focus is also on applications of GM to bioelectronic medicine and monitoring of inflammatory diseases. Another area covered by the division is statistical learning and inference for high-dimensional data whose dimensionality may exceed the number of observations. Finally, the goal of an ongoing collaboration with RaySearch Laboratories AB is the development of machine learning methods for medical image segmentation and radiation dose prediction.

- Financial and insurance mathematics (Boualem Djehiche, Henrik Hult, Anja Janssen, Sigrid Källblad) Today, the finance and insurance industries are going through major and rapid changes, with increasing exposure of potentially catastrophic losses as a result. The division conducts active research on systemic risks, network-information-based credit modelling and rating, and modelling and valuation of life insurance contracts. Moreover, questions related to model risk are addressed using martingale optimal transport theory. Also extreme value theory is playing an increasingly important role in credit risk management, and on-going research studies different types of extremal dependence structures for financial data. Finally, a current research project develops generative models for limit order books and reinforcement learning for trading execution.

Division of Numerical Analysis

Numerical analysis is the science of methods for mathematically based computer simulations and data analysis. This has become increasingly important with the rapid development of more powerful computers and the wider availability of large data sets, driven by applications in areas like physics, biology, finance and data science. Much of traditional experimental work in the sciences has therefore migrated to the computer. The subject is interdisciplinary and has interfaces to other branches of mathematics, computer science and various applications.

The research at the division of numerical analysis involves numerical methods and theory for a wide variety of mathematical problems, such as stochastic, partial and ordinary differential equations, linear algebra and matrix analysis. It includes development and implementation of algorithms, and analysis of their complexity, stability and convergence properties – that is, how fast, robust and accurate they are. Research projects stretch from rigorous mathematical analysis to the development of software on modern computer architectures. The division can be divided into three areas.

- Partial and ordinary differential equations. (Michael Hanke, Patrick Henning, Olof Runborg, Anna-Karin Tornberg and Sara Zahedi) This is a main focus area, with applications e.g. in multiphase flow and micro fluidics (Tornberg, Zahedi), wave propagation (Runborg, Henning), quantum mechanics (Szepessy, Henning), micro magnetics (Runborg) and neuroscience (Hanke). Method development revolves around boundary integral methods, (cut) finite element methods and molecular dynamics. Multiscale problems, PDEs with complex moving geometry and inverse problems are some particular challenges that are addressed. There is also related work on optimal control, uncertainty quantification and differential-algebraic equations.

- Stochastic differential equations (Mattias Sandberg, Anders Szepessy). This area includes research on adaptive multilevel Monte Carlo methods for weak approximations of SDEs, the derivation of stochastic Langevin molecular dynamics from more fundamental models, as well as stochastic models for machine learning.

- Numerical linear algebra (Elias Jarlebring). Research in this area concentrates on eigenvalue problems which are nonlinear in the eigenvalues, the eigenvectors or both, with applications e.g. in quantum mechanics and wave propagation. The nonlinear problems are solved with iterative methods based primarily on the infinite Arnoldi method. There is also work on preconditioning and iterative methods for special linear systems, as well as model reduction for time-delay systems.

As for the multi-disciplinarity, numerical analysis is typically not the end product but a tool in a process with many other components. Collaboration with other departments and subfields in mathematics is therefore essential. One important role of computational mathematics is to tailor and transfer knowledge of numerical methods from one application to another, which is also important for the cooperation within the Department of Mathematics. Some examples from the division are the use of ideas from multiscale ODE methods to compute "shadow" Lagrangian density for quantum states of superfluids (Henning), the introduction of techniques from systems theory to solve PDEs (Jarlebring) and the adaption of fast summation methods developed for Stokes flow to molecular dynamics (Tornberg). Computational mathematics is also an important interface between pure mathematics and applications, in introducing new problems to the mathematics community and

communicating new mathematics to application areas. Wavelets, which originated in harmonic analysis, is a striking example of the latter.

Division of Optimization and Systems Theory

Optimization and Systems Theory is primarily devoted to methods of optimization, including mathematical programming and optimal control, and systems theoretic aspects of analysis, control and signal processing. In addition, attention is given to mathematical economics and applied problems in operations research, systems engineering and control engineering.

At the division of optimization and systems theory, the central research questions and themes lie in

- generalized moment problems (Johan Karlsson, Xiaoming Hu),
- interpolation problems (Johan Karlsson),
- large-scale complex networks of dynamical systems (Xiaoming Hu, Johan Karlsson),
- methods for nonlinear optimization (Anders Forsgren),
- nonlinear estimation and regulation (Xiaoming Hu, Johan Karlsson),
- theory for optimal control (Johan Karlsson, Xiaoming Hu),
- optimal transport and scheduling (Johan Karlsson, Per Enqvist).

These are all topics in applied mathematics in which a crucial aspect is to bridge the gap between theory and applications and to introduce new paradigms to other fields. We have in particular looked into connections to crowd modeling and dynamics, Markov chains, modeling of metabolic networks, multi-agent systems and Schrödinger bridge problem.

The research is strongly tied to applications in radiation therapy (industrial partner: Raysearch Laboratories), contact centers (Teleopti), flight scheduling (Aviolinx), medical imaging (Vironova). Beyond ordinary research activities, we would like to mention here our research collaborations with Swedish companies via industrial PhD projects. We have been particularly strong in this respect and maintain a stream of around three active industrial PhD students. The profile implies that our research is interdisciplinary thus the team members should cover competence in both optimization and systems theory.

Gender balance

Gender balance is an important aspect in hiring at the department. As a whole, we have been successful in achieving a gender balance among new faculty recruitments over the last decade. The department will continue to work along KTH's guidelines on gender equality, diversity, and equal conditions for this positive development to endure.

The Division of Mathematics still have a long way to go in order to achieve gender balance both among faculty members and among PhD students and postdocs, but at least in terms of faculty members, there is a positive trend. The Division of Mathematical statistics and the Division of Numerical analysis both have almost

perfect gender balance among permanent faculty members, but the gender balance among PhD students and postdocs is not as good. The Division of Optimization and systems theory has no female faculty members but among PhD students and postdocs, the gender balance is better.

2c. Contributions to the advancement of the state of the art within the research fields of the department

The following are some selected recent contributions made by the Division of Mathematics.

- The Division of Mathematics has a strong group working in random matrix theory and related stochastic models like random growth and random tilings. Interesting recent contributions include the first computation of the two-time distribution in the KPZ universality class starting from certain last-passage percolation models (Johansson, Johansson-Rahman), and the computation of the inverse Kasteleyn matrix for the two-periodic Aztec diamond (Chhita-Young, Duits-Kuijlaars) and analysis of its asymptotics at the liquid-gas boundary (Chhita-Johansson), the first rigorous analysis of a random tiling model with a gas phase. Other important developments are the proof of central limit theorems for linear statistics of determinantal point processes based on recurrence coefficients (Breuer-Duits), and work on local laws for various ensembles of random matrices (Schnelli et al). Important results on the Stochastic Loewner Equation (SLE) has been obtained e.g. on the almost sure multifractal spectrum for the tip of an SLE curve (Viklund-Lawler). Hedenmalm (with Wennman) has made important progress on the asymptotics of planar orthogonal polynomials, which relates to boundary universality in random normal matrix models.

- One theme in the research in number theory by Kurlberg and co-authors has been proofs and dis-proofs of a number of "wave chaos" conjectures, by the physics community, for Seba billiards. In particular, exhibiting level repulsion for "new" eigenvalues of arithmetic 3d billiards, non-gaussian value distribution of eigenfunctions, quantum ergodicity holding for square billiards [3] although very strong localization occurs on thin subsequences, whereas quantum ergodicity badly breaks down for generic (Diophantine) aspect ratio tori. In another direction, the variance of nodal length fluctuation was determined for random waves on arithmetic tori, and found it to be non-universal, namely dependent on Fourier coefficients of probability measures arising from lattice points on circles (Krishnapur-Kurlberg-Wigman).

- The research in partial differential equations in the group centred around Henrik Shahgholian has advanced the knowledge of free boundary problems. This includes progress in the following areas: Optimal Regularity of solutions to free boundary problem, Homogenization theory, Sand pile dynamics, System case for free boundary problems, Classification of global solutions to the obstacle problem. In particular the resolution of this last mentioned problem has seen new developments. This problem was completely solved in dimensions 2, with complex

analytic methods. In higher dimensions the problem was solved for compact coincidence sets (Dive 1931). The new contribution is a complete proof for dimensions greater than five (Shahgholian-Eberle-Weiss).

- The last five years, several foundational results on derived categories and Tannaka duality for algebraic stacks have been established. A spectacular application of these results is the local structure theorem for algebraic stacks by Alper, Hall and Rydh: algebraic stacks locally look like the quotient of a scheme by a stabilizer group. In the presence of infinite automorphism groups, the local structure of algebraic stacks was not known except in a few explicit cases. It is shown that (essentially) every stack étale-locally look like the quotient of an affine scheme by a stabilizer group. This opens up a wealth of tools from equivariant geometry to be used on algebraic stacks.

- The work of Wojciech Chachólski and collaborators is concerned with using homology in Topological Data Analysis. One of the biggest challenges in this area is to extract homology based invariants that are stable and suitable for statistical analysis, whose outcomes could be used as an input for machine learning algorithms (vectorising geometry). One of the main research fronts in modern data science is supervised learning. The main achievement of the group's research is a proposal of how to extract homology-based invariants in a supervised way, allowing optimizing over various models for the observed homological information. On-going efforts are aimed at defining an algorithmic approach to concretely use noise systems for computations.

- Some of the main achievements within the group of dynamical systems are the establishment of a new continuity property of the SRB measure for families of unimodal maps. (Michael Benedicks and collaborators), the proof of existence of Arnold diffusion in a pendulum lattice (Saprykina and collaborators), and the foundation of a new research program for global rigidity of partially hyperbolic actions, which has led to the discovery of a new phenomenon called centralizer rigidity (Damjanovic and collaborators).

- The research of Hans Ringström is concerned with mathematical aspects of general relativity. Generic big bang singularities are expected to exhibit chaos and spatial localization. Solving non-linear PDE's such as Einstein's equations in such a setting can be expected to be non-trivial. One result, published in 2019, demonstrates that it is possible to analyse solutions to the Klein-Gordon equation in the context of a chaotic (Mixmaster type) big bang singularity. In a related result, posted in 2017, optimal energy estimates and detailed asymptotics of solutions to systems of wave equations were derived in a large class of settings relevant in cosmology.

- In Combinatorics, Petter Brändén and June Huh (Institute for Advanced Study) recently developed a theory of Lorentzian polynomials to serve as a framework for certain problems in algebraic geometry, convex geometry and combinatorics pertaining to Hodge theory, geometric inequalities, and log-concavity in

combinatorics. They applied the theory to prove the strongest form of Mason's conjecture in matroid theory from 1972.

- Johan Håstad has been working on projects about approximability of NP-hard optimization problem, algorithms running in weakly exponential time, and proof complexity, the search for efficient proofs in various proof-systems. These three areas share some techniques but also touch on other areas in computational complexity. The strongest result in the area is in proof complexity where he can give the best bounds to date for the size of proof in the so-called bounded-depth Frege proof system. When it comes to approximability he has recently extended the classical lower bounds of Håstad to apply to the unique factor graph setting.

The following are some selected recent contributions made by the Division of Mathematical Statistics.

- Several novel results in mean-field theory, optimal control, and games have been established: new approaches to modeling of crowd dynamics and electricity price dynamics using mean-field-type games; formulation and solution of a new class of reflected backward stochastic differential equations of mean-field type. Moreover, Djehiche et al. (2015) establish a stochastic maximum principle for optimal control of mean-field-type stochastic differential equations depending not only on the state and the control but also on the mean of the state.

- Derivation of conditions for the existence of unique strong solutions to reflected stochastic differential equations on non-smooth time-dependent domains.

- A Benamou-Brenier-type formulation of the martingale transport problem for two given d-dimensional distributions in convex order. The unique solution of this problem turns out to be a Markov martingale with several notable properties.

- Extension of recent results on the universality phenomenon of spectral statistics to sparse sample covariance matrices, and the establishment of a local law for the eigenvalue density up to the upper spectral edge. Under a suitable sparsity condition, it is shown that the GOE Tracy–Widom law describes the limiting distribution of the rescaled, shifted extremal eigenvalues.

- Douc *et al.* (2014) establish stochastic boundedness of the asymptotic variance of SMC methods under close to minimal assumptions being satisfied also for models with a non-compact state space. This yields the most general time-uniform convergence result for SMC methods obtained so far.

- Analysis of importance-sampling estimators using large-deviation theory, and the derivation of an extension of Sanov's theorem to this setting. The result can be used for quantifying the performance of an importance-sampling algorithm and yields an estimate of the sample size needed to reach a desired precision.

- Development of novel particle SMC methods for Bayesian structure learning in decomposable graphical models. By a technique referred to as temporalisation, a static graph posterior is targeted by means of a dynamical sequence of graph laws, allowing SMC methods to be applied.

- Analysis of the asymptotic behaviour of the power-law threshold and the corresponding power-law tail index given by the so-called minimum distance selection procedure. The method is particularly popular in computer science, and the results show that the limit is non-normal with a relatively high variance.

The following are some selected recent contributions made by the Division of Numerical analysis.

- Development and analysis of multiscale methods, for problems where small scale features need to be simulated over large scales (Henning, Runborg). The main results have been on optimal error estimates and complexity for heterogeneous multiscale methods (HMM) and localized orthogonal decomposition (LOD), in applications like solid mechanics, wave propagation, magnetization dynamics as well as co-simulation methods in neuroscience.

- Numerical methods for multiphase flow and micro-fluidics with complex and evolving geometry involving for instance deforming droplets and moving fibers in Stokes flow (Tornberg, Zahedi). The main contributions include techniques for representing and handling such geometry as well as solving PDEs in/on evolving domains in a (provably) stable way using specialized finite element methods (CutFEM), and boundary integral methods, where the focus in particular has been on spectrally accurate quadrature methods for singular kernels and fast summation methods for problems with many droplets/fibers.

- Numerical methods for the Schrödinger equation. In the linear case methods and error estimates have been derived for Born-Oppenheimer molecular dynamics based on deterministic and stochastic models (Sandberg, Szepessy). In the non-linear case finite element methods have been developed and analyzed for Bose-Einstein condensates (Henning).

- Development of fast iterative methods for nonlinear eigenvalue problems, in particular based on the infinite Arnoldi method.The contribution includes theoretical results as well as development of the open source software package NEP-PACK (Jarlebring).

- Numerical methods for stochastic differential equations (SDE), in particular development of algorithms and theory for adaptive multilevel Monte Carlo methods (Szepessy).

The following are some selected recent contributions made by the Division of Optimization and systems theory.

- New approaches for modeling and intervention of multi-agent systems and for reaching non-consensus emergence in which moment dynamics are analyzed (Karlsson, Hu), and for dynamic modeling of elementary flux modes in a metabolic network in which a dynamic framework based on column-generation techniques is used that dynamically identifies a subset of the EFMs as the problem is being solved (Forsgren);

- New methods for ensemble estimation based on optimal transport (Karlssson), for crowd evacuation (Hu), for extending rational covariance extension problem to multi-marginal setting (Karlsson), for improving the quality of queueing systems (Enqvist), for nonlinear optimization in which quasi-Newton methods are in focus (Forsgren), and for radiation therapy planning and optimization (Forsgren);

- New discovered connections between multimarginal optimal transport problems and hidden Markov chains that allow for development of new efficient algorithms for solving certain multimarginal optimal transport problems (Karlsson), and between agent formations and graph topology that explores the topological structure of communication to generate a desired formation (Hu).

2d. Quality and quantity of contributions to the body of scientific knowledge

Highlighted publications

We have chosen the following 11 publications to exemplify the publication record with many publications in top ranked journals in mathematics in general and as well as in numerical analysis, probability, statistics and optimization and systems theory.

1. Alper, Jarod; Hall, Jack; Rydh, David **A Luna étale slice theorem for algebraic stacks**, Ann. of Math. (2) 191 (2020), no. 3, 675–738.
2. Andersson, John; Shahgholian, Henrik; Weiss, Georg S. **On the singularities of a free boundary through Fourier expansion**. Invent. Math. 187 (2012), no. 3, 535–587
3. Breuer, Jonathan; Duits, Maurice. **Central limit theorems for biorthogonal ensembles and asymptotics of recurrence coefficients**. J. Amer. Math. Soc. 30 (2017), no. 1, 27–66
4. Djehiche, Boualem; Tembine, Hamidou; Tempone, Raul **A stochastic maximum principle for risk-sensitive mean-field type control**. *IEEE Transactions on Automatic Control*, 60 (2015), no 10, pp. 2640–2949.
5. Douc, Randa, Moulines; Éric; Olsson, Jimmy **Long-term stability of sequential Monte Carlo methods under verifiable conditions**. *Annals of Applied Probability*, 24 (2014), no. 5, pp. 1767–1802.
6. Hansbo, Peter; Larson, Mats G; Zahedi, Sara **A Cut Finite Element Method for a Stokes Interface Problem**. *Appl. Numer. Math.* 85 (2014), 90–114.
7. Henning, Patrick; Peterseim, Daniel. **Oversampling for the Multiscale Finite Element Method**. *SIAM Multiscale Model. Simul.* 11 (2013), no. 4, 1149–1175.

8. Jarlebring, Elias; Michiels Wim; Meerbergen, Karl. **A Linear Eigenvalue Algorithm for the Nonlinear Eigenvalue Problem**. *Numer. Math.* 122 (2012), no. 1, 169–195.
9. Johansson Viklund, Fredrik; Lawler, Gregory F. **Almost sure multifractal spectrum for the tip of an SLE curve**. Acta Math. 209 (2012), no. 2, 265–322
10. Krishnapur, Manjunath; Kurlberg, Pär; Wigman, Igor **Nodal length fluctuations for arithmetic random waves**. Ann. of Math. (2) 177 (2013), no. 2, 699–737
11. Zhang, Silun; Ringh, Axel; Hu, Xiaoming; Karlsson, Johan **Modeling collective behaviors: A moment-based approach**, *IEEE Trans. Automat. Control* (2020)

Reflection on the department's bibliometrical performance

The library provided us with the following six tables of bibliographic data.

1. Publications in DiVA, fractional counts
2. Publications in DiVA, full counts
3. Citations 3 year window, fractional counts
4. Publication impact, fractionalized (3-year moving average)
5. Journal impact, fractionalized (3-year moving average)
6. International and Swedish non-university co-publications, full counts (3-year moving average)

It is hard to draw very strong conclusions from the data provided. From checking the data for some individuals, we know that the data is missing some key publications, but we do not know to which extent this would effect the overall numbers. Using the data provided, we can see that:

- The number of publications has increased slightly as the department has grown.
- The number of licentiate theses has decreased, which indicates that fewer of our PhD students produce a licentiate thesis at half time.
- Our share of top 10% publications is about average, possibly with a positive trend.
- Our share of publications in top 20% journals is considerably higher than average.
- Our share of Swedish non-university co-publications is low.
- Our share of international co-publications is high.

DiVA publication type	2012	2013	2014	2015	2016	2017	2018	Total	WoS c.
Article, peer review	55,7	57,6	67,3	62,7	56,7	64,5	68,1	432,5	91,9%
Article, other	4,3	4,8	2,3	1,5	0,5	0,7	1,3	15,4	95,7%
Conf. paper, p. rev.	10,9	6,9	11,5	12,8	5,6	10,0	8,7	66,4	54,0%
Conf. paper, other	0,3	0,3		0,3		0,5		1,3	25,0%
Book	0,5	1,0	0,3					1,8	0,0%
Chapter in book	2,0		2,3	1,0		6,7	1,0	13,1	18,4%
Article, book review	1,0							1,0	0,0%
Report	6,2	2,0			1,0			9,2	0,0%
Doctorate thesis	8,0	6,0	11,0	13,0	11,0	5,0	9,0	63,0	0,0%
Licentiate thesis	1,0	7,0	6,0	3,0	2,0	1,0	3,0	23,0	0,0%

Table 1 - Publications in DiVA, fractional counts

DiVA publication type	2012	2013	2014	2015	2016	2017	2018	Total	WoS c.
Article, peer review	89	94	111	110	103	112	121	740	91,4%
Article, other	6	7	3	3	1	1	3	24	95,8%
Conf. paper, p. rev.	21	16	19	20	11	20	15	122	50,8%
Conf. paper, other	1	1		1		1		4	25,0%
Book	1	1	1					3	0,0%
Chapter in book	2		3	1		13	1	20	15,0%
Article, book review	1							1	0,0%
Report	10	2			1			13	0,0%
Doctorate thesis	8	6	11	13	11	5	9	63	0,0%
Licentiate thesis	1	7	6	3	2	1	3	23	0,0%

Table 2 - Publications in DiVA, full counts

Publ. year	Publ.	Total Cit.	Ave. Cit.	P uncited	Share uncited
2012	61,2	87,7	1,4	28,6	0,5
2013	61,6	90,0	1,5	31,6	0,5
2014	68,9	125,6	1,8	30,6	0,4
2015	64,4	107,3	1,7	28,9	0,4
2016	58,5	92,0	1,6	24,5	0,4
Total	314,6	502,7	1,6	144,1	0,5

Table 3 - Citations 3 year window, fractional counts

Publication years	Publications	Average Cf	Top 10% pubs	Share Top 10%
2012-2014	166,0	0,89	14,0	8,5%
2013-2015	173,0	0,99	17,3	10,0%
2014-2016	174,7	0,94	16,6	9,5%
2015-2017	172,7	1,08	20,4	11,8%
Total	338,7	0,98	34,4	10,2%

Table 4 - Publication impact, fractionalized (3-year moving average)

Publ. years	Publ.	Ave. J. Cf	Pubs in Top 20% J's	Share Top 20% J's
2012-2014	166,0	1,22	45,3	27,3%
2013-2015	173,0	1,27	52,8	30,5%
2014-2016	174,7	1,26	58,5	33,5%
2015-2017	172,7	1,26	56,9	33,0%
2016-2018	170,9	1,25	57,8	33,8%
Total	395,8	1,24	121,9	30,8%

Table 5 - Journal impact, fractionalized (3-year moving average)

Publ. years	Publications	Swe. non-univ.	Share	Internat.	Share.
2012-2014	263	13	4,9%	144	54,8%
2013-2015	287	13	4,5%	171	59,6%
2014-2016	297	9	3,0%	187	63,0%
2015-2017	301	13	4,3%	197	65,4%
2016-2018	298	17	5,7%	195	65,4%
Total	665	33	5,0%	406	61,1%

Table 6 – International and Swedish non-university co-publications, full counts (3-year moving average)

2e. Engagement in national and international research collaboration within academia and its outcomes

The members of the Department of Mathematics all have more or less extensive international connections, and the majority of research is done in international collaborations. Newly recruited faculty are mainly external, and they all have established international networks. This makes the research environment at the department truly international, open to new influences, and constantly focused on relevant problems. To give a complete list of all the international collaborations is not possible since each faculty member has co-publications with researchers from at several different universities around the world.

The Knut and Alice Wallenberg Foundation Program for Mathematics, supporting guest professors and postdocs, has been very important for the department. This program has enabled several leading mathematicians to spend longer periods of time at the department, and added to the large and thriving postdoc community at the department.

The national perspective is less important, but there are still a large number of examples of fruitful connections, for example with mathematicians at Stockholm University, Lund University, Linköping University and Chalmers University.

The department is involved in a number of interdisciplinary centres that has resulted in funding for PhD students and postdocs. Some examples are

- **MedTechLabs** run by KTH, Karolinska institutet, and Region Stockholm,
- **SeRC** - the Swedish e-Science Research Centre, a collaboration between KTH, Karolinska institutet, Stockholm University, and Linköping University,
- The **Brummer & Partners MathDataLab**, at our own department,
- The Linné centre **FLOW**, with Department of Engineering Mechanics at KTH,
- The VR centre **Interface** (with Department of Engineering Mechanics and Department of Fibre and Polymer Technology at KTH),
- The Linné centre **ACCESS** (with School of Electrical Engineering and Computer Science at KTH)
- **CAS** - The Centre for Autonomous Systems with the School of Electrical Engineering and Computer Science at KTH.

In addition the department is a partner in the EU COST action network **EU-MORNET** on model reduction methods, and the Stockholm Mathematics Centre (**SMC**).

The faculty members of the department participate in, and organize conferences and workshops of many kinds. Unfortunately it is complicated and expensive to host such events at the department, so local activities are not so frequent as could be wished. Particular examples are research semesters at Institut Mittag-Leffler. The past years there have been several such programs co-organized by members of the division. Also programs at MSRI and other research institutes have been co-organized by our faculty members.

2f. Follow up from previous evaluations

In the RAE 2012 each division within the department was a separate unit of assessment and therefore we present the follow up separately for each division. The assessment in general was very positive for the whole department.

The Division of Mathematics was suggested to secure stable funding to increase the size of the PhD program and to ensure that the associate professors have sufficient time to develop their research program. Unfortunately, we have not been able to secure stable funding for the PhD program that is more than ever depending on external funding. The internal funding for research has since then been more evenly distributed among the faculty members so that the difference between the conditions for full professors and associate professors is much smaller than before, but still our younger faculty members need to be successful in winning awards and grants in order to provide more time for research.

In addition, it was suggested that KTH should work together with the Division of Mathematics to create an undergraduate mathematics major. This has finally been realized in collaboration not only with all the units of the department but also with part of the School of Electrical Engineering and Computer Science. In 2020, KTH launches the five-year program in *Engineering Mathematics* that will be further described in §5.

The Division of Mathematical Statistics was suggested to "*hire additional professors to increase the size of this unit, to increase the productivity and international visibility of this group*". Moreover, it was suggested that "*further adjunct positions for industrial mathematicians should be created*'" Since RAE 2012, the division has lost two full professors (T. Koski and T. Rydén) and three associate professors (F. Lindskog, G. Englund, and H. Lang). Of these, three retired. One associate professor has been promoted to full professor (H. Hult). On the other hand, during the same time period the division has recruited five associate professors (J. Olsson, A. Janssen, P. Nyquist, S. Källblad, and J. Andén[1]) and 1.5 assistant professors on tenure track (T. Önskog and K. Schnelli, who is shared with the Mathematics division). Therefore, the size of the division is only about one full-time position larger than in 2012. Still, the new division members, who are relatively young, have strong research records, good international visibility, and potential to be promoted to full professors. Concerning adjunct positions, the Mathematics department has recently announced 2 such positions, of which one is intended for the Mathematical Statistics division.

It was also suggested that the Division of Mathematical Statistics should "*formulate a clear and realistic strategy for its future development*". As a subject, mathematical statistics is currently undergoing major changes. As established in the division's self-evaluation in connection with RAE 2012, "*the 21st century will be characterized by complex multidisciplinary problems accompanied by massive data sets and information technology*", which poses a challenge to every statistics department in

[1] Joakim Andén will start his position in the division on 1 March 2020.

the world, "*as there are many categories of researchers outside the cadre of professional statisticians willing and able to become active in large complex data sets*". In this development, the division's intention is to distinguish itself from other actors by keeping a clear focus on the mathematical—or inferential—aspects of complex data science. When it comes to the activities of the department, this is not only visible through the recruitment of expertise in data science (most recently an associate professor, J. Andén, with focus on model-driven machine learning), but also through a gradual change of the internal research and educational focus towards machine learning and artificial intelligence (as seen above), also in connection with the Brummer & Partners MathDataLab.

For the Division of Numerical Analysis, the panel noted that stable funding is critical to growth and improvement, but besides strongly advocating that the numerical analysis group move to the Department of Mathematics, it gave very few specific recommendations. One small suggestion was that the Division of Numerical Analysis should make a greater effort to interact with the general public. This has been done e.g. with a project to provide high schools with mathematics oriented programming problems.

The main recommendation for the Division of Optimization and Systems Theory was: *"The unit clearly needs more professors, but this hiring must be accompanied by a clear and realistic strategy for the future ... This unit, ..., has great potential for continued achievement in research and applications. Their future success critically depends on their ability to grow and to attract high quality faculty".*
Unfortunately, the growth issue has become even more critical now than eight years ago. We recruited one new assistant professor in 2013. In 2016 we had an unsuccessful recruitment process for an assistant professor where the excellent female candidate who was offered the position declined. The process for a new recruitment has started and we hope this would be the first step in remedying this problem.

3. Viability

3a. Funding; internal and external

During the period 2013-2020, the internal funding for research has been stable and slightly decreasing. On the other hand the external funding has been increasing drastically and is expected to be 2.5 times as high in 2020 as it was in 2013. Thereby, the balance between internal and external funding has been switched in favour of the external funding. See Table 1 and Figure 1 below. New developments that have led to this shift are the start of the *KAW Mathematics Program* in 2013, the start of the *Wallenberg AI, Autonomous Systems and Software Program* (WASP) in 2014 and the creation of the *Brummer & Partners MathDataLab* in 2017.

Year	2013	2015	2016	2017	2018	2019
External Research Funding (MSEK)	29.0	30.0	39.5	45.0	50.0	60.0
Internal Research Funding (MSEK)	46.4	42.7	41.6	44.0	42.7	43.0
Total Research Funding (MSEK)	**75.4**	**72.7**	**81.1**	**89.0**	**92.7**	**103.0**

Table 7 - Balance between internal and external research funding

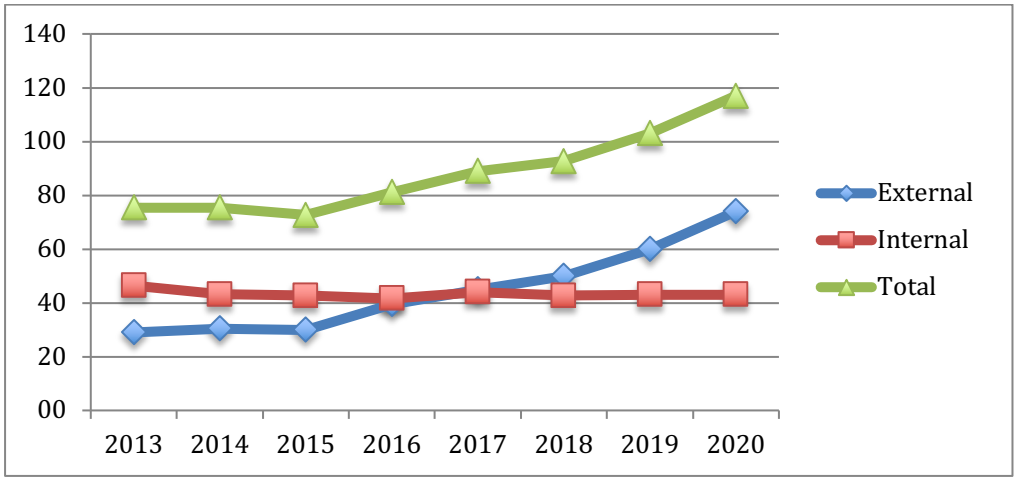


Figure 1 - Balance between internal and external research funding

The main source for the external funding in 2013-2019 has been the Swedish Research Council (VR). In 2020 we expect that the funding from KAW (Knut and Alice Wallenberg Foundation) will dominate. See Table 2 and Figure 2 below.

Year	2012	2013	2014	2015	2016	2017	2018	2019
VR	21.1	17.2	18.8	19.6	27.7	25.4	26.0	21.8
KAW	5.1	5.0	5.4	5.4	6.3	8.2	10.2	18.2
SSF	2.3	1.3	0.8	2.2	1.5	2.2	5.0	6.5
EU					1.3	2.7	3.0	4.6
GG	1.6	2.8	2.9	1.9	1.9	3.9	3.0	3.4
SU	1.2	0.7	0.9					
Total	31.3	27.0	28.7	29.0	38.6	42.4	47.2	54.5

Table 8 - Five most prominent external funding sources for research

Observe that some external funding is missing from the last years even though it would have been one of the five largest in the earlier years. One example is Brummer & Partners MathDataLab where the funding is almost 3 MSEK for 2019.

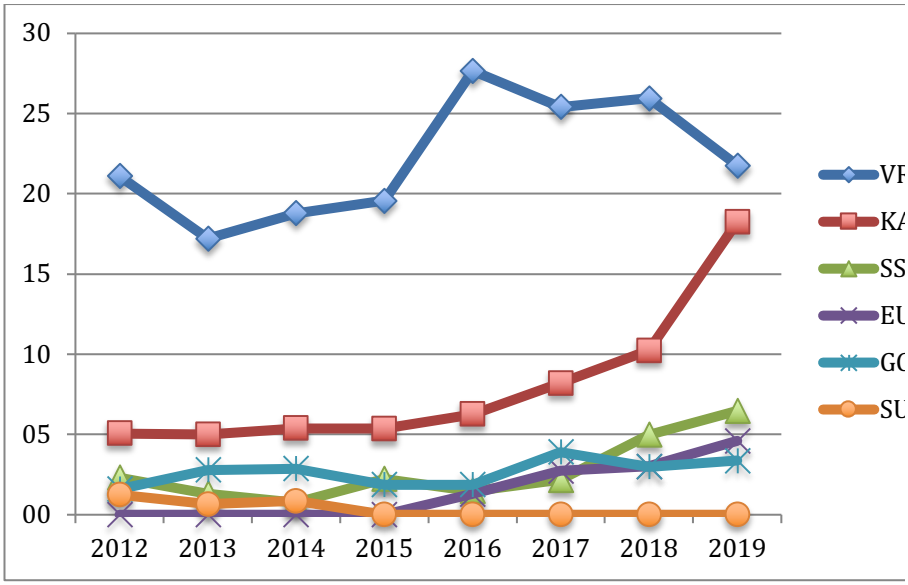


Figure 2 - Five most prominent external funding sources for research

In 2015 a donation for research at the department was given in the name of Brummer & Partners. This donation was established in collaboration with KTH Fundraising. In the initial setup the donation from Brummer & Partners was supposed to be used for a named professorship. However, recruiting a professor at this level turned out to be hard and instead the donation made it possible to start the Brummer & Partners MathDataLab that is focusing on research on complex data. It is a new phenomenon for the department to have research funding donated directly to the department. Most of the external funding which is not from the research council comes from foundations that are based on donations, like the Knut and Alice Wallenberg Foundation (KAW) and The Göran Gustafsson Foundation (GG). Further work has been done in collaboration with KTH Fundraising in order to explore if there are other similar opportunities for research funding in the future.

3b. Academic culture

The research in mathematics is performed in an international context where meetings are essential for the development.

Research seminars, reading groups etc

The department has a large number of regular seminar series, some of which are organized jointly with the department of mathematics at Stockholm University. Examples of such series are

- Algebra and geometry
- Analysis
- Random matrix
- Number theory
- Combinatorics
- Numerical analysis
- Mathematical statistics
- Optimization and systems theory

In the most active seminar series we have had 30-40 seminars per year.

Within some research groups there is a tradition of arranging reading groups in order to learn new techniques. Recent topics have been *AI*, *Machine learning*, *Lurie's higher algebra* and *Derived algebraic geometry*.

Conferences and workshops

Within the Stockholm area there are a number of conferences and workshops arranged every year. Many of them have members from our faculty on the organizing committee and most of them have several participants from our department. There are a number of conferences organized at Institut Mittag-Leffler in Djursholm and also symposia organized by the Royal Academy of Sciences (KVA).

Research programs at international research institutes

There are several international research institutes where our faculty take part in longer or shorter research programs. Some examples are MSRI, MFO and BIRS. Several members of our faculty have spent sabbaticals or longer research visits at such institutes and some faculty members have been part in organizing programs and conferences at these institutes. There are also several members that have been involved in research in pairs programs at various institutions.

Guest researchers at KTH

We have every year several long-term visitors to our department. In particular, during the last six years we have had nine guest professorships financed by the KAW Mathematics program.

- Professor Robert Bruner, Wayne State University, Detroit, USA
- Professor Gernot Akemann, Bielefeld University, Germany (2019)
- Professor Gregory G. Smith, Queen's University, Canada (2018)
- Professor Bassam Fayad, Université Paris Diderot (2017)
- Professor Alfonso Montes Rodriguez, Universidad de Sevilla (2016)
- Professor Alicia Dickenstein, Universidad de Buenos Aires (2016)
- Professor Arno Kuijlaars, KU Leuven (2016)
- Professor Michael Siegel, New Jersey Institute of Technology (2015)
- Professor Lars Andersson, Max Planck Institute for Gravitational Physics, Germany (2014)

Research platforms at KTH

Since some time, KTH has developed a number of cross-disciplinary research platforms. The department has been involved in some of these platforms, in particular in the Life Science Technology platform where Ozan Öktem has been the vice director (2012-2016) and later the director (2016-18).

Institut Mittag-Leffler

The department has a very close connection with the international research institute Institut Mittag-Leffler in Djursholm. Over time, several of our faculty members have been part of the leadership at the institute. Hans Ringström is currently the vice director and previously, Ari Laptev, Anders Björner and Dan Laksov have been directors. Several of the semester long programs have had faculty members from our

department on the organizing committee with the most recent example the program on *Algebraic and enumerative combinatorics* during spring 2020 with our professors Petter Brändén and Svante Linusson as two of the organisers.[2] In relation to these programs there have been some conferences organized at KTH. The institute also have summer workshops since a few years and many of them have had organizers and participants from KTH.

PhD programs

Within our PhD programs there are several important meetings where research is in focus. The most important meetings are the regular supervision meetings. These meetings can be between a single PhD student and their supervisor or in a group where one supervisor meets with a several PhD students.
In the PhD program in Applied and Computational Mathematics there are yearly PhD presentations where the PhD students present their research to several members of the faculty. The PhD students organize the graduate student seminar, which is a weekly seminar where PhD students present their field and their research to other PhD students with no faculty attending. This is organized in collaboration with the PhD students in Mathematics at Stockholm University.

3c. Current faculty situation

	Female	Male	Total
Professor	2	19	21
Associate Professor	10	18	28
Assistant Professor	3	3	6
Lecturer[3]	1	2	5
Total	**16**	**42**	**58**

Table 9 - Gender distribution among faculty members

	Female	Male	Total
PhD student	11	36	47
Postdoc	6	13	19
Researcher	1	11	12
Research engineer	1	1	2
Total	**19**	**61**	**80**

Table 10 - gender distribution among PhD students, postdocs and researchers

In recent years, recruitments have been done at the assistant and associate professor levels only. As the department has a need for teachers we have to balance between assistant professorships, where the initial five years have limited teaching and associate professorships.

[2] This program did however unfortunately have to terminate early due to the Corona virus
[3] Universitetsadjunkt

3d. Recruitment strategies

The recruitment strategies of the department of mathematics have several priorities. One of our priorities is to employ strong promising researchers who have the potential to contribute substantially to the development of their research areas. At the same time, we believe that collaborations and interdisciplinary research are fundamental to progress in mathematics and its applications, and another priority is to employ researchers with expertise in areas bridging several research groups. Teaching at all levels at KTH is a very important task for our department. It is both a necessity and a strength that all faculty members are involved in teaching at engineering programs and masters programs with a wide variety of students. A further priority when recruiting is to find new faculty with knowledge, talent, and enthusiasm for teaching and supervision. This might sound like competing priorities; luckily this need not be the case. In past recruitments we have been remarkably successful in fulfilling these separate priorities. We are very happy over the fact that so many talented mathematicians are interested in working at KTH.

The department has had several retirements during the past 10-15 years, both at the level of associate and of full professor. Due to the financial constraints and our recruitment strategy, we are still in the process of building the department to the size it needs to be for all teaching and research duties that we have. Recent employments have all been at the assistant or associate professor level. KTH has a tenure track system, which we value as the most appropriate way for recruiting emerging talents and fostering their development within KTH.

In recent years, all recruitments of faculty members, post docs, researchers and PhD candidates have been done internationally with a large number of applicants. It has been a strategy to give the positions a broad profile in order to achieve high competition. In order to increase the number of female faculty members, we have had three cases where we have been able to hire two faculty members instead of one, in order to hire more women. Our faculty members have very active international networks, which we use to find and encourage female mathematicians to apply to our open positions.

As an example of a recent recruitment, we would like to mention the hiring of four assistant professors initially funded by the Wallenberg WASP initiative. They will be part of a new division at the department where pure and applied mathematicians together explore the important areas of artificial intelligence, machine learning, and further mathematics necessary for new generations of computer applications. These four work interdisciplinary, and have already made connections between different research groups at the department.

Another example of a recent recruitment is the hiring of two associate professors at the division of mathematics. We had the great luck to be able to hire two exceptionally strong mathematicians. Unfortunately, after less than a year, both of them have left the department. With the international competition for the most excellent researchers, we have to realize that situations like this will sometimes occur. We need

to provide faculty support and other initiatives that will increase the chances of retaining successful hires so that they stay and build their careers at KTH.

3e. Infrastructure and facilities

The main needs for physical infrastructure within the research at the department are for office space, seminar rooms, library access and computing.

During the last decade, the department has grown in terms of faculty, PhD students and postdocs. Since the division of numerical analysis moved in, we have rebuilt the mathematics library into office space and one seminar room. The remaining two seminar rooms have been transformed into office space for postdocs. Part of our teaching administration has moved to join the central administration at the school level. Still we have trouble in finding enough office space. This has lead us to move our emeriti professors into offices that are not suitable as working spaces for more than a few hours per day. In order to continue to be an attractive department we will have to find ways to increase the availability of office space. This problem will become even more critical if our external funding continues to increase.

Regarding computing resources the department has four small compute servers located at the department but the main needs for large-scale computations are covered within centres that are used for large-scale computations, e.g. SNIC (www.snic.se) and PDC (www.pdc.kth.se). Our four compute servers have slightly different characteristics; one with a high core count, one with a large memory, and two that are GPU accelerated. The two GPU accelerated servers are mainly used for machine learning and any member of the department in need of higher processing power is given access. M.Sc. students are also granted access when needed if their projects are supported by members of our faculty.

4. Strategies and organization

4a. Goals for development 5–10 years ahead

Overall visions

In 5-10 years the department aspires to

- be an internationally leading research environment in an increasing number of subjects within the mathematical sciences,
- have an international visibility that together with a reputation as an excellent working environment makes it a top choice employer.

In order to achieve these overall visions, we break them down into goals in three categories: research environment, faculty development and international visibility. We will also discuss how to reach these goals and how they relate to the development areas discussed in Section 1a.

We do not here specifically discuss different research areas, except for one important exception, which is mathematics for artificial intelligence and machine learning. This

is a field that has grown, and will continue to grow, rapidly. It does not belong to one division of the department but involves many sub-disciplines in the department and is a great opportunity to increase the collaboration within the department, as was highlighted in section 1a. This will be discussed at the end of this subsection.

Research environment and faculty development

The goals in the two areas of research environment and faculty development are discussed jointly, since the goals as well as the strategies to reach these goals are tightly connected.

Research environment

Our goals are to be

- A vibrating research environment with many natural meeting places where research is discussed and disseminated.
- A department that continues to have a large proportion of faculty engaged in research, with a range from researcher initiated research to multidisciplinary collaborative projects.
- A department that has maintained a high level of external funding, allowing for a research intensive environment.

Faculty development

Our goals are to be

- A department that is, and has a consistent history of, hiring excellent faculty with a gender balance, such that the overall ratio of women to male faculty continues to increase.
- An attractive working place for everyone that allows for many personalities, and allows each individual to develop optimally.
- A working environment based on open-mindedness, curiosity and respect.

As has been described earlier in the text, the department has seen a substantial development since RAE2012. Many excellent hires have been made, including many with an international background and a good proportion of females (see section 1a). A rapid increase in external funding unprecedented in the history of the department has allowed the department to become more research intensive, including also a large body of postdocs.

In the two development areas (see section 1a) “increased internal collaboration” and “build on strength with more research active faculty” we outline measures that will be important for further advancement to reach the goals related to research environment. “Further development of recruitment practices” is discussed as one development area in 1a and relates to faculty development above. The softer goals are partly also targeted through research, as discussed with “increased internal collaboration”, and the division structure was pointed out as having a positive effect on the working environment. However, there are many different activities at the department that contribute to the softer goals.

We do believe that we already at the current stage to a large extent have a working environment that is based on open-mindedness, curiosity and respect, and that has room for many different personalities. We however need to constantly stay alert and further improve. As the department becomes more heterogenous with new hires, we must make sure both that these new faculty members receive the support they need to be well integrated into the department, and that it is naturally acknowledged that diversity is enriching the department. Here, it is important that the leadership at the department take an active role.

To recruit well and to be an attractive working place, we also need to be able to provide good working conditions, such as sufficient time for research. The limitations due to our internal funding situation were discussed at the end of section 1a, and we work hard to mitigate its impact.

International visibility

Our goals are to

- Increase the number of shorter and longer sabbatical visits for our faculty.
- Further increase the number of sabbatical visitors to our department.
- Enhance local collaboration in the Stockholm area to highlight the research strengths of the region, hereby building a joint visibility.

International visibility can be achieved in many different ways. Highly cited publications and key note lectures at international conferences are two important contributions, prestigious prizes yet another. The base for this is of course that we produce excellent research, where we do set our goals high. There are however also other factors that contribute to international visibility and reputation, and in our strategy as outlined here we focus on activities that we can influence more directly.

The QS World Ranking by Subject ranks our mathematics department as number 38 in the world this year and as number 44 last year. The QS ranking compiles four sources. The first two assess the department's international reputation in mathematics; the next two evaluates the research impact by citations and the h-index based on Elsevier's Scopus database. The aim of the QS ranking is to provide information to students regarding the value and quality of degrees from different universities, and hence, the international reputation is important also here.

This ranking indicates that we have a strong international reputation today, that we want to enhance further. Recent awards to the faculty members include the EMS prize (Sara Zahedi 2016), the Gödel-prize (Johan Håstad 2011) and the Knuth-prize (Johan Håstad 2018). Five members of our faculty have been invited speakers at the International Congress of Mathematicians (ICM)[4]. One faculty member (Lenells) has an ERC consolidator grant and one faculty member has an ERC consortium grant (Chacholski together with KI). Some of our faculty members have key assignments in international boards.

[4] Anna-Karin Tornberg, Hans Ringström, Kurt Johansson, Johan Håstad, Anders Szepessy

International doctoral students and postdocs are also important for our international reputation and visibility, as they function as ambassadors for KTH as they disperse out in the world. The number of postdocs in the department has increased substantially in the last years, and the number is currently over 30. A vast majority of these individuals are from outside of Sweden. This has become possible due to the high level of external funding that we have been able to attract. Hence the goal listed under "research environment" to sustain the current level of funding is important for the international visibility not only in that it allows us to write more excellent research papers, but also in building this body of international researchers with strong ties to KTH.

International visibility as well as research quality benefit also from mobility of more senior researchers. We have in recent years had a number of guest professors visiting the department as funded by the KAW mathematics program (see section 3b), and we plan to encourage our faculty to be even more active in applying for such funds. We also want to increase the number of sabbatical visits made by our faculty. There have previously been no internal funds to support this, even though sabbaticals have been arranged on a case to case basis with other means. KTH has now started a sabbatical program, albeit still on a small scale, recently extending it such that it can cover costs of salaries and not only travel costs. Only a few of our faculty have so far attempted to take advantage of this program. We plan to investigate how we can enable future sabbaticals for a larger part of our faculty.

With our focus to maintain high visibility promoted by fruitful interactions, we aim also to extend our long term collaboration with Stockholm University (SU) and Institute Mittag-Leffler and support more interaction with Karolinska Institutet (KI). This is in line with the university alliance "Stockholm trio" between KTH, SU and KI that was founded in 2019 and aims to highlight the excellent research environment that the three universities constitute together.

Mathematics for AI and Machine Learning

Today ubiquitous computer-dependent processing algorithms allow enormous amounts of data to be collected, and the impact of artificial intelligence (AI) and machine learning (ML) on the society is profound. This has allowed a new field, data science, where mathematics and computer science meet, to flourish. In today's data science, algorithmic thinking is emphasized, while the *inferential analysis*, i.e., the assessment of the accuracy, of these often very innovative algorithms is typically sidelined, as this analysis requires generally a higher, far more advanced level of mathematical consideration. Such an analysis is essential and indispensable for any AI or ML procedure running in practical applications. Indeed, a rapidly growing amount of scientific research involves the development of ML-based predictive models on the basis of large — and often costly — standard data sets circulating in the scientific community. In this research, focus is typically entirely on an ML-algorithm's predictive performance for the data at hand and not on the statistical accuracy of the estimator. Without well-founded understanding of the algorithms involved it is difficult to give guarantees for the quality of the obtained results and to avoid that

anomalies in the data lead to spurious results. Thus, without doubt the coming era of massive data will require new solutions and theories ensuring a sound basis for the recent spectacular algorithmic developments.

In this environment, where many categories of researchers are willing and able to become active in large, complex data sets, the strategy of the Mathematics department is to maintain focus on the inferential aspects of data science. By addressing questions like: *What can be learned efficiently? What is hard to learn?* and *How much data is needed to separate the signal from the noise?*", the goal is to provide a mathematical logic for reliability, guidance, and correction. This attitude is illustrated by the department's on-going active research in probability theory, generative models, computational and high-dimensional statistics, time-series analysis, graphical models, inverse problems, optimization, numerical analysis, complexity analysis, and topological data analysis.

By bringing all this expertise together, we aim for a strong standing internationally in this growing but very competitive field. The external funding provided through the WASP initiative for assistant professors, postdocs and PhD students, together with the enabling activities of the Brummer and Partners Math Data Lab give us an opportunity to reach a critical mass in this research field through a combination of new recruitments and activation of already available internal expertise.

4b. Congruence with university-level goals for research as set out in "A leading KTH - Development Plan 2018-23" and with the school(s) development plan(s) respectively.

We have gathered five quotes from the development plan for 2018-23 *A Leading KTH* that have a relation the goals for research of our department.

"Research breakthroughs sometime come when one least expects them. It goes without saying that basic and curiosity-driven research has a place at a technical university together with applied and commercial research. KTH has world-class research expertise in a number of fields and this must be more clearly highlighted both externally and internally."[5]

It is indeed impossible to predict when and where research breakthroughs will occur, but the vision formulated by the department is an enabler for groundbreaking research: to have many excellent researchers in a thriving and open research environment, involved in a range from researcher initiated research to multidisciplinary collaborative projects.

The department does have world-class expertise in a number of sub-fields, and is determined to strengthen and broaden that position. With this, combined with its ambition to create more visibility it aspires to further contribute also to "a visible KTH":

[5] *Leading Research* from Development Plan 2018-23

"A visible KTH contributes world-class research in more fields, and is associated with this internationally and nationally"[6]

International visibility can be enhanced by international mobility. This includes PhD students and postdocs that moves from KTH to other countries, professors from international institutions that are hosted on sabbaticals and our own faculty that undertake sabbaticals. In addition to visibility, exchanges also give exposure to new ideas which can further increase the quality of research at the department. Hence, such activities must be encouraged as part of the departments overreaching goal, in line with "A KTH in a global world":

"Teachers and researchers should be active internationally. International mobility among teachers and researchers must be encouraged. Sabbaticals at overseas universities form part of the faculty's skills development, both with regard to education and research."[7]

The next two quotes are essential to the vision of the department. To attract the very best, we need not only to be internationally visible with outstanding research, we must also be known to provide a working environment where all employees can develop and thrive. The quotes come from an "open KTH" and an "equal-opportunities KTH":

"An open KTH offers a good work environment characterized by openness and skills development"[8]

"An equal-opportunities KTH enjoys a more even distribution of women and men within the organisation and on decision making bodies "[9]

As more women have been recruited to the department, the gender balance is slowly improving, and it is a important goal that it should continue to do so. However, as noted in the strength and weaknesses discussion, there are still few females on the senior level. Even if the department has a strong will to include more women in decision making bodies on the department level and above, it must be balanced with the need to "protect" younger faculty to allow them time to develop and build their merits in research and teaching.

Another theme in the development plan is "An integrated KTH". This is a mindset that is very natural for our faculty, both in terms of "one KTH" as we teach students all over KTH, as well as in terms of integration between research and teaching. Education is extremely important to the department, even though it is not discussed extensively in this research assessment. Hence, we closely adhere to the overall goal for KTH:

---

[6] *A visible KTH* from Development Plan 2018-23
[7] *A KTH in a global world* from Development Plan 2018-23
[8] *An open KTH* from Development Plan 2018-23
[9] *An equal-opportunities KTH* from Development Plan 2018-23

"An integrated KTH recruits and employs teachers who combine great dedication to teaching with world-class research"[10]

We are proud of how well we have succeeded with this in our recruitments since the last RAE. We have not specified this as a future goal, but will certainly continue to have this as a central guideline.

4c. Leadership structure and collegial structure

The formal leadership structure consists of

- One department head (prefekt) (Mats Boij)
- One department vice head (proprefekt) (Anna-Karin Tornberg)
- Five division heads – one for each division (Mattias Dahl, Xiaoming Hu, Johan Håstad, Jimmy Olsson, Anna-Karin Tornberg)
- One vice division head for the largest division (Division of Mathematics) (Svante Linusson)

The department has a leading group consisting of the head of the department, the heads of the divisions, the director of studies, the administrative head and one student representative.

The division of Numerical Analysis joined the department just prior to the last research evaluation (RAE 2012), with that move consolidating mathematical sciences within the same department at KTH. The department has adapted to that move with a range of measures, from practical issues such as reassignment of offices to achieve a good mixing of faculty to successive organization changes involving e.g. the director of studies and teaching assignments.

There have been recent changes in the leadership of the department. Sandra Di Rocco was the department head 2012-2019 and Boualem Djehiche the department vice head 2014-2019. It is a temporary situation that Anna-Karin Tornberg is remaining as division head for the Division of Numerical Analysis while being department vice head. The leadership structure of the department is under revision and we plan to come up with a new structure that will start in July 2020. The self-evaluation will be used as a basis for this revision.

Our research groups do not have formal leaders but are formed around common research interests, collaborations and research seminars.

The Brummer & Partners MathDataLab has a scientific steering board and a director, Prof. Henrik Hult. The board consists of the department head and the director together with external advisors that have been appointed as affiliated professors, Prof. Per-Gunnar Martinsson (Oxford) and Prof. Konstantin Mischaikow (Rutgers).

[10] *An integrated KTH* from Development Plan 2018-23

4d. Strategies for high quality

The main resources for funding of research are external and they are distributed through national and international peer-review committees based on the applications of our faculty. Internally, all members of our faculty are encouraged to apply for external funding both nationally and internationally. We are also open for many junior researchers that are not members of our faculty that apply for starting grants through VR (Swedish Research Council) even though this does not lead to permanent positions within the department. This has led to several such grants in the past. In order to be competitive in their applications, our faculty members need to maintain a high profile research program with publications in prestigious journals. Attempts have been made to offer collegial feedback on applications in order to improve even more on the success rate but few members have made use of this offer. We plan to make new more ambitious attempts to provide support for our faculty when applying for larger grants such as e.g., an ERC starting grant or consolidator grant.

Our quality assurance system includes policies and strategies for sustaining and developing quality of research and societal impact, such as international recruitment, faculty renewal, and collaboration with stakeholders in the society. We should point out that quality is also periodically reviewed by the Swedish Higher Education Authority.

The department's strategy in the recruitment is important for the quality of research. We make our uttermost to hire excellent researchers with a strong capacity of producing high qualitative research. An important part of the department strategy is also trust. We trust the researchers to know which problems in their respective areas that are most important to work on and feasible to tackle.

Large funding agencies, such as VR, already demand that all research is made available through open access. It is also in the interest of the individual researcher to spread their work as much as possible. Mathematicians often publish their papers as preprints before they are accepted on their own homepage and on arXiv.org. This means that we already have a good dissemination through open access. We could make this a department policy that everyone is expected to do this, to get that last paper out there as well.

5. Interaction between research and teaching at all three levels (BSc, MSc, PhD) of education

We strongly believe that education and research are tightly connected. This connection is more obvious at higher levels but it is present also on the bachelor level. It is our stated goal, which we mostly fulfill, to have active researchers as teachers in all our courses. In particular, it is important that mathematics courses are, with few exceptions, given by the mathematics department. This is mostly the case in KTH today and considering the quality of mathematics education, it should remain that way.

A fundamental feature of mathematics is the permanency of the subject. This is naturally reflected by the fact that material contained in the first year courses only changes slowly and is quite similar even in an international perspective. An active researcher may, however, give small glimpses of modern mathematics also in basic courses and offer a perspective on the material not shared by teachers without this background.

In more applied areas the connection is more immediate and the best example might be the new track *Mathematics for Data Science* within our master program in *Applied and computational mathematics* that is tightly connected to our research programs. The high level understanding of researchers is also important in the construction of new programs to get a good mix of courses. Here we would like to mention the new five-year program *Engineering Mathematics* that will start receiving students in the fall of 2020 and has been designed totally from scratch. We are very proud of this program and we are confident that it will become the flagship program of our school. Recent figures from the first application round shows that this has been an extremely successful launch of a new program with over 300 first hand applicants for 30 places.

Our mathematics education at a glance

The main contribution of our department in the educational efforts of KTH is through the basic courses in mathematics, mathematical statistics and numerical methods that are vital parts of all of our five-year engineering programs. We have over 1500 new students yearly on these programs and we contribute with about one semester of their curriculum.

Programs that are closely related to the department are

- The 5-year engineering program in **Engineering Mathematics** with 30-40 students yearly starting in 2020.
- The master program in **Mathematics** in collaboration with Stockholm University started in 2011 and currently has 15-30 students yearly.
- The master program in **Applied and Computational Mathematics** started in 2011 and has an increasing number of students, currently over 100 students yearly.
- The doctoral program in **Mathematics** with 5-6 new students yearly
- The doctoral program in **Applied and Computational Mathematics** with 5-6 new students yearly

We will briefly describe these programs and for each of them comment on the research and training interactions that are relevant. In addition we list strengths and weaknesses. At the end we also comment on the BSc and MSc theses.

The five-year program Engineering Mathematics, CTMAT

Background.

This new program will start in the fall 2020. Its start shows one of the most important aspects of the connection of research and education at our department, namely to

see the need for new competence and have faculty members with broad scientific experience setting up a program that provides relevant university education. It is particularly interesting for our department to initiate and continue to develop this program.

Research and teaching interaction.

The new program in Engineering Mathematics will have a seminar series where invited researchers give presentations about their research for the students in the program. The research seminar series provides the students with an opportunity to hear from researchers at the department as well as visitors and gives an opportunity for the students to meet and discuss with researchers. The program also includes the basic course SA1006 *Ingenjörsfärdigheter i Teknisk matematik*, where different companies will be invited to give lectures on how they use mathematics and programming in their work and research. Students will within the course also study and lead smaller research projects that relates to the research that is done at the invited companies.

The master program in Mathematics, TMAKM

Background.

The master's Program in Mathematics is a joint initiative of the Mathematics Departments of Stockholm University (SU) and KTH. Students follow courses at both universities and several of the core courses are shared, meaning that they have two teachers, one of each university. The general purpose of the program is to give students an opportunity to deepen their theoretical knowledge in mathematics. In the beginning of the program the students study mandatory courses in analysis, Algebra & Geometry, Topology and Discrete Mathematics. After that the students are given plenty of freedom to choose their own specialisation, with 45 hp credits for elective courses and 30 hp for a degree project. Many students view this as a strength of the program and show maturity in selecting their course package, often with help from the degree project advisor or the programme directors.

The number of students that start each year in our program has more than doubled the last years. Where 5 years ago around 10-15 students started the program, this number has increased to around 30 in the last two years. There are three sources of potential students: the undergraduate program at SU, the CTFYS program in Physics at KTH, Engineering Mathematics and students from outside Stockholm. In recent years, the number of foreign students has increased significantly.

In a survey distributed amongst the student in our program in the fall of 2019, the students were asked what their primary reason was to study this program. More than 50% of the students answered that they aspired an academic career. Most students found the possibility of designing their own profile through many elective courses, very attractive. Several of our students are successful in getting a PhD position in Sweden or abroad.

Research and teaching interaction.

The obvious benefit of having a joint program is that it combines the strength and expertise of two departments. Through that we are able to offer a variety of

interesting courses for the students, while sharing the costs. In the core course in our program, we made a strategic choice of having teachers from both departments. This brings the students into contact with more researchers that would otherwise be possible: researchers that are potential advisors for the degree projects.

Apart from core courses in the program we offer more specialised courses that are designed to reflect the research interests and activities at our departments. Examples of that are Chaotic Dynamical Systems and Differential Geometry, which are courses that are scheduled every second year. We also offer courses that have a specialised topic and are steps towards active research areas. These courses are called Topics in Mathematics and the content varies from year to year. Examples of such topics are ”Combinatorial Topology” and ”Random walks and Lattice models.” Many students find their project degree through these topics. In the degree project, most students chose to work on research-oriented projects (although projects directed towards industrial applications are also chosen).

Students sometimes take part in PhD courses, although we have an on-going discussion how much we should allow in this respect. It can be clearly interesting for our top students to get challenged by more advanced topics. There is however a risk that, in their enthusiasm, some students overestimate their background. It is proposed that students with high grades in the core courses should be allowed to elect some of the PhD courses that are on a reasonable level. Some students also apply for exchange programs at top universities in Europe, including ETH, EPFL, and Paris. This is strongly encouraged.

Students are also encouraged to participate in other activities, such as the SMC colloquium, research seminars and SMC master classes. Stimulated by the interaction with engaged teachers, some students start reading groups on special topics and ask teachers for guidance.

Strength and weakness of the program.

The strength of the program lies in the fact that we can offer a wide variety of interesting courses due to the collaboration with the Mathematics Department at Stockholm University. The large amount of freedom and elective courses is highly appreciated among students and well used. The Stockholm mathematics community hosts top researchers in the world and the students can obviously benefit from this expertise. There are a number of highly engaged teachers in the program, who also take an interest in guidance of the students outside course activities. A weakness of the program lies in the administration. Having to deal with two different administrations with very different mentalities can be confusing and frustrating for the students, as well as for researchers with responsibilities in the program. Also, the number of administrative tasks is increasing, without having a beneficial impact on the program.

Research and teaching interaction for the master program in Applied and Computational Mathematics, TTMAM

Background.

This master program has been created when the Division of Numerical Analysis moved from the School of Computer Science and Communication to the Department of Mathematics. The existing master programmes in Scientific Computing (CSC) and Mathematics (SCI) have been joined and restructured to the actual programme and another master programme in Mathematics, which is done in collaboration with Stockholm University. The basic philosophy in constructing the curriculum consists of providing all students a broad and thorough mathematical basis as well as enabling to delve into one subject in detail thus educating experts being able to bridge the gap between actual research and its applications in real life problems.
After the basic mathematical courses (30 credits) the students specialize in one of four tracks Computational Mathematics, Financial Mathematics, Optimization and Systems Theory, Mathematics of Data Science.

The connection to forefront research appears in many different ways:

- Invitation of external lecturers in some of the courses, for example in SF2561 Finite Element Method, SF2863 Systems Engineering and SF2980 Risk Management.
- The programme has a Programme Council consisting of representatives of companies who have hired our graduates and where research collaborations exist.
- Most of the programme's teachers are active researchers and committed to teaching.
- Many of the programme's teachers have contacts, and often even research collaborations, with companies and public authorities.
- The master thesis projects are carried out in research environments, very often at companies, research institutes, and public authorities.
- The programme management, but even in more depth our research groups, discuss regularly the structure and contents of this programme.

During the last years, the programme has changed its structure by incorporating important new developments in research and society. In particular, the creation of the Brummer & Partners MathDataLab as well as the installation of WASP scientists have driven the programme structure both to a new study track, namely Mathematics of Data Science, as well as changes in the existing courses.

The programme is also well integrated in international collaborations. In particular, dual-master programmes are aligned with TTMAM. Examples include the master programme Computer Simulations for Science and Engineering (COSSE, jointly with TU Delft and TU Berlin) and a dual-master programme with UC Louvain-la-Neuve.

Strengths

- According to the latest evaluation by UKÄ, the programme has a very high quality and is in par with similar programmes at leading universities worldwide.

- The programme has many applicants from KTH's engineering programmes. Moreover, the number of external to KTH applicants is increasing every year reaching now 392 applicants for around 30 positions.
- The teachers of the programme are highly qualified and highly committed to teaching.
- The contents of the programme correspond to the expectations both of the students and of the employers.
- According to the graduate questionnaire, for more than three quarter of the graduates, the knowledge and skills learned were highly relevant for their job.
- Many teachers have close contacts to research both in academy and in industry.
- A large number of international students contribute to a high level of the courses and an open atmosphere.

Weaknesses

- So far, there was no programme in applied or engineering mathematics at KTH. Most of the students so far have backgrounds in engineering physics, vehicle engineering, machine engineering, or computer science. This situation is about to change.
- The interest of KTH's students to take part in international dual-master and double-degree programmes is extremely low. In contrast, we have many incoming students in these programmes.
- The number of female applicants and students is rather low compared to international programmes of the same subject.

The doctoral program in mathematics

Background.

The PhD program in pure mathematics has currently around 25 PhD students. The course requirement for the program is 60 ECTS points (8 full courses), of which 2 have to be taken in each of the areas algebra/combinatorics/logic, analysis, and geometry/topology (the "breadth requirement"). We offer all of our courses in collaboration with the department of mathematics at SU, and all courses thus jointly offered are open to all PhD students at SU and KTH. In this way, we are able to offer a greater variety of courses than we would be able to on our own.

We aim to offer 6-8 PhD courses each year, of which 2-3 should be "broad". By a broad course we mean a course that appeals and is accessible to all PhD students, with no advanced prerequisites. These courses guarantee that all students can meet the breadth requirement. In principle, the broad courses can be taught by a number of different faculty members.

All other courses are more advanced courses and have a closer tie to research. The main motivations for choosing a topic for such advanced courses are the instructor's research interests and his (and others') students' wishes and needs. For instance, our new faculty Liam Solus is giving a new PhD course in applied combinatorics and statistics in 2020/21, which is central to his research interests and especially (but not exclusively) geared towards the PhD students in the WASP program, who study mathematics and its connections to artificial intelligence.

As in other PhD programs, one of the obstacles is that the financing of PhD courses is not on solid grounds, in the sense that compensation can only be applied for from the school or, possibly, the department, on a case-by-case basis, but only for reasonably broad courses, and a guarantee cannot be given even then. One might argue that teaching specialised PhD courses is part of research or PhD supervision, but it would be beneficial if the administrative and bureaucratic hurdles to doing so were kept to a minimum.
A good PhD program offers new and cutting-edge courses when such advances occur in mathematics and a competent and knowledgeable person is available to teach the course, but for this, the establishing of new courses should not be met with roadblocks, as it has been the case in the past couple of years. It is vital for having a dynamic program at the forefront of research.

Strengths

- Broad education in advanced topics in mathematics, giving the PhD students an excellent position in both the academic and non-academic job market
- Great success in obtaining grants for PhD students, leading to a growing program with highly competent supervisors
- Increased interdisciplinary with the WASP program and B&P MathDataLab

Weaknesses

- Effectively no "open" PhD positions (departmentally funded, not tied to a grant and an advisor). This decreases the attractiveness of the program as a whole, and our ability to recruit the best candidates. SU has a number of such positions.
- Lacking administrative and financial support for PhD courses.
- Currently no reliably and periodically given broad courses.

The doctoral program in applied and computational mathematics

Background.

The purpose of the doctoral program applied and computational mathematics is to provide PhD education in mathematics at KTH, together with the doctoral program in mathematics. The program in applied and computational mathematics was initiated 2011. Previously the corresponding PhD education in applied mathematics was separated into three subjects: mathematical statistics, numerical analysis and optimization & system theory. In the new applied and computational mathematics program the PhD education of the three divisions is unified with the aim to provide a broader PhD education that better suits modern applied mathematics, which often combines techniques from stochastic, numerics and optimization. The new program also has a benefit of bringing the faculty closer together and creating a larger more dynamic research and teaching environment. The program attracts around 30 PhD students and they are almost all funded by external resources obtained in competition from national agencies as the National Research Council. Obtaining this funding shows that the supervisors in the program are highly qualified.

Clearly the PhD education is closely linked to the research at the department through the supervision but also through the offered PhD courses. The program has four

central courses on probability, numerics and optimization that are given regularly and intended to be taken by all PhD students. The program offers also several additional courses related to the PhD education. The PhD students are encouraged to take PhD courses given by the doctoral program in mathematics and other doctoral programs, as well as from other universities. The requirements for a PhD in applied and computational mathematics is to defend a thesis and to take 100 course credits, with at least 60 on the PhD level. Compared to the other PhD programs at KTH our program has more compulsory course work with the purpose to provide a broad background for the future career as applied mathematician.

Research and teaching interaction.

As in most research areas also the research in applied mathematics seems to require a growing theoretical background and use more sophisticated techniques to make an impact. The setup combining stochastic, numerics and optimization looks promising also for the future. In addition to the traditional careers for PhDs in mathematics, the fast technological development of handling data in the society, based both on improvements in hardware and algorithms, is likely to continue to offer PhDs in applied and computational mathematics good careers in society and academia.
A practical difficulty in our program has sometimes been to offer sufficiently many PhD courses. A reason for this may be the setup where undergraduate teaching is "paid" but teaching PhD courses are currently not paid in the sense that teaching PhD courses are often not included in the individual yearly plan of the teacher's duties. The current academic year 12 PhD courses are given. The program has anyway been able to create new PhD courses often related to recent research, as e.g.:

- Numerical algorithms for data-intensive science,
- Computational methods for stochastic differential equations and machine learning,
- Approximation theory, given as special topic course,
- Mathematics projects in school,
- Functional programming,
- Boundary integral methods.

Sometimes the courses are based on joint Master level and PhD level course where the course development is paid by the budget for Master courses.

PhD student are encouraged to formulate and supervise Bachelor and Master thesis project with the aim to train the PhD students and to provide more projects for undergraduate students. Since the PhD students often formulate projects related to their research it also increases the interaction with research at the undergraduate level.

Strenghts

- the integration of stochastics, numerics and optimization, which seem to provide PhDs with good background for their future careers.
- the researchers successfully obtain funding for PhD students in high competition. This high quality of supervisors also contributes to that several good candidates apply for announced PhD positions.

Weakness

- the lack of nice administrative setup to offer PhD courses so that researchers find it more attractive to teach PhD courses.
- the complicated administrative setup at KTH to install new PhD courses.

Bachelor and Master thesis projects

The department supervises more than one hundred master thesis students yearly. Some master thesis projects lead to publications in journals. Several of the master projects have connections outside KTH and many are related to mathematics statistics. Therefore the education related to master thesis in mathematics statistics has been well setup in order to supervise many students with a not so large set of supervisors. It is likely that mathematics statistics will remain attractive for many master level students and that the mathematics statistics group can benefit from more contributions in supervision from other faculty members in the future.

6. Impact and engagement in society

6a. Relevance of research to society at large

The relevance to society of the research at the Department of Mathematics primarily stems from its connection to education. As outlined in section 5, a strong and active research environment is required to sustain and develop educational programs in science and engineering. Another more direct impact comes from collaborative research projects that are pursued together with societal actors. Societal relevance also comes through activities for improving the mathematical literacy (numeracy) among young people and decision makers.

The interplay between research and education along with its societal relevance is discussed in section 5. Focus here is therefore on *collaborative research projects* and on activities that aims to improve the *mathematical literacy*. As outlined below, the department has initiated strategic initiatives on industrial mathematics, life sciences, and artificial Intelligence that complements collaborations initiated and led by individual faculty members. The aim with the former has been to further develop new application areas for mathematics. Next, the section on mathematical literacy describes the long tradition that the department has regarding outreach towards high schools, which is now pursued together with Stockholm University.

Collaborative research projects

Collaborative research projects are typically initiated and led by individual faculty members at the department. As an example, faculty at the divisions of mathematical statistics, optimization and systems theory, and numerical analysis all have an established network with key stakeholders that serve as a source for joint projects. Some projects at optimization and systems theory and numerical analysis are also pursued as part of externally hosted research infrastructures, like the ACCESS Linnaeus Centre (2006-2016), the Linné FLOW Centre, and the Swedish e-Science Research Centre.

An overall ambition with the applied mathematical research is not only to provide means for addressing specific problems from applications, it is also to develop *new* mathematical theory. This is often required when dealing with demanding challenges that typically cannot be addressed by merely adapting existing mathematical theory/methods, some examples will be given in the case studies section. This type of applied mathematical research often requires combining expertise from multiple areas of mathematics, incl. areas usually associated with "pure" mathematics. To explore and further develop new application areas for mathematics that bears these traits, the department complements the above-mentioned bottom-up approach to collaboration with a few strategic top-down initiatives. This far, the focus of these efforts has been on *industrial mathematics*, *life sciences*, and *artificial Intelligence (AI)*.

Industrial mathematics

Between 2006-2016, the department founded and hosted the Centre for Industrial and Applied Mathematics (CIAM) that supported joint research projects and initiatives to educate a new generation of mathematicians with an experience from industrial applications. Projects at CIAM involved faculty from all divisions at the department. Each project required involvement of faculty from at least two divisions within the department, which in turn strengthened the inter-departmental collaboration. Besides supporting specific joint projects, CIAM also launched activities for establishing partnerships with key stakeholders in finance and life sciences. These served as basis for the strategic initiatives in *life sciences* and *artificial Intelligence* that are described below. Key industrial stakeholders related to CIAM were LM Ericsson, ABB, AstraZeneca, General Motors, Saab, Volvo, Handelsbanken, Swedbank, Comsol, and RaySearch Laboratories.

In parallel to hosting CIAM, the department also pursues activities for strengthening industrial mathematics in Sweden. An example is by taking part in founding the *Swedish Network for Mathematics in Industry (EU-MATHS-IN.se)* in 2014 as part of the European Service Network of Mathematics for Industry and Innovation (EU-MATHS-IN). Within this role, the department hosted the first and second *Swedish Study Group on Mathematics in Industry* in 2015 and 2018, respectively. These weeklong workshops build upon an internationally recognized format for technology and knowledge transfer between academic mathematicians and industry. The idea is to allow industrial scientists to work alongside academic mathematicians on problems of direct industrial relevance.

Societal impact from joint such research with industrial stakeholders comes in many forms. One is to offer insight and/or methods for addressing specific challenges. It is however difficult to judge to what extent the mathematics really materializes in a product/service since such information is often not publicly available. An indirect measure of impact is to see whether the industrial partner takes part in multiple collaborations over a longer period of time. One can also count number of patents filed during such collaborations. Another aspect of societal impact relates to improving the mathematical literacy among decision makers. The industrial partner often employs the PhD students and the post-docs that are involved in joint projects after the completion of the project. There, they tend to act as ambassadors for

mathematics and they also improve the mathematical literacy among decision makers in industry.

Life sciences

In 2013, the department launched activities to systematically explore and identify possibilities for applied mathematical research in life sciences. This was initially done through CIAM and it was founded on the conviction that addressing challenges in life sciences will require involving notions/tools from a wide range of mathematical fields, some currently viewed as pure mathematics. As an example, phenomena in cell and molecular biology often involve dynamical systems with an underlying combinatorial/algebraic structure, like dynamics of gene regulatory networks and chemical pathways. These all touch on areas of mathematics where the department has strong scholarly traditions. An important catalyser was the large investments into life science research that were made in the Stockholm-Uppsala region. The starting point for this was in 2013 when SciLifeLab in Stockholm became a national infrastructure for molecular biosciences. This was followed by the opening of BioMedicum (2018), MedTechLabs (2018), and BioClinicum (2019), all research infrastructures for life science.

Concretely, the above initiative by the department further strengthened already ongoing collaborations with Karolinska Institute (mainly by Koski and Pavlenko). It also initiated a line of research in the intersection of topology, algebraic geometry, combinatorics, and statistics (Chachólski, Linusson, and Di Rocco) for analysis of chemical reaction networks and genomics data. Likewise, it contributed in opening up for research in the intersection of analysis, differential geometry, optimization and numerical methods with applications to biomedical imaging and image guided therapeutics (Forsgren, Strömberg, Kurlberg, Karlsson, and Öktem). There are now extensive collaborations within these areas that involve both clinical (Karolinska University Hospital and Cambridge University Hospitals) and industrial stakeholders (Novartis, AstraZeneca, Elekta, RaySearch Laboratories, Philips Healthcare, Siemens Healthineers, and Thermo Fisher Scientific).

Artificial intelligence (AI)

The first strategic initiative taken by the department towards positioning mathematical research in the context of artificial intelligence (AI) came in 2015 when the department secured a larger donation (15.5 MSEK) for establishing MathDataLab, a centre that focuses on mathematics of complex data. It currently engages about 15 faculty from all divisions at the department. It supported several workshops with industry participation (Nov 2017, June 2018, Jan 2019, June 2019, Oct 2019), it hosts study groups on specific topics and in June 2020, it will organize an international conference on “Mathematics of Complex Data”. Its Director (Hult) was also recently appointed as Research Director for the second strategic research area at MedTechLabs (see section on life sciences) with a 5-year budget of 15 MSEK. Developing mathematical theory and methods for AI and applying them to address challenges in life science is a reoccurring theme in several of the larger applied research projects at the department, like topological data analysis applied to genomics data (Chachólski), deep learning for optimal scheduling and treatment

planning in radiotheraphy (Forsgren), and deep learning for image reconstruction in medical imaging (Öktem).

The next major opportunity came in 2017 when the Knut and Alice Wallenberg Foundation launched the WASP/AI national research program for AI with a budget of a billion SEK. The program considers two main topics, one of which is led by Håstad at the department and focuses on understanding of the mathematical principles behind AI. The recruitment in 2018-2019 of four assistant professors was made possible thanks to funding from WASP/AI.

Mathematical literacy (numeracy)

The ability to understand and critically judge arguments that refer to modelling and uncertainty is becoming increasingly important in our society. This requires citizens and decision makers that are numerically literate. An essential element is to have an efficient educational system with high standards that allows different levels to interact and collaborate.

Alongside its mission to offer mathematics courses for engineering programs at KTH, the department also promotes educational initiatives towards schools. Jointly with Stockholm University (through Stockholm Mathematics Centre), the department organizes the Mathematics Club (directed towards middle school students) and the Mathematics Circle (for high school students). A similar initiative is to have projects that involve programming and mathematics with high school students and their teachers. PhD students at the department that undergo specific training for the task lead these projects. A further initiative along these lines is the engagement by Thunberg at the department in developing a course module on usage of problem solving in teaching mathematics. This was part of a national training program for mathematics teachers (Matematiklyftet) pursued by the Swedish National Agency for Education (Skolverket).

Finally, faculty from the department is active in outreach activities towards the general public and schools. These are typically as part of the Sonja Kowalewsky days and the Pi-day, the latter organized by Stockholm Mathematics Centre.

Summary and analysis

Mathematics is increasingly used in society and the traditional applications to physics and engineering are complemented with applications to chemistry, life sciences, social sciences, and behavioral sciences to name a few. This development also influences what societal stakeholders that are natural to consider for collaborations. Next, many challenges in these areas involve understanding and simulating complex (non-linear and/or multiscale) phenomena, recovering models from incomplete and/or highly noisy data, and identifying patterns and causalities in complex (large-scale and/or heterogeneous) data. Furthermore, part of the challenge is often to determine what to formalize mathematically, like in molecular biology where one seeks to quantify the “similarity” between chemical pathways.

It is clear that challenges of the above type require using a broad spectrum of mathematical theories and techniques, some considered as “pure”. To recognize this and leverage upon the strong research at the department has been the driving force behind the strategic initiatives for collaborative research outlined earlier in this section. There is however no outspoken specific priority regarding external stakeholders, but these strategic top-down initiatives in industrial mathematics, life sciences, and AI indirectly imposes a priority towards external stakeholders active in these areas. Furthermore, the timing of the initiatives in life sciences and AI were well chosen bearing in mind the large investments that are now being made.

Joint positions between academia and society are yet to be announced. The division of mathematical statistics has had adjunct professors and one associate professor at the division of mathematics is half time in industry. Overall, there are no formal reasons preventing such positions, even though some formal matters need to be resolved regarding the forms of recruitment if the position is a permanent faculty position. A possibility is to consider “shared” positions, e.g., with another department at KTH or even with a department at Karolinska Institutet (KI). The latter is indeed possible since there are examples of such shared positions between KTH and KI. Another option is to consider utilizing the SciLifeLab Fellows program. KTH has the mandate to present profiles for candidates to this career program and it would be natural to have at least one such position focusing on mathematical theory.

6b. Research dissemination beyond academia

The collaborative research with non-academic stakeholders is an important part of communicating the research results beyond academia. This applies in particular to the mathematical research related to life sciences and AI that involves non-academic stakeholders. Similarly, outreach activities for improving the mathematical literacy (numeracy) are an important part of communicating the importance of mathematics in society.

Faculty members at the department also contribute to briefing and policy papers and take part in public debates. An example is when Öktem from the division of mathematics served as Vice Director (2012–2016) and Director (2016–2018) for the Life Science Technologies platform at KTH. This is one of five strategic research platforms at KTH with a mission to support and catalyse interdisciplinary research related to life sciences. The Directorship position is usually reserved for full professors and it involves writing KTH response to various briefing and policy papers and taking part in high-level meetings with KTH strategic partners active in life sciences. This position offered ample opportunities to communicate the relevance of mathematical research to non-academic stakeholders in life sciences.

The current strategy for communicating the mathematical research at the department beyond academia is to utilize on-going collaborations. We put particular emphasis on examples that involve multiple areas of mathematics and/or examples involving applications that are easy to understand. The strategy also includes gathering collaborations under a few topical areas, like “Mathematics of Complex Data” or

"Mathematical Imaging Sciences". These are further complemented by on-going outreach activities that target mathematical literacy.

6c. Sustainability and the United Nations' Sustainable Development Goals (SDG)

Several reports[11] show that mathematical sciences have a significant impact on the economy. As such, an active mathematical research community indirectly contributes towards SGD 8 (promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all). The connection is more direct for applied and industrial mathematical research. On the other hand, almost all of the strong applied mathematical research environments come together with strong research environments in pure mathematics. The latter is essential thus not only essential for sustaining an educational curriculum in mathematics and computational sciences at an advanced level (see also section 5). It is also important in the development of applied mathematics, and especially so in applications that involve conceptual issues (i.e., where the main challenge is "what to compute", not necessarily "how to compute").

Research at the department that applies to life sciences is directly related to SGD 3 (ensure healthy lives and promote well-being for all at all ages). Likewise, research related to extreme value theory, rare event simulation and risk management is directly applicable to model and assess stability of the financial systems and the solidity of insurance companies. As such, this mathematical research relates to SGD 8 (promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all). Furthermore, industrial mathematical research relates to SGD 9 (build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation). Likewise, research in theory and methods for modelling and simulating multiscale phenomena and for uncertainty quantification relate directly to SGD 13 (take urgent action to combat climate change and its impacts). Finally, outreach activities that target mathematical literacy are also directly related to SGD 4 (ensure inclusive and equitable quality education and promote lifelong learning opportunities for all).

6d. Impact cases

We provide four impact cases, two old (in the sense that they were mentioned also in RAE 2012) and two new. The old ones ("Optimization of radiation therapy" and "Rational design of social policies") are mentioned because they demonstrate

[11] *Socio-economic impact of mathematical research and mathematical technology in Spain*, Spanish State Research Agency, 2019
Formulas for Insight and Innovation. Mathematical Sciences in the Netherlands, Platform Wiskunde Nederland, 2016
Etude de l'Impact Socio-Economique des Mathématiques en France, Société Mathématique de France, 2015
Measuring the Economic Benefits of Mathematical Science Research in the UK, EPSRC, 2013

prolonged collaboration with societal actors, which in turn is a clear sign that the collaboration is highly valued by both sides. The two new ones ("Topological Data Analysis of Genomics Data" and "Image reconstruction in medicine") are indirectly the result of the previously mentioned strategic initiatives in industrial mathematics and life sciences.

Optimization of radiation therapy

RaySearch Laboratories AB has a long-standing research collaboration with the department that dates back to 2003. The main form of collaboration has been in the form a series of industrial PhD student projects. The research has been focused on optimization of radiation therapy and this far it has resulted in five PhD thesis and six journal publications. The collaboration was also selected as a showcase when KTH had its 100th anniversary celebrations at campus.

Originally the research concerned nonlinear optimization related to intensity-modulated radiation therapy with one KTH professor specialized in nonlinear optimization as main PhD student advisor. The first student graduated in 2008 and two others that graduated in 2013 succeeded him. A pair of third generation industrial PhD students that graduated in 2018 and 2019, respectively, followed them. By then, the scope of the research had shifted and broadened significantly. The first project concerned the fundamentals of the optimization problems. The second generation of students dealt with multiobjective optimization and robust optimization. The third generation of students studied automated treatment planning and adaptive treatment planning. In several cases, ideas suggested in the PhD theses gave an impact in the real treatment planning system not long after the students had graduated. Several of the research questions considered were closely related to research on fundamental methods for nonlinear optimization.

The scope of the joint research has also widened. In 2017, two new industrial PhD students started with new PhD student advisors from KTH. One working on scheduling problems related to planning of the clinic's schedule and one working on statistical-learning methods for finding good treatment plans. This introduced techniques from statistical learning (deep learning) into the collaboration, and as such it has contributed to considering fundamentally new optimization problems and also fundamentally new approaches for the problems that arise. RaySearch Laboratories have just launched an additional industrial PhD student project in early 2020 related to statistical learning and optimization, and one more industrial PhD student is planned for 2020.

Topological Data Analysis of Genomics Data

The Topological Data Analysis group at the department is a vibrant research environment with broad interests ranging from fundamental mathematical research, connections to machine learning, and concrete applications in life sciences. It has funding from several sources, like Vetenskapsrådet and WASP.

The strategic initiative towards life sciences was an important catalyser for starting this group and the first application area was based on collaboration with researchers

at the Karolinska Institutet. The aim was to analyze genomics data relevant for multiple sclerosis. The above collaborative work subsequently led to the development of a classifier suitable for repeated measurements that samples from the data space and builds a network graph based on the data topology. The algorithm and software constitute an accurate classifier and a feature selection tool applicable to cases where there are repeated measurements.

The applied work mentioned above also opened up for pure mathematical research. One was on using combinatorics to present multidimensional persistent homology. Another was to develop theory for persistent homology in a supervised learning setting, thus allowing one to optimize over various models for the observed homological information. The focus on the latter is to study the space of stable translations from homological information into information that can be analysed through more basic operations such as counting and integration enabling the use of statistical tools to its outcomes. This connects topological data analysis with statistical learning.

Finally, it is worth mentioning that in November 2016, faculty members of the Topological Data Analysis started the spin-off company DV Analytics AB.

Image reconstruction in medicine

The project was launched in 2014 and runs until 2020 with a 21 MSEK initial grant from SSF. Later additional funding was added, so the total project budget is close to 26 MSEK. The aim is to develop mathematical methods for image reconstruction that significantly reduces the total dose/acquisition time in medical imaging. The research is spearheaded by four clinical challenges: (a) Increase image contrast in CT imaging of Alzheimer's disease, (b) increase the sensitivity/resolution in PET imaging for detection of lung tumours, (c) improve soft tissue contrast in C-arm 3D CBCT imaging during Gamma Knife treatment planning, and (d) reconstruction methods for spectral CT.

The project involves a wide range of mathematical fields, like group representation theory (for tomography with unknown orientations), microlocal analysis (to encode and track edges in images reconstructed from noisy data), non-smooth optimization, and diffeomorphic modelling of motion. One mathematical contribution was the development of infinite dimensional differential geometric theory for using shape based regularizes in image reconstruction, which was later extended to spatiotemporal imaging. A recent line of development uses deep learning based techniques to learn shape deformations from example data. The project also pioneered development of domain adapted deep learning architectures for solving inverse. The resulting algorithms are computationally feasible, give state-of-the-art performance, and allow for uncertainty quantification in large-scale inverse problems. A key feature is to integrate handcrafted models from analysis into deep neural network. The latest line of development is to integrate a handcrafted microlocal canonical relation into the deep neural network. This ensures the trained model transforms edges in a way consistent with mathematical analysis. It also establishes a unexpected connection between microlocal analysis and deep learning.

The project has this far generated five patents, four PhD dissertations, more than 75 peer reviewed publications, and a software library that is currently used by several research groups worldwide. It also involved funding six faculty (four at the department), 10 post-docs, and 2 research associates. Finally, it involved four industrial collaborators (Elekta, Philips Healthcare, Siemens Healthineers, Thermo Fisher Scientific).

Ration design of social policies

Linusson at the division of mathematics has since long been involved in various applications of Combinatorics. One is in life sciences (algebraic statistics), another is in the design of voting system that adhere, as much as possible, to the principle of proportionality.

A key part of the voting system is to use equalization mandates to proportionality between parties and different parts of the country. These played an important role in determining the outcome of the 2010 elections. Sweden's Election Review Board consulted Linusson for analyzing the outcome and this opened up an application area for Combinatorics. In 2018 elections one used negative equalization mandates to get a better proportionality between parties and regions. Linusson was given the task by Sweden's Election Review Board to investigate the stability of the new system.

As such, Linusson’s mathematical expertise has had a concrete impact on the rational design of social policies.

6e. Structure for increased impact

Initiatives for improving mathematical literacy (numeracy) have been successful and the department is expanding these activate. An example is the Mathematics Club that is directed towards middle school students. These activities have sustained funding through Stockholm Mathematics Center and they are also a highly prioritized. As such, the department will continue to pursue them. A further extension that has been mentioned is to allow for “summer internships” where selected students (undergraduate or high-school) make a project with researchers at the department.

The status regarding strategies for increased impact from research collaboration is more complex. The department has until recently pursued a strategy where traditional bottoms-up approach for collaborations is complemented with strategic top-down initiatives. The latter is based on actively identifying future application areas for mathematics that match expertise and interests of faculty at the department. This has been quite a successful strategy in the sense that it has generated new research and societal impact. As an example, both life sciences and AI constitute exciting application areas for mathematics where large investments are being made. The strategic initiatives by the department towards these two areas actually preceded these investments. Hence, the department was clearly on the “right track” in identifying applications areas with a large potential.

Much of the above strategic initiatives was done as part of CIAM, the industrial mathematics center that was closed in 2016. They served as a key catalyzers for both MathDataLab, the WASP recruitments and the “Topological Data Analysis of Genomics Data” and “Image reconstruction in medicine“ projects mentioned earlier. Currently there is no infrastructure for catalyzing new collaborations, which is a key component in such strategic initiatives. In fact, there is a history of building up large well-functioning infrastructures for collaboration, which typically last 5-15 years, and then closing them down. Examples are PSCI - Parallel and Scientific Computing Institute (1995-2005), CIAM (2006-2016), and ACCESS (2006-2016) that are all discontinued, and MathDataLab (2017-) that is currently the only active center for applied mathematical research.

Discontinuing existing centers is part of the natural evolution of academic research, but one could try to better build on experiences and contact networks that have been worked up from establishing and running these centers. This clearly requires an infrastructure that offers some degree of continuity, somewhat similar to how Stockholm Mathematics Center is used to continually fund activities for improving mathematical literacy (numeracy). KTH already has a centrally funded infrastructure for catalyzing multidisciplinary research through its six Research Platforms (Digitalization, Energy, Industrial Transformation, Life Science Technologies, Materials, and Transport). The department could explore possibilities for using a suitable subset of these; alternatively one could suggest a new Research Platform on “Modelling and Simulation” (or something similar). Another alternative is to team up with an external stakeholder, just like how Chalmers/University of Gothenburg and Fraunhofer Institute jointly established the Fraunhofer-Chalmers Centre for Industrial Mathematics. In this regard, the department could consider contacting RISE to explore their interest in taking more active part in developing MathDataLab to integrate AI with other areas of mathematics and computational sciences. RISE is making large investements into applied AI research, which in turn aligns well with the profile that MathDataLab has.

Department of Engineering Mechanics

1. Overall analysis and conclusions; strengths and development areas

1a. Limited SWOT-analysis

The starting point for this analysis is an analysis of strengths and weaknesses of the department of Engineering Mechanics with the foci *Research* and *Organisation.* Itemized lists with respect to each focus will be presented and commented. This analysis is followed by presenting key development areas for the department.

Research:

Strengths	*Weaknesses*
• Strong publication record in top journals of the discipline(s) • From high to low TRL: strong in the full range from fundamental research (ERC) to applied work with direct industrial relevance • International presence and influence (keynotes, key references, collaborations, sabbaticals) and industrial collaboration (industrial PhD students, EU-projects, centra) • Resilient to the funding landscape and attracting research funding from various sources • Systematic and strategic work to identify and engage in multi-disciplinary research questions	• Lack of time and funding to develop truly transformative research questions and read as well as publish in high-impact multi-disciplinary journals • People dependent and related collaborations • Often possibly related work at high and low TRL does not interact • Too many administrative tasks, and admin time overhead is substantial • Faculty has to little time to perform own research (too many engagements in different tasks at KTH)

Organisation:

Strengths	*Weaknesses*
• Qualified staff – internationally recognised as teachers and researchers • Access to state-of-the-art experimental and numerical infrastructure • Significant roles in national and international commissions of trust and many external relations and interactions • Education (basic and advanced level) and research • Many commissions within KTH	• Maintaining laboratories becomes a goal of its own • Volatile competences • Faculty structure: many professors and few assistant professors • Informal leadership structures can dominate and have a conservative effect • The issue of academic housekeeping is clearly visible

In order to build on these strengths and improve on the weaknesses, the following development areas have been identified. For each development area, a brief comment is given:

- *Multidisciplinarity, disciplinary depth and broad TRL spectrum*
  We aim at being a department with a high international standing on all three of these aspects. Our units and research groups are typically strong in one or two of these aspects, and we strongly believe that cross-departmental structures are necessary in order to develop the underlying potential in these differences.

- *Generational renewal and faculty recruitment*
  Different parts of the department are in different phases. On the department level, it is important to focus on recruitment of capable young faculty where needed, and as a whole we must focus on ensuring that new faculty are of high quality, are given good conditions to develop as academics and feel free to act beyond disciplinary borders.

- *Working environment with special focus on what we at KTH call JML (equality and diversity)*
  Quite often, issues when it comes to gender and inclusion are brought to the management's attention. We intend to work with continuous discussions and competence development of leaders and employees to develop a working environment free from such issues.

- *Scientific infrastructure: labs and computational resources: maintaining and developing*
  A continuous discussion on needs and possibilities must be maintained, while continuously matching the needs to funding opportunities. Furthermore, the systems for prioritizing investments in new and present infrastructure together with funding and distribution of related costs must be transparent and accepted

by most.

- *Master education and administration*
  There is a symbiosis between the master education and the research activities through e.g. the possibility to have project courses that contribute to research and knowledge transfer (in courses and through alumni). Parts of the department have a history of being thought leaders on engineering education and this ambition should be kept. Furthermore, it is important that the administrative support is efficient and accessible in a transparent manner.

1b. Summary statement on contributions of department on impact, infrastructure and sustainable development

The impact of the department can be itemized as follows:

- Impact cases where research results have been brought to direct use.
- Clinical, industrial and societal collaborations that has a continuous but more diffuse impact on best practice and future developments.
- Transfer of knowledge to industry and other actors, to a large extent through alumni and, in particular, industrial PhD students and affiliated faculty.
- Disciplinary work of very high quality leading several research fields.
- Examples of high impact transdisciplinary scientific work from which novel disciplinary research directions can be identified.

In terms of infrastructure, the department contributes in the following ways:

- Maintains and develops an extensive experimental infrastructure (the Odqvist Laboratory)
- Maintains and develops numerical codes for scientific computing
- Has a leading role on the national level in using and developing computational resources
- Uses and contributes to the development of large scale national and international experimental infrastructures (MAXIV, Desy, etc)

Finally, sustainable development is a main driver for many research activities at the department and the main contributions are summarized as:

- Contributes to development of future sustainable transports with a holistic perspective from the components of vehicles, via the vehicle as a system (including humans interacting with it) to the function of the vehicle in the overall transport system.
- Improved health will be a direct result on work on e.g. moveability, flow and fluid-structure interaction in the cardio-vascular and respiratory system.

- The work on lightweight structures and biomaterials leads to increased efficiency of the use of fossil resources and/or a transfer to biological sources.

2. Research profile

2a. General information of the department

The Department of Engineering Mechanics was formed January 1, 2020, through a merger of the previous departments of Aeronautical & Vehicle Engineering, Solid Mechanics and Mechanics. It is one of four departments at the School of Engineering Sciences. The department has around 200 employees, out of which: 30 (5 female) professors, 21 (4 female) associate professors, 5 assistant professors (1 female), 21 researchers, 21 postdocs, 85 PhD students and 15 technical staff. At present, the Department of Engineering Mechanics is organized in two divisions: *Vehicle Engineering & Solid Mechanics* and *Fluid Mechanics & Engineering Acoustics*. The divisions are divided into a total of eight units and each unit consists of several research groups. The activities of the research groups can be organized in the following broad disciplines. As with any such listing, there a both individual researchers and research groups whose work contributes to several of the disciplines listed below.

- Rail and road vehicle engineering on the ground
- Naval engineering on and below the water surface
- Aerospace engineering
- Solid mechanics
- Composites and lightweight design
- Sound and vibrations
- Fluid mechanics
- Biomechanics

The experimental activities are (of course) performed in laboratories, and from an administrative perspective each laboratory belongs to one of the units. Nevertheless, most labs are used also by researchers at other units. The laboratories maintained by the department are:

- The Solid Mechanics laboratory
- The Lightweight Structures and Maritime Robotics laboratories
- The Fluid Physics laboratory
- The Vehicle Engineering laboratory
- The MWL laboratory for sound and vibration
- The MovAbility laboratory

The department is also a significant user of national and international computational and experimental resources.

2b. Central research questions and themes, knowledge gaps addressed, main research activities and composition of research team(s)

The research performed at the department is broad and can be summarized in 3 central research themes, ranging from system behavior on a global level to microscale dynamics and their effects on macroscopic modelling:

- Energy, transport and sustainable mobility
- Biomechanics, bioengineering and health
- Materials and structures: processing, functionalising, characterising and utilizing

This holistic perspective is presently under development (the research themes were identified late 2019 as a part of the merger process). In this presentation of our research, an attempt is made to utilize these themes to structure our work. Of course, the knowledge produced by most fundamental activities is relevant for two or all three of the overarching themes. Some, but far from all, of these overlaps are mentioned below and whether a certain activity should have been presented under one or the other theme can be debated.

In parallel with the research themes, a key aspect of our research is to develop, adapt and extend models and tools, an effort necessarily multidisciplinary and rich in collaborations; in particular, we are active in advanced and large-scale computing, machine learning and new experimental methods.

In general, the research questions and approach to research at the department is twofold: i) tool-related questions (high-fidelity numerical models and measurement techniques with known range of applicability and level of approximation), ii) knowledge- and application-driven questions (related to a specific knowledge gap and technological solution whose solution is anyway strongly dependent and enabled by the tools developed). In the following, we provide details of the different areas and present concrete examples.

i) Energy, transport and sustainable mobility

For the *Road Vehicle* research group common research activities are studies of vehicle conceptual design and vehicle dynamic analysis including both interaction with the environment and human interaction. Important activities in cooperation with the Conceptual design group (see below) are also how to translate societal needs and goals into sustainable vehicle and transport system solutions. The research questions can be grouped into the following themes:

- Innovative vehicle concepts (e.g. greener, smarter and safer over-actuated vehicles);
- Driver-vehicle interaction (subjective-objective correlation, driver modelling, driving simulators, remote driving etc.);
- Vehicle dynamics control (optimizing energy, safety, comfort etc. depending on driving conditions and transportation task);

- Vehicle system and environment interaction (tyre-road modelling, energy losses, wear, active suspension, crosswind, optimality in design configurations etc.).

The *Conceptual Vehicle Design* research groups focus on how to translate societal needs for transport functionality into a plan for sustainable vehicle solutions. This includes the development of methods to link effects across different system scales so that vehicles may be optimal from a wider transport perspective. An important aspect here is to avoid suboptimal shifting of burdens and benefits which often occurs in traditional reductive approaches. Multifunctional design also involves many questions around how to model different functions with an appropriate non-biased fidelity and how to include secondary knock-on effects when evaluating the effect of change on a system.

The main research focus of the *Rail Vehicle* research group is the dynamic interaction between rail vehicles (train) and track. Modelling and simulation play a major role in the research efforts where digital twins of the real system are developed to predict system behavior, optimize system parameters and to predict maintenance needs and total cost of operation. With the help of such detailed simulation models, system performance like ride comfort, running stability and vehicle-track interaction forces is improved. The models are validated against on-track measurements usually carried out by our external partners since measurements in laboratory environment in most cases are not possible. To cope with higher future demands in this area, in several recent research projects the introduction of active suspensions is investigated. Another important research topic is the mechanics of the wheel rail contact, triggered partly by the desire of running trains with ever higher axle loads. By developing new contact theories and implementing theories for wear and high cycle fatigue in our models, the wear and fatigue behavior of the contact partners is predicted and the system optimized.

Another important subsystem is the dynamic interaction between rail vehicle pantographs and catenary: Important research questions here are reduced contact force variation and less wear and fatigue. An important goal of rail operation is minimization of maintenance cost. Therefore a growing research topic in the group is condition-based maintenance based on predictions with digital twins and/or machine learning.

Even though rail transport is very energy efficient today, research on how to make train design and operation even more energy and power efficient is ongoing. Energy and CO2 labelling can be mentioned as example. Together with the lightweight group studies on replacing conventional steel structures like bogie frames with composites are ongoing.

The *Naval* Research group is agile and versatile, addressing research questions associated with traditional ship science as well as topics tailored for both collaborations with Swedish industry, government bodies, other universities and

various groups. A typical sign of the group is the constant strive for coupling between theory, simulations and experimental verification.

Among the more traditional topics are performance, research questions considering performance of high-speed craft and their operational/working conditions for development of modern safety guidelines and criteria for both design and operation. Further, research in the area of autonomous maritime robotics and underwater technology is growing, where research efforts range from surface vessels for arctic measurements, climate related sensor technology, acoustics and sonars, to pure underwater vehicle-related technologies. A growing research theme is also sustainable shipping, for example better use of the inland waterways and the efforts in the field of alternative propulsion, mainly sailing.

Within the *Flight Dynamics* research group, aircraft trajectory optimization is used to find a flight path that minimizes a chosen merit function. Various merit functions are investigated such as Global Warming Potential (GWP) and Human Toxic Potential (HTP) in order to reduce impact on climate and local environment. It appears that a combined merit function that reduces the impact in climate is suitable for the main part of the flight, but the merit function should be adjusted to better consider the impact on human health in the neighborhood of the airport during take-off and landing. Recently, work has started on development of electrical aircraft demonstrators, including hydrogen powered drones.

The *Space Technology* group is focusing on two main research themes:
1. Deployable structures technologies for small satellites using thin high-strain composite shell structures.
2. Mechanical shock analysis and testing to qualify the developed hardware.
The space technology research is very applied, from the initial sketches and structural ideas to production of flight-qualified hardware. The research team in space technology is currently only one full-time faculty member within the department, but with strong connections to the researchers on composite structures and vibration testing in the Marcus Wallenberg Laboratory for Sound and Vibration Research.

The *Markus Wallenberg Sound and Vibration* research Lab (MWL) is working on noise and vibration reduction on a system level which requires models on a higher level, as well as consideration of other functions of the system. Research activities related to Swedish national centres and EU funding for quiet transport all involve multi-functional and multi-disciplinary aspects. Recent projects are focusing on e.g. multi-functional panel and noise shield design and compact silencer design for road vehicles. Research conducted at MWL on the improvement of sound transmission properties of periodic flat panels, curved panels and sandwich structures, using distributed embedded resonators, for vibro-acoustic applications, has received much attention. Assessment of noise levels from transport systems is treated in several projects, involving development of long term out-door measurements around airports as well as assessment methods for noise exposure in transport systems. All MWL researchers active in this field are also active and benefit from the activities in the more fundamental research areas further described below.

One of our traditional strengths in fluid mechanics is *boundary layer flow, stability, transition, turbulence and control*. The main research themes deal with the understanding of the process by which ordered laminar flow transitions to complex turbulent flow. In particular, we have pioneered the understanding of the mechanisms of so-called bypass transition, both from a mathematical point of view to an engineering-oriented explanation of transition caused by free stream turbulence in turbomachinery flows. This research is based on large scale computations on high performance computers, including the largest in the world for example within the so called PRACE program in Europe, as well as laboratory experiments. As examples, over the last two decades we have realised and tested in the wind-tunnel a passive flow control technique which stabilizes boundary layer flows and accomplishes transition delay that can give skin-friction drag reduction with up to 70%.

We also perform numerical, theoretical and experimental studies of the flow very close to solid walls, such as the surface of vehicles or ducted geometries. At sufficiently high Reynolds numbers, the flow in these thin boundary layers is turbulent, and its behavior is extremely complex. However, around 25% of the energy spent worldwide to move fluids in contact with surfaces is due to phenomena within turbulent boundary layers. Over the years we have also carried out renown turbulent boundary layer measurements, from one of the first thorough experimental turbulent boundary layer measurements and first detailed pressure fluctuation measurements to experiments in the first turbulent asymptotic suction boundary layer. We are currently active in a basic research campaign on high Reynolds number turbulent flow in the pipe flow facility CICLoPE in Italy, where we are designing a new test section that will be manufactured later this year.

In parallel to experiment and fully-resolved simulations we work on modelling of turbulent flows and turbulent heat transfer and of atmospheric boundary layers. Existing turbulence models and turbulent heat transfer models for computational fluid dynamics (CFD) used in research and engineering applications are quite often less accurate than desired. We have worked on the development of new models for the subgrid-scales in large-eddy simulations, scaled-resolved modelling with variable resolution and averaging modelling for compressible turbulent flows and we have performed extensive validations of the new models.

ii) Biomechanics, bioengineering and health

In recent years, we have been moving into biomechanics and bioengineering. The classically strong areas at KTH Solid Mechanics have been strengthened by new research on the mechanical characterization of *Soft Biological Tissues* (SBT). The SBT research focuses on vascular tissues and it has led to collaboration with many world-class clinical institutions, such as Karolinska Institutet and University Hospital, Heidelberg University, University of Liege, as well as engineering schools at TU Eindhoven, TU Munich, Yale, University of Calgary, Politecnico di Torino and University of Houston. Examples of the work, both experimental and numerical/theoretical, are the multi-scale modelling of fibrous composites towards the adaptation of vascular tissue and in-vitro experimental investigation of soft biological tissues.

Also very recently, we have inaugurated the new *KTH MoveAbility Lab*. The goal is to build up fundamental knowledge of the tissue and systemic behavior of persons with disability through studies spanning several biological scales. On a tissue level, changes in bone structure and predominantly bone growth due to abnormal mechanical loading are studied. On the systemic level, we study the strategies employed by the central nervous to select a motion pattern, as they are central for successful prediction of treatment design and outcome. On an organism level and for our knowledge and scientific developments to approach the end-user, we design and prototype assistance-as-needed exoskeleton assistive devices that empower each individual to locomote to her best ability. As such, we use a combination of experiments on humans and on biological tissues, with modelling and multiscale simulations of the neuromusculoskeletal system. We also create prototypes of devices designed to assist motion in the lower limbs, and compute required assistance through both musculoskeletal models and machine learning methods.

The overall goal of the *biofluid* research is to develop tools for early detection of risks for development of cardiovascular, respiratory and voice pathologies in various clinical situations. The research questions are based on direct clinical needs and approached from a fundamental fluid dynamical viewpoint. This includes in particular treatments associated with severe heart and lung failure, stenosis formation in blood vessels, obstructive airway disorders (e.g. Obstructive Sleep Apnea), voice disorders. These are clinical scenarios in which today's predictive tools and understanding of underlying physics are lacking or insufficient. This is a highly cross-disciplinary activity involving several disciplines in engineering as well as medicine.
As example of activity, combined computational and experimental fluid dynamics of blood flow are used to Improve and minimize complication due to clinical treatment through i) model development of blood fluid properties, particulate transport and interaction; ii) assessment of uncertainties and propagation of uncertainties along the path of information propagation (from patient data and back to treatment); iii) enabling knowledge based component development and predictive indicators.

iii) Materials and structures: processing, functionalizing, characterizing and utilizing

This theme focuses on characterization and design of materials and structures at the microscale and their consequences for industrial processes and new products and technologies. For major clarity, we present here our activities in terms of questions related to solid materials, solid-fluid and fluid-fluid interactions, respectively.

Solid materials

Solid materials are mainly studied in the Solid Mechanics unit and by the Lightweight Structures group. The work of the solid mechanics unit can be grouped as follows: contact mechanics, fibre based materials and packaging technology, material and fracture mechanics, reliability and fatigue and soft tissue mechanics (the latter is presented under the research theme Biomechanics, bioengineering and health). Here, a short description of the other groups working on solid materials is given.

The *Contact Mechanics group* originates from research dealing with the mechanics of indentation testing initiated in the 1990's. In a short time, this research field started to attract large attention and the interest was also directed towards other related contact problems such as compaction mechanics, mechanics of rough surfaces and also general contact problems. During the period 2012-2019 the research in contact mechanics to a large extent focused on *micromechanics and macromechanics of powder compaction*. In the first case, discrete element modelling (DEM) has been the main issue and the research at the Unit is in the international forefront when it comes to applying advanced contact mechanics to DEM-modelling of powder compaction. The second case concerns constitutive modelling of powder compacted materials with a very close coupling between theoretical/numerical and experimental research. During the period 2012-2019 also *rock mechanics* has emerged as an important research direction. In particular, different aspects of rock drilling have been investigated based on contact mechanics modelling. Analysis of *shot peening* is also a part of the contact mechanics research area.

The *Fibre-based Materials and Packaging Technology* group focuses primarily on paper, but recently also nanocellulose foams, biopolymer networks, and biocomposites are considered. In manufacturing and end-use, fibre networks are subjected to complex multiaxial stress-states, and the objective of the research is to bring insights into deformation and damage mechanisms in process and product design. The research ranges from fundamental problems at microscopic scale to product-related problems at macroscopic scale. Efficient converting of carton board packaging requires knowledge on relations between converting and material parameters. By combining experimental techniques with finite element analysis, recent research has clarified these relations, and we can support carton-board manufacturers on how to improve materials and processes with confidence. In contrast to the tensile response, the compressive behaviour of fibre networks is scarcely understood, particularly in relation to the failure mechanisms at the fibre level. The compressive properties are studied on multiple scales. We have identified the deficiency with standard testing procedures, proposed recommendations as to how the results of the testing should be interpreted as well as presented the factors affecting the compressive properties. In characterization of the fibre network microstructure, computer micro- and nanotomography are important tools, and we cooperate with e.g. DESY in Hamburg and MAX IV in Lund.

The *Material- and Fracture Mechanics* research focuses on the deformation and failure in materials in a broad sense, as it addresses phenomena occurring at the scale ranging from nano-meters to large scale structures. Topics of special interest addressed by the group are static and dynamic fracture mechanics; local and non-local plasticity; constitutive modeling; finite element modeling; micromechanics; testing of materials and parameter estimation by inverse modeling; degradation of fracture properties due to operating environment, ageing and radiation. The research during the period 2012-2019 has primarily been devoted to four main areas. Damage mechanics modelling of metallic materials, as for example development of micromechanics based constitutive models for deformation and failure in nodular cast iron, and pioneering experiments and modelling to reveal the mechanisms involved in

shear dominated fracture at low stress triaxiality; Studies on the coupling between dislocation mechanics and strain gradient plasticity theory and applications to steels reinforced by precipitates and small particles; Degradation of nuclear materials due to ageing and radiation; Long-term properties and degradation of lithium-ion batteries is a research area that recently has been initiated.

The *Lightweight Structures* group is centered around the context of making structures lighter and thus decreasing energy consumption, environmental footprint and improving resource efficiency. The group performs research on lightweight materials and structures with a main focus on composite materials and sandwich structures, but also on lightweight welded steel structures. The research encompasses materials, structures, design, manufacturing, durability and integrated functionality, coupling theoretical, numerical and experimental studies. The vision of the group is to contribute to Swedish industry and society and the UN sustainability goals by performing high-class research towards lighter, multifunctional and resource efficient materials and structures.

Solid-fluid interactions

Motivated by recent developments in miniaturization, a significant research effort is devoted to understanding and controlling solid-fluid interaction problems. In particular, we investigate and design surfaces to control both small-scale phenomena (wetting, drops, particles) and large-scale transport phenomena (turbulence, heat transfer). Today, we lack versatile methods to engineer surfaces that are sufficiently complex to achieve multiple objectives. Therefore, one of our goals is to develop a framework for designing surface textures given sets of criteria related to friction, heat transfer as well as fouling and particle adhesion under fluid flows. This includes multiphase/multicomponent transport between free fluids and porous media, which is relevant, for example, to describe the drying process in materials. We also incorporate the effects of surface chemistry into our textured surface in order to create advanced surfaces and porous materials for different applications.

Another important solid-fluid interaction activity is the work on assembly of biomaterials, where we investigate the flow of elongated structures from millimeter sized fibers to nanometer sized molecules. The work stretches from fundamental investigations combining theoretical, numerical and experimental studies of how particles behave in flows to multidisciplinary and applied studies on novel material processes; either disintegrating fibers or assembling of molecules and supramolecular building blocks into macroscopic materials. This work utlilizes advanced and, for the field of fluid mechanics, less traditional experimental methods such as Magnetic Resonance Velocimetry, Optical Coherence Tomography and diffraction measurements with X-rays and neutrons.

Fluid-fluid interactions

A new research area, born with a new recruitment in 2018, is shock waves. Shocks are closely connected to high energy density. A shock or a blast wave is often created by an abrupt release of energy confined in space. Oppositely, an already existing shock, propagating in a medium when confined to a small volume has a potential to increase in strength and generate very high energy concentration. This is manifested by

extreme temperatures and pressures in e.g. gas that are hard or even impossible to achieve by other methods. These extreme conditions may result in substantial material damage when occurring uncontrolled or may be used with advantage if monitored in a well-defined environment. The main objective of this research is to investigate, understand and actively control the complex, highly nonlinear physical mechanisms of strong shock propagation in gas and liquid-gas systems. The question of stabilization of converging shocks is one of the examples of important physical properties of strong shocks that is addressed by our research. A second area of research is strong blast wave interaction with various types of multiphase media and includes spectacular physical phenomena as negative pressures, cavitation, creation of hypersonic jets as well as various types of flow instabilities and is not less attractive than shock focusing. Next and important part of our research activity is metrology. We are a part of a European project dealing with measurements of transient pressure and temperatures in connection to shocks.

A new direction of research, initiated with the multidisciplinary research centre INTERFACE, is devoted to high-fidelity numerical simulations of multiphase flows laden with droplets/bubbles. We wish to use multiscale approaches to model complex heat and mass transport processes at interfaces, such as evaporation, boiling, absorption. We are developing numerical tools that we plan to share with the research community that can run on modern architectures (order hundred thousand of CPUs and GPUs). We identified gaps in our knowledge of interfacial phenomena: as example wetting and the effect of intrusions (single particles/bubbles as well as emulsions) in different fluids, including polymer suspensions and fluids with a microstructure. In particular, we need a significantly improved understanding of the heat and mass transfer in complex mixtures as those used as refrigerants and working fluids (biogas) in waste-recovery and modern energy-conversion systems. Examples of present activities are the simulations of droplet evaporation and boiling flows, considering multicomponent mixtures.

A very challenging problem that we have started to investigate recently is single and multicomponent fluid systems where one or two of the components is visco-elastic or visco-elastic-plastic. Progress in the development of computational codes and computational resources has recently made it feasible to investigate these systems through direct numerical simulations and our activities in this area are at the forefront of science.

Generally, the simulation based work in fluid mechanics is characterized by a multidisciplinary approach in order to devise innovative and efficient analysis methods. For instance, we work closely with HPC centers and application experts to continuously improve the numerical codes employed for our simulations. We also work closely with experts in machine learning and data visualization; these collaborations have led to more efficient methods for data analysis and handling. As in most of the department's activities, the interaction between experiments and numerics is a key to success and during 2012-2019, the links between experiments and numerics have been strengthened and we now have several groups with both numerical and experimental activities.

2c. Contributions to the advancement of the state of the art within the research fields of the department

Due to the broad activities of the department, an itemized list highlighting selected contributions based on published results is given. The societal context of the contributions is provided for some of the items. Among other contributions, we have:

- supported the development of sustainable transport by developing better analysis methods to calculate CO2 emissions using traceable data and computational models. We perform independent investigations of the different means of transportation for travel. The focus of the investigations is on traveling by train, boat, aircraft, car and bus. The analysis considers time, cost, environmental impact, safety and work environment and how to weigh these different objectives in a reasonable way.
- contributed to more sustainable transport by facilitating increased use of lighter materials as for example composites. Advancements in this area have been made for example in predictive models for composites manufacturing, fatigue design of welded structures, novel 3D composites and structural power composites.
- been leading the development of methodologies for prediction of long-term wheel and rail damage development (wear, fatigue), proposed a European scheme on energy labelling of rail vehicles and contributed to the advancement of the usage of active suspension systems in rail vehicles together with Swedish rail industry.
- contributed to the state-of-the-art of over-actuated vehicle designs regarding safety, energy efficiency, driving performance and concepts that is now a reality for many new autonomous vehicles, e.g. ZOOX, Scania NXT, EasyMile, Navia, Ollie. We have also developed methods for handling and evaluating of large data sets in vehicle dynamics research through machine learning such as Self-organizing Maps and General Regression Neural Networks, which has been well-received by both scientific and industrial community, currently adopted by Volvo Cars and being considered at JK Tyres.
- contributed to IMO (International Maritime Organization) stability guidelines, built buoys collecting data for climate research that have been deployed over the entire planet and contributed to understanding the ocean heat transfer. We have also contributed to understanding the human-boat interaction onboard high speed craft and performed groundbreaking work on large sailing vessels.
- designed and manufacted very thin high-strain composites, investigated their visco-elastic time-dependent and temperature-dependent behavior and brought some of the designs into space-qualified hardware. Practical solutions for on-ground testing simulating zero-gravity environments for the deployment testing is also an important contribution.

- created individualized multiscale models of the human femur during growth and created a framework to simulate growth based on tissue stress and strain in the area surrounding the cartilaginous growth plate. In recent animal pilot studies, our data suggests that we can affect the longitudinal growth of long bones by a large amount (up to 20%) by varying frequency and magnitude of load in immature bone.
- developed powerful methods based on Padé approximants in order to establish surrogate models adapted to univariate and multivariate problems. These methods have been applied in order to drastically speed up frequency sweeps, widely used in the field of numerical methods for acoustics, as well as multi-parametric sweeps.
- developed and refined experimental procedures for accurate acoustic flow-duct measurements. The methodologies are now used by many other research laboratories, as well as industry. Characterization of aeroacoustic sources using multi-port methods has also been developed.
- developed acoustic models and improved the understanding of the acoustic or vibrational behaviour of e.g. micro-perforated plates and wind-turbine blades.
- performed cross-disciplinary work involving acoustics, fluid dynamics, and turbocharging technology that have contributed towards understanding *aerothermodynamic heat losses* and associated mechanisms and contributed towards understanding the origin of the oscillation modes in screeching supersonic jets.
- presented a proof of concept for clot detection in artificial blood pumps, currently undergoing a larger clinical study (after ethical approval) and lab-studies for improving localization capability.
- created individualized multiscale models of the human femur during growth and created a framework to simulate growth based on tissue stress and strain in the area surrounding the cartilaginous growth plate. In recent animal pilot studies, our data suggests that we can affect the longitudinal growth of long bones by a large amount (up to 20%) by varying frequency and magnitude of load in immature bone.
- developed wake models for flow behind wind turbines that can be applied to wind farms and be used to improve the performance of the farms.
- demonstrated passive flow control methods for skin-friction drag reduction with up to 70% drag reduction, developed a novel semi-empirical model for boundary-layer transition prediction method for the free-stream turbulence (FST) induced transition scenario and created a database for such transition.
- developed methods for resolved temperature measurements including probe manufacturing with advanced sensor coating.
- performed large-scale interface resolved simulations of particle-laden flows (one of the first groups doing so), complemented with experiments. The simulations have shed new light on the transport of finite-size particles of different shapes and sizes in wall bounded turbulence.
- have provided the most detailed characterization of the TBLs around a wing section available in the literature, and we have conducted high-fidelity simulations of wings at an unprecedented Re of 1 million.

- have obtained a better understanding of the strong influence of system rotation on turbulent wall-bounded flows and turbulent heat transfer through detailed numerical simulations. We have also produced highly accurate numerical data of rotating turbulent flows with heat transfer that can and have been used by other researchers for theoretical and modelling purposes.
- have pioneered the use of machine-learning methods for temporal and spatial predictions of turbulent flows in a number of configurations.

2d. Quality and quantity of contributions to the body of scientific knowledge

The contribution to scientific knowledge of the department starts with publication in highly ranked specialized disciplinary journals and at relevant conferences in respective discipline. From this starting point, we are also striving to, and sometimes succeed to, publish in more general (e.g. Physical Review Letters, ACS Nano) and multidisciplinary (e.g. Nature Communications, PNAS) journals. The high level of our scientific contribution is illustrated by the fact that Linné FLOW Centre was evaluated as one of the top three research centres in engineering sciences in the final evaluation of the prestigious Linnaeus program.

The bibliometric performance varies for different parts of the department. This variation reflects differences in how we perceive, and prioritize, knowledge development and utilization of results. In order to be relevant both as a fundamental research institution and an industrial innovation partner, a wide range of perspectives must coexist. While some activities are aligned with the traditional publication landscape and have a long history of considering publication in peer-reviewed journals as their main objective, other activities have traditionally aimed at impact through other means as can be deduced from section 6d. On the whole, the bibliometric parameters indicate that efforts are needed to ensure that publication is made in top journals (the fraction of top journal publications is presently decreasing). Furthermore, the field normalized citation index shows a decreasing trend and it is probably necessary to work actively also with this aspect.

Ten journal publications that we would like to highlight are listed below. The publications have been chosen since they illustrate the breadth and high level of the scientific contributions of the department.

Spatial orientation of collagen fibers in the abdominal aortic aneurysm's wall and its relation to wall mechanics
T.C. Gasser, S. Galinetti, X. Xing, C. Forsell, J. Swedenborg & J. Roy, Acta Biomaterialia 8, 2012.

A novel method to model wheel-rail normal contact in vehicle dynamics simulation
M. Shahzamanian Sichani, R. Enblom & M. Berg, Vehicle System Dynamics, 52 (12) , 2014.

Links between subjective assessments and objective metrics for steering
M. Nybacka, X. He, G. Gil Gómez, E. Bakker & L. Drugge, International Journal of Automotive Technology, 15 (6), 2014.

Universal Scaling Laws for Dense Particle Suspensions in Turbulent Wall-Bounded Flows
P. Costa, F. Picano, L. Brandt and W.-P. Breugem, Physical Review Letters, 117, 2016.

Aerodynamic and aeroacoustic analyses of a submerged air inlet in a low-Mach-number flow N. Pignier, C. J. O'Reilly & S. Boij, Computers and fluids, 133, 2016

Influence of muscle groups' activation on proximal femoral growth tendency
P. Yadav, S. Shefelbine, E. Pontén & E.M. Gutierrez-Farewik, Biomechanics and Modeling in Mechanobiology, 16 (6), 2017

Flow-induced platelet activation in components of the extracorporeal membrane oxygenation circuit
G. Fuchs, N. Berg, L.M. Broman, & L. Prahl Wittberg, Scientific Reports 8, 2018.

Multiscale Control of Nanocellulose Assembly: Transferring Remarkable Nanoscale Fibril Mechanics to Macroscale
N. Mittal, F. Ansari, K. Gowda.V, C. Brouzet, P. Chen, P. T. Larsson, S.V. Roth, F. Lundell, L. Wågberg, N.A. Kotov & L.D. Söderberg. ACS Nano, 12 (7), 2018.

Critical Point for Bifurcation Cascades and Featureless Turbulence
J. Canton, E. Rinaldi, R. Örlü & P. Schlatter. Phys. Rev. Lett. 124, 2020

2e. Engagement in national and international research collaboration within academia and its outcomes

A large portion of the research activities during 2012-2019 has been connected to a research center. In most cases, these centers serve as a basis for primarily academic and industrial collaboration. Many of the contributions listed above have been obtained within the frameworks of one of the following centers or networks, which all involve national and/or international collaboration partners:

- Swedish e-Science Research Center (KI, SU, LiU)
- Wallenberg Wood Science Center (Chalmers, LiU)
- Bolin Centre for Climate Research (SU, SMHI)
- Standup for Wind (UU, LTU, SLU)
- LIGHTer
- TRENoP (LiU, VTI),
- SEC (LiU, UU, LU, Chalmers),
- NFFP-MIAU (LiU, Chalmer)
- Vehicle Dynamics Competence Area (Chalmers, SAFER),

- ECO2 Centre for Vehicle Design (Univ. of Graz, Wageningen University, Univ. of Eastern Finland, Univ. of Le Mans)
- EU-ALLEGRA (Trinity College Dublin)
- EU-MorphElle (TU Munich, University of Bristol)
- EVERSAFE (TU Chemnitz, Fraunhofer-Gesellschaft, VTI),
- KTH Railway Group (Univ. of Illinois (UIUC), Beijing Jiaotong University, Bandung Institute of Technology, Chalmers, LTU)
- Shift2Rail Joint Undertaking (University of Huddersfield, Politecnico di Milano, TU Graz, Nebrija University, University of Leeds, University of Southampton, TU Berlin, CEIT, Virtual Vehicle, University of Sheffield)

In addition to the structured collaborations in the centers and networks listed above, there are also collaborations with a large number of academic institutions, e.g. Heidelberg University, University of Liege, TU Eindhoven, Politecnico di Torino, Yale, University of Calgary, University of Houston, Harvard University, California Institute of Technology, Columbia University, University of Manchester, KAIST, Tohoku University, Tokyo University, Ain Sham.

The outcome of these collaborations ranges from occasional publications, via career long collaborations in research and education to ensuring long term funding on a high level. A proper presentation of the scientific outcomes of all these collaborations would require a bibliographical analysis on a level that is out of the scope at the present level of this RAE report.

2f. Follow up from previous evaluations

In the RAE 2012, the activities at the department were split on four Units of Assessment (UoA). Below, the recommendations for each unit have been extracted from the reports for each UoA are given in italics and for each recommendation, follow up comments are provided

Unit of Assessment: Vehicle engineering.

- *Recruit truly international tenure-track assistant professors educated abroad in order to maintain intellectual diversity.*
  One assistant professor without any previous educational background at KTH has been recruited to the area and the effect aimed for by the panel is clear. As can be seen in the recruitment strategy below, recruiting externally educated candidates is part of our recruitment strategy.
- *Strengthen and deepen the already recognised subject areas and reassess areas with subcritical size, such as naval architecture, with a view to investing in or discontinuing subcritical areas.*
  The particular area of naval architecture have grown beyond subcriticality, as illustrated by the establishment of the SMARC research center funded by KAW. Efforts are presently being made to strengthen the faculty also in other potentially subcritical areas such as space technology.

- *Focus on enhancement of publication quality and consequential scientific impact.*
  Scientific publication has been pushed and some of the outcomes are among the journal papers listed above.

Unit of Assesment: Solid Mechanics.

- *This calls for a more permanent solution of the field of Biomechanics within the UoA. In fact, a more general plan for coordination of the Biomechanics activities within the UoAs 7.2, 7.3 and 7.4 is strongly recommended.*
  There is now a full time professor in Biomechanics at the unit who is supervising substantial research activities. When it comes to the second part of the recommendation, the BioMeX center has coordinated activities and been instrumental in establishing a national network. We also hope that the fact that the activities in biomechanics now belong to the same department will facilitate the coordination asked for.
- *There appears to be a need for the UoA to develop a procedure for an ongoing discussion and development of the research strategy, to identify new promising areas or new trends within the fields of research*.
  To some extent, the discussion asked for has been established among the faculty of the unit and some results of this is discussed in the description of the research above. In particular, this discussion will have to be held during the coming years when new faculty is to be recruited.
- *Traditionally, Solid Mechanics is a male dominated subject area, and a more equal gender balance will require an active effort.*
  Improving the gender balance has been one of the driving forces behind the department merger. The development in this respect in the Solid Mechanics area has been slow but, on the other hand, there has not been any faculty recruitment since RAE 2012. When it comes to postdocs and PhD students, the situation has improved recently and the age structure at the unit is such that a considerable number of faculty positions will be recruited in the coming years and efforts will be made to improve the gender balance.

Unit of Assessment: Fluid Mechanics.

- *The recruitment of truly international tenure-track assistant professors educated abroad should also be actively pursued in order to maintain intellectual and gender diversity.*
  Since RAE 2012, three assistant professors have been recruited to the UoA. Two of these had their master and PhD diploma from abroad. The third has a master and PhD from KTH, but spent her postdoc at Cambridge and obtained a tenure track position at Nottingham University before returning to KTH. One of them is female, and it can mentioned that she was promoted to associate professor 2019 and received an ERC starting grant the same year.

- *As previously mentioned, the UoA is encouraged to enlarge its experimental component by hiring another Professor in experimental fluid mechanics*
  One of the three assistant professors mentioned above is an experimentalist and since RAE 2012, two associate professors in experimental fluid mechanics have been promoted to full professors. Furthermore, the connection between experimental and numerical work has been strengthened and several faculty members who originate from a numerical paradigm are have developed experimental activities in the Fluid Physics Laboratory.
- *The panel strongly recommends that the biomechanics component of the UoA join forces with its counterparts in the Mechanics-Biomechanics and Solid Mechanics UoA's to form a vibrant entity which is visible internationally and which leads to strongly collaborative research.*
  The comment to this comment is provided under the UoA Solid Mechanics.

Unit of Assessment: Biomechanics.

- *This UoA should be dissolved and its personnel redistributed among the other relevant applied mechanics programmes that they articulate with, as previously suggested in RAE2008. Such an action would provide the junior staff members with improved possibilities to seek and establish synergy with other disciplines, and enhance their ability to gain international visibility. In addition, it is strongly recommended that biomechanics from UoA 7.4 join forces with biomechanics in UoA 7.2 & 7.3, to form a high quality programme that enables more collaboration, enhances effectiveness and raises international visibility.*
  After the department merger, the unit of assessment does not exist as an individual organizational entity. When it comes to the need of joining forces in the field of Biomechanics, this aspect is commented on under the Unit of Assessment Solid Mechanics.

3. Viability

3a. Funding; internal and external

The total turnover of the department is 300 MSEK out of which 160 MSEK are external grants and missions. The internal funding (140 MSEK) is split 83/57 between research and teaching. In addition to the internal funding, 10-20 MSEK external funding is necessary to cover the cost for all permanent staff, premises and overhead costs. External funding beyond this enables recruitment of PhD students, postdocs, time-limited researchers and infrastructure investments. The ratio between external to internal funding is probably near the maximum if a culture that is sometimes called "researcher hotel" is to be avoided. In such a culture, researchers (and faculty) consider themselves to be guests as long as the funds are being raised, and do not fully engage in departmental and university matters.

3b. Academic culture

The general opinion at the department is that the academic culture is essential for a stimulating and productive research climate leading to high quality research. Participation, respect, responsibility and open-mindedness among colleagues are key acts to create and sustain a promotive and positive atmosphere. For academic staff it is important to feel included and to have fora where one can make oneself heard. A good psychosocial environment must be built from the base, i.e. locally in the organization, with respect and open-mindedness and willingness among colleagues to take responsibility.

Internationally, we have a rather flat organizational structure, with students on all levels having a quite direct access and close contact with the academic personnel. A non-hierarchical academic structure comes with the drawback of letting informal power structures grow if units are too large, which has been evidenced in the past through informal contradictions both internally and across departments. Awareness about and proactive work against similar contradictions is important for the research environment at the department and will continue promoting research quality.

At the newly formed department, meeting-places for research have been created and developed locally on unit level over many decades and there are both similarities and discrepancies in terms of meeting-places. Overall the culture can be characterized as friendly, open and non-hierarchic. Regular meetings, typically weekly, for discussing project progress and research topics, are common on research group level. Nevertheless, daily discussions and ad-hoc meetings, is the most frequent arena were research is discussed. The informal climate with an (informally ordained) open-door philosophy makes this efficient. However, from time-to-time both faculty and students are under high pressure, which at times makes it a challenge to create relaxed academic meetings despite active efforts.

Locally, on unit or division level, seminar series where research is presented and discussed are common meeting places and seen as quality influencers. Results presented during these seminars can both be peer-reviewed works and ongoing works, and seminars are given by all categories of employees from PhD students to professors including invited renown researchers. However, open meetings and seminars intended both to widening participants' scientific horizon and promoting focused research discussions tend to gain unwilling low priority by the faculty due to the number of administrative tasks that are being carried out very dutifully. Generally, lacking time for, or down prioritizing, the academic discussion is accepted within the present culture. This is, from time-to-time, noticeable by overall poor participation in seminars as well as mental absence by e-mailing during meetings. Our awareness will hopefully give gradual improvements on the above issues.

Participation in seminars and contributing to department or university wide needs, or lack thereof, is of course part of collegial cooperation and loyalty. Discussions of this loyalty also addresses the term academic house-keeping, which is a term that assembles the whole set of precautions that are necessary for the academic work

place to run efficiently and qualitatively but usually not being recognised in the academic career. Gender studies show that the distribution of the academic house-keeping is clearly non-uniform and most of it is performed by women. In our context, with few women, also administrators, PhD-students, researchers and research engineers tend to do the house-keeping. Thus, some of us more than others, make the seminars or other events meaningful and valuable. Even though, the collaborative and solidary academic culture within some of the research groups has been a key factor of the successful development since last RAE, it seems to be a cultural acceptance for unequal participation in the diversity of university activities.

Some examples of formal meetings at the department where research is discussed:

- Research group meetings – the format can differ between research groups. What they have in common is that they are regular and follow a structure. In more applied research constellations faculty and graduate students work in teams often in interaction with industrial partners.
- Scientific workshops are a common place to discuss new research initiatives among academy, industry and governmental agencies. These are typically organized and sustained by the research centres, such as CCGEx , BioMEx Center, ECO2… (etc.)
- The Strategic Innovation Programmes launched by VINNOVA gives another platform of meetings to discuss research in various formats, e.g. conferences, round table discussions, seminars and targeted workshops.
- KTH's research platforms, e.g. KTH Transport Platform and KTH Industrial Transformation, have initiated workshops and conferences to discuss research matters and strategy. The breadth of research areas in these platforms allows for fruitful multi-disciplinary discussions, including the exposure to different academic cultures within KTH.
- Journal clubs and workshops are organized locally at the department with goals to increase critical evaluation, support and coach one another for presentations (collegial supervision).
- The KTH Space Center at the department is the key hub for multi-disciplinary strategic discussions on space research at KTH and possible collaborations. Here, monthly reference group meetings are organized.
- Every 6-8 weeks the research center CCGEx organize online reference group meetings via *Skype for business* with industry, faculty and PhD students.
- There are good examples within the department where active PhD and postdoc groups have emerged. This is a meeting format where they present and discuss their own research topics, without the presence of supervisors.
- Most units have regular "Swedish fika", where all types of matters are brought up and discussed in an informal manner and quite often research questions are ventilated. In addition of being another meeting point for research this social gathering contributes to a nice working atmosphere.
- In the various labs at the department regular senior lab meetings are held, which is the main platform where research infrastructure and personnel including lab maintenance are discussed locally. As an umbrella to these labs

we have the Odqvist Laboratory with its own management group and board, whose members consist of staff from the department.

- There is also an example of weekly meetings with a fixed agenda where the entire unit gathers, including PhD students, postdocs as well as technical staff apart from researchers and faculty, where deadlines of scientific conferences and research proposals are announced.
- Another format of research activity where scientific journal publications are being paid attention to is the so-called "Paper cake meeting". This type of meeting typically takes place 4 times a year where one of the authors presents a recently published paper in 5 minutes. Typically, there are 3-4 papers presented per meeting, which is followed by cakes and coffee.

Research groups within units have often weekly "pulse meetings", where the members meet to give a short update on their scientific projects, absence dates, teaching, and where from time-to-time short/long term research goals are outlined.

3c. Current faculty situation

The total faculty of 56 persons consists of 30 (5 female) professors, 21 (4 female) associate professors, 5 assistant professors (1 female). There are three balances that need to be discussed: age, positions and gender.

The age balance differs between the disciplines and in some areas there is a fairly good balance (Naval, Road and Rail, Aeronautics, Fluid Mechanics, Biomechanics) whereas other areas soon will face substantial retirements and need to make new recruitments (Solid Mechanics, Sound and Vibration, Space).

The upcoming retirements are also a factor behind the second balance to be discussed, namely the balance between associate and full professors. With retirements and the following recruitments, which will primarily be made at the assistant professor level, the portion of the faculty that are full professors will not increase even when promotions from associate to full professor are taken into account. It is also worth mentioning that during the last decades, professors have been appointed to rectors at KTH and elsewhere, pro rector, vice rectors and deans. These full-time or near full-time appointments mean that the number of full professors that are active is lower than the number listed above.

When it comes to gender, the situation varies over the department. Even though the situation improves (i.e. the female/male ration among faculty is increasing) slowly but there are still several units where all faculty is male. Anecdotally, one can get the impression that units or groups with senior faculty that are women also tend to be more probable to have female faculty on more junior level. The upcoming generational renewal is an opportunity to improve the gender balance and it must be ensured that no opportunities are lost. Furthermore, a speed up of this rather slow procedure could probably be facilitated by recruiting guest, affiliated and adjunct faculty that increase the female/male ratio.

3d. Recruitment strategies

A detailed faculty development plan for the new department is yet to be created. With that said, the department of course needs to maintain high competence in combination with the strong loyalty to KTH that historically characterizes KTH faculty, other employees and students. When recruiting faculty, it must be ensured that positions are announced with wide enough subject descriptions and attractive conditions in terms of academic environment, access to infrastructure, funding and other aspects. This is necessary to ensure a significant number of high-quality international applicants. Secondly, it is important that the department helps in speeding up the evaluation process as much as possible, since the KTH procedures tend to take a fairly long time and candidates might not be available any more if they have already received other positions.

We will develop department wide activities that enhance the postdoc experience at KTH. Talented postdocs are key to maintain high quality research activities, and by demonstrating that we care, both while they are with us and when it comes to their continued careers, we hope the KTH Engineering Mechanics can remain/develop into an attractive postdoc destination. In order to have access to talented postdocs, it is of course also necessary to maintain and share our international networks.

PhD student recruitment is typically done by a PI who has received a grant. From a strategical perspective, there are two aspects of such a recruitment that need to be addressed. The first is to ensure that the advertisement is formulated and spread in a manner that attracts high quality applicants of all genders. The second strategical aspect is the selection of the candidate. Here, professional assistance has proven to be very useful to scan large set of candidates and probe for competencies that the typical PI cannot detect. Furthermore, it would probably be wise to provide a structure for “second opinions” from colleagues regarding candidates that are highly ranked by the PI.

3e. Infrastructure and facilities

The department comprises large lab facilities, specialized towards different fields and applications of mechanics, more specifically solid and fluid mechanics, including lightweight structures and materials, biomaterials and acoustics (fluid and structural). There are also labs or parts of larger labs that are devoted to aeronautics, space technology, road and rail vehicles, naval architecture and biodynamics/biomechanics. The lab facilities constitute part of the backbone for many of the research groups for which experimental work is an integral part of the research. The experimental work is partly “bread and butter” in the sense that it provides measurements and characterization for model input, analysis and verification. Other activities are focused towards experimental method development, new manufacturing technologies and innovative material production. In connection to the labs, there are several workshops with workshop technicians. The setup and capabilities of each workshop together with the competences of the affiliated technicians is to some extent geared to the lab even though a portion of the workshop tasks are of a more general nature.

The majority of the labs are coordinated through the center *Odqvist Laboratory for Experimental Mechanics*, which started as a joint initiative between the three former departments several years before they merged into one. The coordination helps addressing common goals and challenges, facilitating joint applications for expensive equipment, avoid unnecessary redundancy of hardware and sharing knowledge, experience and expertise. The Odqvist Lab is acknowledged as one of KTH's eight experimental infrastructures for research. Several of the department's labs are also parts of and resources for larger national and international research centra and international collaborations that research groups at the department are engaged in.

The laboratory resources at the department are used in parallel for research, education and collaboration projects with industrial partners and research institutes. Many of the laboratories have been built and developed for decades to support research and education. They are well equipped and renowned, in Sweden and in international communities, for advanced experimental capacity and competence. They are also frequently engaged by external clients who seek expertise in experimental work. New lab units have also been established recently to support emerging research in e.g. human motion mechanics (MoveAbility) and underwater robotics (SMaRC).

Two important additional aspects of the laboratory infrastructure are the personnel and competence development and the role of the infrastructure in the education. Starting with the latter, the physical infrastructure with integrated laboratory facilities and creative educational workspaces enables bridging between research and teaching, promoting further development of the engineering education in the spirit of the CDIO concept as well as vitalised experimental research activities. The available experimental resources have enabled many important research grants and collaborations with enterprises and society.

The second aspect, namely personnel and competence development, is handled somewhat differently in different labs. Some labs are maintained by lab supervisors, who also are able to assist and have expertise in many if not all kind of measurements that are made in the lab. Other labs are dependent on a continuous competence transfer between PhD students and postdocs to maintain the capabilities. Such a setup is of course fragile, but sometimes necessary when a wide spectrum of quite specialised needs is at hand.

In addition to physical labs, codes and computational resources are important infrastructures for the activities at the department. A variety of commercial solvers for computational fluid dynamics (CFD), computational aeroacoustics (CAA) and finite element analysis (FEA) as well as developmental research "in-house" and advanced post-processing codes are generally available. The department has access to several high-performance clusters for parallel computations including a Cray XC40 system with a theoretical peak performance of nearly 2 petaflops. Access to these facilities is allocated by committees in Sweden (SNIC/SNAC), in Europe (through the Partnership

for Advanced Computing in Europe, PRACE) and in the United States (through resources from the Department of Energy, DOE). At department level, a division(B) UNIX-cluster is supported by a local file system which makes data management and file sharing among researchers easy. There is a local computational cluster designated for solid mechanics, enabling a high degree of customization in terms of available software, compilers, storage, easiness of use, etc. Having it locally enables immediate access and a high throughput.

Several research groups at the department work with large-scale simulations of turbulent flow, acoustics and vibrations, and are largely dependent on High-Performance Computing facilities. This applies to both basic research from first principles, often together with international academic partners, as e.g. in the Swedish e-Science Centre, and to more applied research projects in collaboration with industrial partners, as e.g. in the Centre for ECO2 Vehicle Design and the Competence Center for Gas Exchange. In the Solid Mechanics unit, on the other hand, the majority of the PhD students and post-docs use local computational clusters for their research. In the future more data storage is required, which likely would benefit from coordination at school or university level, not necessarily at the department level.

The labs have been successful in applications for larger investments in state-of-the-art equipment and test platforms and facilities, although such funding opportunities have become fewer in recent years. It has partly been compensated by internal strategic allocation of resources, centrally at KTH, where the department has also been successful in the internal competition for such means. That is of course positive but also brings challenges since more advanced equipment is expensive also to support and maintain, and funding for such costs seldom comes with the funding of the equipment. In order to build, maintain and develop experimental capability we also need to build and maintain competence among key staff. Allowing that experimental competence to a great extent depends on heritage between PhD students makes it very vulnerable and makes long term strategic development and quality assurance challenging. A “critical mass” of technicians and research engineers has to be assured both for continuity and sustainability. Unfortunately, the required level of expertise of such personnel, and thus the associated costs, is also constantly increasing.

In conclusion, maintaining and developing an extensive infrastructure as described above does not come without challenges. The new department opens up possibilities when it comes to coordinate lab staff across the department. Such coordination could bring substantial synergies. However, it is a challenge to organize such coordination in a manner that encourages collaboration while still satisfying the different groups needs when it comes to fundamental studies in specialized disciplines.

Another continuous challenge is the costs for lab premises, since they increase at a considerably higher rate than the basic funding to the universities from the government. The increase in cost for the premises has also been sudden and difficult to predict, which causes stress and at times a feeling of fatigue. This is a key question

for the department, since external funding agencies are many times reluctant to provide full coverage for "overhead costs".

In short, the experimental facilities and infrastructure are necessary for the high-quality research (and education) at the department. However, the expenses to maintain these facilities are in general difficult to fund through allowances in available research grants. It is clear the KTH infrastructure initiative has been instrumental to, to some extent, offsetting this issue.

4. Strategies and organization

4a. Goals for development 5-10 years ahead

In ten years, the department aims to be one of the most exciting places in the world where disciplinary excellence, high level multidisciplinary works and fascinating demonstrators on both high and low TRL-levels are produced in a collaborative manner and the links between research and education are strong.

In order to reach this ambitious goal, arenas for cross-disciplinary and technology discussions beyond organisational borders must be created. A first step in this direction is the formation of *thematic areas*, that will facilitate discussions and interaction between researchers from different units. Future plans include a formalization of technology platforms, that can be used to make sure that good fundamental ideas from fundamental disciplines are brought to, or at least tested at, higher TRL-levels.

4b. Congruence with university-level goals for research as set out in "A leading KTH – Development plan 2018-2023" and with the schools development plan(s) respectively.

The congruence between the department's development and the university-level goals is very good. This is demonstrated by providing the goals for research set out in the development in italics, followed by a comment on how the department is aligned with these goals.

A leading KTH conducts applied research augmented by curiosity- driven basic research and cross-disciplinary collaborations.
From this report, it should be clear the Augmentation of applied research by curiosity-driven basic research is intended to be the core of the department of Engineering Mechanics, and a firm basis for cross-disciplinary collaborations.

A leading KTH is characterised by digitalisation, sustainable development, internationalisation and equal opportunities.
The department is a national and international leader in digitalization of research in the form of e-science, the research activities are to a large extent motivated by sustainable development, and we have strong international networks and collaborations. We are also making efforts to provide equal opportunities.

A leading KTH works within a first-class joint infrastructure and is driven forward by professional leadership.

The overarching structures of the Odqvist Laboratory and SeRC assist the expertise and passion invested in the individual laboratories and computational codes resulting in infrastructure of high class that is accessible also by external users. The leadership at all levels strives to act professionally at all occasions and maintain a high level of professionality through courses and other activities.

An integrated KTH recruits and employs teachers who combine great dedication to teaching with world-class research.

The department of Engineering Mechanics intends to assists its teachers to live up to these standards by ensuring that both teaching and research achievements are recognized, by highlighting good examples and by providing support when needed.

An integrated KTH has a robust joint infrastructure that is used for both teaching and research.

All laboratory exercises at the department are made in, or in direct connection to, the research laboratories. On master level, students are working in the research laboratories during project courses and thesis work.

A visible KTH has more teachers and researchers engaged in the public discourse

The research themes of the department: energy, transportation, health and materials, are arguably some of the most critical aspects for the future society. Some of our teachers are present in the public discourse, and we aim at maintaining a continuous discussion ensuring that relevant opportunities are grabbed. An illustration of the societal relevance of our activities is that the combined contribution from the governmental agencies TRV, FMV and SSM is one of the five major funding sources of the department 2019.

An open KTH employs teachers and researchers who to a large degree move between academia and society

The department lives up to this goal in two ways. The first is by recruiting faculty with industrial experience. There are several examples of this, including the latest employed assistant professor. The second is by encouraging faculty to engage in mobility programs. There are multiple examples of faculty who for a period of time has spent part-time at industrial companies. In many cases, such periods has ignited new research directions.

An increasingly digitalized KTH has increased its world-class research into digitalisation in various areas

Our utilization of machine learning methods in combination with high fidelity numerical simulations or processing of large datasets from experiments or simulations show that we are at the forefront of this development. A high competence when it comes to digitalisation is necessary in order to for us to be a driver when it comes to digitalisation of “our” applications.

A more sustainable KTH develops research areas with sustainability as their natural driving force
To a large extent, our activities related to energy, transport, health and materials are already motivated by economic, ecological or societal sustainability. For some activities, fully or partly related to defence technologies and nuclear energy, a deepened discussion is necessary although the ultimate motivation for the faculty involved comes from the sustainable development goals regarding political stability and clean energy for all.

A more sustainable KTH provides a unique multidisciplinary research and education environment in which different perspectives are integrated
This goal resonates with the CDIO initiative, in which the department of Engineering Mechanics and the Vehicle Engineering Program were key players. When it comes to multidisciplinarity, we hope that our collaborations with the other schools (detailed in the next sentence) eventually will make a clear imprint on the educational activities, including more cross-school project courses and even master programs. We work with the ABE school when it comes to construction and materials and in the transport area, the CBH school when it comes to biomaterials, batteries and processes, the EECS school when it comes to microsystems, satellites, visualization and high performance computing and the ITM school when it comes to energy, industrial transformation and learning. Within the SCI school, there are collaborations e.g. with numerical analysis in the Mathematics department within the INTERFACE project, and with the department of Physics through the KTH Space Center.

A more international KTH has increased its research grants from the EU
The funding to the department from EU has increased year by year and in 2019, EU was the top external funding source of the department (up from second in 2018).

An equal opportunities KTH has gender-aware management
The management group is gender balanced and maintains a continuous discussion on gender related issues.

4c. Leadership structure and collegial structure

One of the opportunities in the new department is the possibility to identify the factors in the formal and collegial leaderships that worked well in the previous departments and take care of and further develop these. At the same time, less functional structures should be identified to avoid transferring them into the new organization.

The department is led by a management group consisting of the head and vice head together with the two division managers. There is also a department "council" consisting of the management group, three directors of studies, the eight unit leaders and the director of the Odqvist Laboratory. It is also intended that the thematic areas are represented in the council. The management group meets weekly and discusses all aspects related to the department. The department council meets weekly during the corona-period but will have less frequent meetings once things are back to

normal. The department council is meant as a forum for information in both directions. The intention is that the council will identify aspects that need to be discussed, even though the discussions are not necessarily held in the council. Furthermore, each division has a management group, where the head of division and unit leaders discuss all questions related to the activities.

The management group is responsible for the department's economy, strategy on department level including pursuing new faculty positions, and interaction with the school and KTH. The units are responsible for the management of the research groups that belong to the unit and for the economy of the unit. The divisions serve as an interface between the department and unit levels. The intention is also that the two divisions shall let the units focus on the aspects that need to be developed without too much interference from units with very different needs.

Each unit typically consists of a number of research leaders. Each research leader takes the responsibility to set general goals and directions of his/her research and supervise the individuals (PhD students, PostDocs, researchers) that are engaged in his/her research area. The exact format of how the collegial structure is in terms of group meetings, seminars, varies in-between research groups and units. The level of "collegial" also varies. In some units and groups, several research leaders have joined forces and established joint groups.

In the new department we are striving to create a formal and collegial structure that promotes faculty from different organizational units to meet and discuss research, educational and work environmental matters. The responsibility of this work has to be shared by both the formal and collegial leadership. However, the formal leadership has the responsibility to facilitate the organizational structures that promotes and encourages collegial discussion and collaborations focused on future research subject/areas/challenges. Such initiatives may be promoting and stimulating development within strategic areas or coordinate efforts to apply for thematic funding of research. An example of this are the thematic research areas that was formulated in the startup of the new department. The initiative came from the formal leadership, but thematic areas identified by faculty members from the former three departments. The thematic areas span over all units, and if these are to be successful depends on the motivation and will of the "researching body". If this is to be successful, the formal leadership needs to support this development.

4d. Strategies for high quality

In order to achieve high quality, a combination of formal procedures and continuous informal discussions are necessary. Research results at the department are typically produced in a context that is closely related to the PhD education. There are thus a number of formal requirements maintained by KTH and an important task of the department is to ensure that the complementing discussions happen and that everyone involved is assisted in first understanding and then striving towards the relevant requirements. Important tools in this work (aimed at different career stages) are supervision meetings, group meeting and performance reviews.

However, the KTH requirements typically set a minimum level but do not give much guidance on how to reach beyond this level. Of course, the research at the department typically goes far beyond the minimum required but the department has not yet developed and implemented a cohesive quality system. When such a system is in place, important factors will probably be:

1. identification of publication channels that would, by us or from an outside perspective, be considered as an increase in quality, or would improve the dissemination of the results;
2. assistance in organizing collegial discussions on how contributions in these publication channels differ from the typical publications from the group/unit;
3. a critical reflection over whether these differences are imprints of quality, jargon or other aspects;
4. definition of actions that with a high probability will lead towards publication in the identified publication channels; examples of such actions can be redefining research questions, identify collaboration partners whose contribution would complement the work, adjusting the style of presentation or selection of material to be presented, or others.

However, it must be noted that scientific impact of our publications is an important, but not the only indicator of quality. Employability of our PhD students, and being an attractive research partner for industry are two other important factors. In order to maintain a high relevance for different societal actors, the knowledge transfer occurring during collaborations with these actors is critical. Such collaboration is achieved by obtaining funding in schemes aimed at supporting such collaboration, maintaining a significant number of adjunct faculty and participate in mobility programs.

5. Interaction between research and teaching

5a. Interaction between research and teaching at all three levels (BSc, MSc, PhD) of education

Economically, teaching at BSc and MSc level represents approximately one sixth of the turnover of the department (equally split between the levels). The department contributes with courses in basic mechanics, solid mechanics and fluid mechanics to 12 of KTH's 19 five year engineering programs. On the master level, the department is the main stakeholder in five master programs:

- Aerospace Engineering
- Engineering Mechanics
- Naval Architecture
- Railway Engineering
- Vehicle Engineering

The PhD education is organized in three PhD programs

- Vehicle and Maritime Engineering
- Solid Mechanics
- Engineering Mechanics

Two of the three departments that merged into Engineering Mechanics (Aerospace and Vehicle Engineering, and Solid Mechanics) have been global thought leaders when it comes to engineering education for nearly two decades through the CDIO initiative (Conceive, Design, Implement, Operate). The aim of the CDIO initiative is to develop an educational environment that educates "Engineers that know how to engineer" by combining (i) strong abilities in engineering fundamentals (math, physics, programming, electronics, basic mechanics, solid mechanics, etc), (ii) advanced knowledge in the chosen field and (iii) an ability to develop value creating systems in a multidisciplinary and diverse context. The above forms the underlying educational philosophy for most of the faculty at Engineering Mechanics. From a research perspective, more than a few teachers have contributed to the literature on engineering education in addition to their contribution to respective research field.

The contents of the basic courses at the Department are well established. Changes in the basic courses can be characterized as continuous improvements. Challenges here are to follow and possibly adapt recent findings in engineering didactics research, but also to adopt new technological possibilities for assessment, and continually adjust the content so that it still provides the necessary basic knowledge but also is appropriate given the present state of engineering tools such as computational methods and experimental techniques.

The basic courses in acoustics and solid- and fluid mechanics, as well as many MSc courses, contain laboratory exercises. These laboratory exercises are performed in the actual research laboratories. Thus, the students are exposed to the research activities in the laboratories during these exercises even though the content of many exercises as such is of a fundamental nature. Thus, most of the laboratory infrastructure at the department serves educational purposes in addition to their role in the research activities. It is a well-known fact that experimental research activities are financially demanding. This is also the case for many of the units in the Department. Thus, the laboratory works related to teaching activities, both on the basic and advanced level, are a mean to secure economic soundness of the laboratories and thereby ensuring future experimental research activities.

Most of the courses at MSc level are developed and/or changed on a regular basis. The driving forces for this are both new trends in industry and in research. Recently developed MSc courses are almost entirely based on developing research areas. On the other hand, redesigns of courses have been motivated by both industrial demands and research trends of the Department.

In addition to the direct links between research and education in the master thesis projects, the department gives several *capstone courses*, i.e. courses in which a student group executes a project in which they need to combine the knowledge gained from all their courses. These projects also include redefinitions of the task as the understanding of the problem at hand develops. The topics for the projects in these courses are often chosen so that the students get in touch with research activities.

The PhD level courses are highly influenced by development of the research at the Department. This is valid for more general PhD level courses but of course even more so for specific courses dealing with a specific research area at the Department.

Many of the PhD-students at different units in the Department are very much involved in teaching both on the basic and on the advanced level. In this context it should be emphasized that teaching on the basic level gives the PhD-student important fundamental knowledge about mechanics which is of great value in their research activities. This is of course also true for teaching in the advanced level courses but in this case it is more related to a specific research area. Accordingly, in general it is at the Department considered that teaching is a very important part of also the research activities. This is particularly so for PhD-students but to some extent also for faculty

Another obvious coupling between education and research at the Department concerns thesis work on the MSc level. Many thesis topics at the Department are closely integrated with a particular research project or research area. Such a thesis work often leads to journal articles or conference proceedings. This is certainly beneficial for the Department (but also for an MSc student with doctoral studies in mind). Also, thesis works performed in the industry are sometimes directly related to the research at the Department or can lead to industrially funded research projects or industrially supported research applications.

On the PhD level, the research centra have come to provide a crucial link between current research and the education by offering specialized courses. These courses are not limited to the department when it comes to content and participation; they typically have a national or international perspective. The centra ECO2, FLOW, BiMAC, SeRC, CCGeX and ITRL have all organized such concentrated courses focusing on current topics on a regular basis. (The courses are often called “Summer courses” although they can be given all year round.) These courses utilize the international networks and reputation of the faculty to attract not only top-class teachers but also to attract a critical mass of students. Thus, they fill the dual purpose of (i) making sure that our PhD students get an education regarding the research front that is wider than what is available at the department and (ii) provide a mean by which our research results are disseminated.

Concluding this section, it should also be said that the educational development at the department is characterized by continuous development (often referred to with the Japanese term *Kaizen*) and it is with great interest we look forward to feedback from the panel.

6. Impact and engagement in society

6a. Relevance of research to society at large

From the previous description of the research at the department, it should be clear that there is substantial potential for societal relevance. This potential is turned in

reality by collaborations with societal actors such as companies, hospitals and public authorities. Our work is relevant to, and we collaborate with a large number of small and large companies in Sweden and abroad in the road vehicle, train, aerospace, naval, material (metal and paper), energy, space, food and medical industries (a complete listing is exhaustive and will not be given). We also collaborate directly with clinics on aspects of e.g. ECMO intensive care. At our department we have the contact persons for the strategic partnerships with Saab, Scania and Bombardier.

When it comes to public authorities, it can be noted that a significant part of the funding to the department is provided directly from such sources. The Swedish Innovation Agency (VINNOVA) is usually among our five largest funding sources and the combined contribution from other authorities (excluding VR, the Swedish Research Council), e.g. the Radiation Protection Agency, the Transport Administration, the Defence Material Administration and the Maritime Administration, is often one of the top five funding sources.

In many of these collaborations, the gender perspective is less apparent. However, it is of course present in the medically related work, where gender differences must be addressed in order not to miss out on important aspects.

6b. Research dissemination beyond academia

Research dissemination beyond academia is ensured though a variety of dissemination modes.

For the department of Engineering Mechanics, dissemination starts with our education of engineers and PhDs, including industrial PhD students. By providing highly educated engineers to the industry and other societal actors, we establish a necessary precondition for dissemination and utilization of research results. In the case of PhD students, there is also a substantial dissemination simply from the fact that the person is present in both the academical and industrial context. A similar philosophy lies behind our affiliated and adjunct faculty as well as the support of our faculty participating in mobility programs.

Research is also disseminated through joint research projects with industries and public authorities, both bilateral projects and multilateral projects as parts of research centers (see earlier listing). Researchers at the department have also patented and, in some cases, commercialised technologies based on the research results (some examples are given in the impact cases below).

Furthermore, our researchers occasionally participate in the public debate through articles, in particular in transport related issues (two fairly recent examples consider domestic air traffic and the development of the Swedish railway network). With irregular regularity (i.e. now and then) we also contribute with popular science presentations in media or educational material.

6c. Sustainability and the United Nations' Sustainable Development Goals

Without doubt, at least 60-80% of our work is motivated by sustainable development. In order to be sure to reach the next level (80-100%), one would need to discuss the necessity of nuclear energy, efficient internal combustion engines and defence in relation to the sustainability development goals and after such a discussion, we would probably reach 80-100%.

This means that almost all of our fundamental as well as applied activities are motivated by sustainable development. The relevance starts with research on biomaterials and energy storage, optimization of fluid mechanical aspects of processes, motors and vehicles as well as efficient material usage by high-performance materials and optimal constructions. On the vehicle and system level it continues to design of safe and resource minimizing vehicles and drones that assist in monitoring our planetary system. Obviously, the health related activities are also strongly connected to the SDG.

In terms of integration since 2015, several research centers and other activities that are motivated by SDG has been active long before that. However, we have complemented the obvious relevance of applied work by activities aimed at ensuring the awareness of SDG among everyone involved in fundamental fluid mechanics research in the FLOW community, (previous Linneaus Center). In practice, this was ensured through an elaborate group activity during annual meetings of the research center 2017 and 2018. As of today, it is probably not possible (at least not advisable) to initiate activities within Engineering Mechanics without ensuring a high relevance with respect to the SDG.

6d. Impact cases

In the following, four impact cases are presented. Three of those are examples of how knowledge from research activities have been commercialized in startups or in pre-existing companies. In these three cases, the link between the research and the impact is very clear. The fourth impact case is of a more scientific nature, but has been included since it demonstrates the inspirational power of science. Often, the impact of our work is hard to derive, since the knowledge produced at the department enters larger companies. Even though there are innovations from those companies that benefitted from the knowledge, the direct link can be hard to derive.

Impact case 1:
Digitized quality assurance of welded structures - towards industry 4.0

Professor Zuheir Barsoum, Department of Engineering Mechanics

Summary of the Impact

Many welded structures could be 20 – 40% lighter in vehicle applications if higher strength steel is used with an increased weld quality which will also result in a higher durability.

Winteria® has developed a sophisticated assessment procedure allowing for faster geometry readings with higher accuracy. The solution contains several numerical evaluation algorithms to allow for stable and objective geometry assessments. The measurement system contains of both hardware and software Winteria®

- Start-up company Winteria AB which have received large publicity and funding, including funding for start-ups by Vinnova Vinn Verifiering
- Commercial product; robust inline quality assurance for welded components in serial production
- The company is incubated by KTH Innovation and STING
- Major Swedish vehicle manufacturers as pilot clients today

Underpinning research

The research that led to this innovation was started in 2010 (Project LOST and WIQ) where a novel weld quality system was developed which had a link to the structural durability of welded components where the international quality standard did not have a link. This new quality system was introduced as corporate standard in several companies (Volvo CE, HIAB, among others). The next challenge was how to assure the quality levels, since the tools and gauges used were to rough and approximate. New research projects were started 2013 (LightStruct and OnWeld) to develop algorithms together with lasers to measure the quality levels digitally and automated in collaboration with Swerea KIMAB. The new concept showed promising result and the involved companies in the projects wanted to have a commercially available system. In 2015, the researchers involved (*Zuheir Barsoum* (professor at the department), *Thomas Stenberg*, *Eric Lindgren* and *Martin Engman*) started the company Winteria AB to commercialize the product. This was supported by KTH Innovation, Vinnova (Vinn Verifiering), STING Incubator, among other organizations. Today several systems are installed at major vehicle manufacturer and steel manufacturers, e.g., HIAB and SSAB, research institutes, e.g. SWERIM and CETIM, and universities, e.g. Lappeenranta University of Technology. The innovative technology has received several prizes and large publicity.

Advantages and expected impact in the future

There are many advantages of introducing robotized and digitalized quality assurance in welding production, particularly when the welded structures and components are subjected to critical loads, e.g. fatigue loading, weld quality becomes of the outmost importance and basically determines the fatigue life. The quality assurance system presented by Winteria also gives a unique ability to optimize the welding production process by increasing productivity and ultimately save weight of the welded structures. Also, it gives a unique possibility for continuous process development and instant feedback about the produced and expected weld quality.

The research that led to the innovative Winteria technology targets several of the UN sustainable development goals; *9 – Industry, innovation and infrastructure, 12 – responsible consumption and production, 13 – climate action*. These sustainable development goals are through increase in productivity by 50 %, saving up to 30 % of filler material usage and reduce component weight up to 40 % while increasing the weld quality of the products. This will enable the production of optimized lightweight welded structure

which will in turn lead to lower environmental impact, reduce emissions and result into more energy efficient products and sustainable use of natural resources. This means that the welding production is enabled to be more efficient, more sustainable and produce better products with increased competitiveness.

Several research projects are ongoing currently at the department including several industrial partners where the technology is further developed. For example, SSAB, Swedish Steel Company, is currently supporting the research group (lightweight structures) with a yearly endowment (2 MSEK/year for 5 year) to continue the research within design and fabrication of lightweight welded structures of high strength steel.

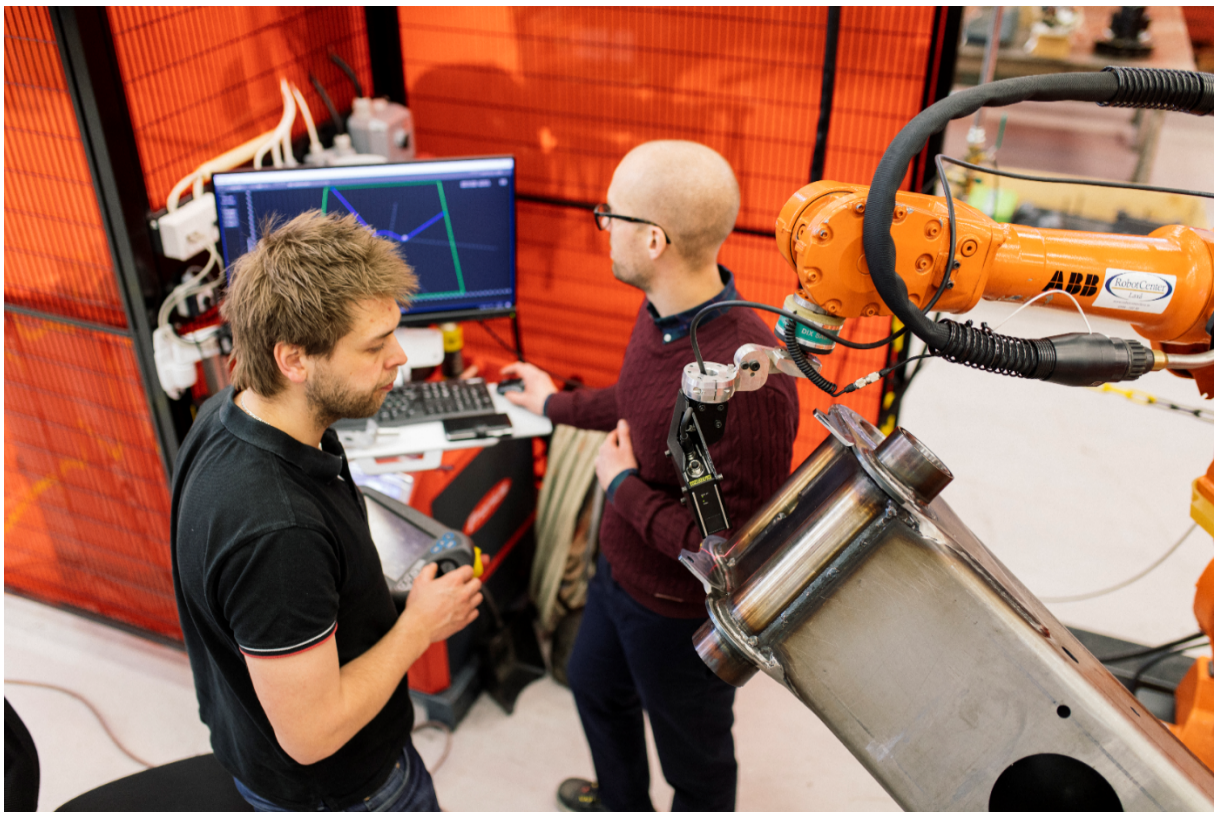
Sources to corroborate the impact

Users:

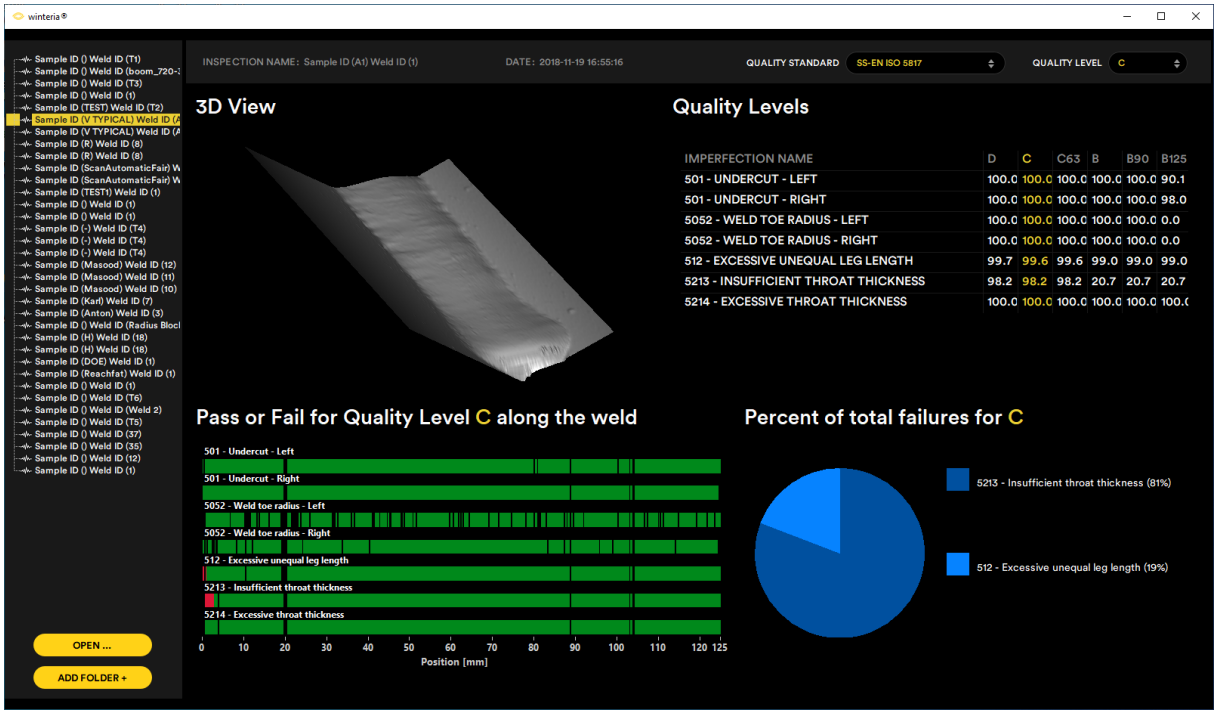
1. Volvo Construction Equipment (Hasse Olsson, Hasse.Olsson@volvo.com)
2. HIAB Cargotec (Svante Widehammar, svante.widehammar@hiab.com)
3. Swerea KIMAB (Joakim Hedegård, joakim.hedegard@swerea.se)
4. SSAB (Mikael Reinberth, mikael.reinberth@ssab.com)

External (*selected*):

1. The Winner of University Challenge 2015 (https://www.youtube.com/watch?v=GR8GUrG6dCk)
2. Commercial marketing video: (https://www.youtube.com/watch?v=TqE6HwapZOY&t=1s)
3. KTH School of Science: from Research to Impact (https://www.youtube.com/watch?v=hZNyNqbhmtM&t=12s)
4. www.winteria.com



Winteria®: Installation of robotized Winteria system at crane manufacturer HIAB.



Winteria®: One of the GUI:s in the Winteria system. Determining the quality level of a scanned fillet weld. Green bars indicate that current weld fulfills the demanded quality level (D) for all the imperfections types according to the international weld quality standard ISO 5817.

Impact case 2:
Integration of vascular biomechanics simulation in the clinical decision-making of Abdominal Aortic Aneurysm patients.

Mechanical modelling of soft tissues performed at KTH has resulted in commercial software that is used by a large number of hospitals worldwide to support the clinical workflow of Abdominal Aortic Aneurysm (AAA) patients.

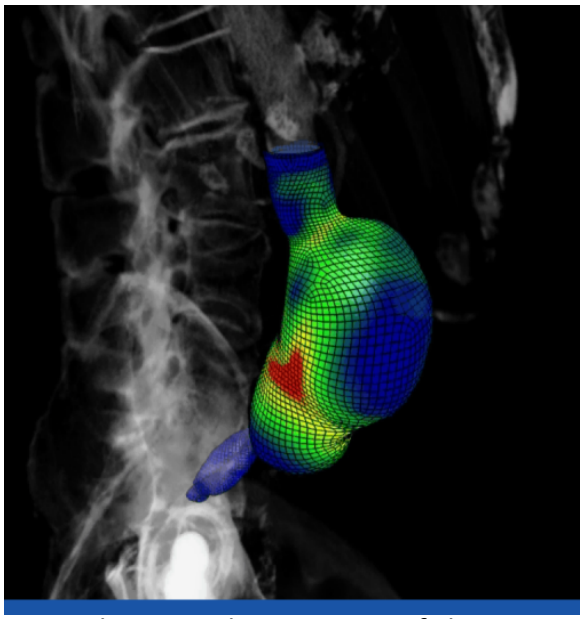


Figure 3: A4clinics screen-shot illustrating the distribution of the wall rupture risk index all over the aneurysm. All steps of the simulation pipeline (image reconstruction, Finite Element computation, visualization) are integrated in stand-alone software, which allows the acquisition of such information in less than 10 minutes.

To foster the translation of the mechanical modelling of vascular biomechanical research into medical applications, the Soft Tissue Mechanics (SBT) team established contacts with a number of vascular clinical institutes. This allowed them to build a highly effective network (see Table 1) towards the delivery of targeted biomedical research. Given these activities, the group became one of the most well-known groups in AAA research, amongst both, engineering and clinical researchers. Approximately half of the group's current research is published in premium clinical journals and Gasser is a frequently invited speaker at clinical meetings. It also allowed the team to acquire funding towards the commercial exploration of a system that helps vascular clinicians in making a decision whether or not an AAA should be surgically treated. Figure 1 shows an A4clinics screen shot that illustrates the distribution of a rupture risk index, whilst Figure 2 demonstrates the workflow and the clinical diagnostic report that is generated by A4clinics. The acquisition of this information requires less than 15 minutes on standard PC hardware and the software is commonly operated by medical-trained users, such as medical PhD students and surgeons.

Aside from turning the research of the SBT team into a commercial software, the team also pushed the business development tasks, such as patenting (A4clinics is patented by PCT/EP2008/064157) and CE approval of the proposed simulation approach. A4clinics was the first ever

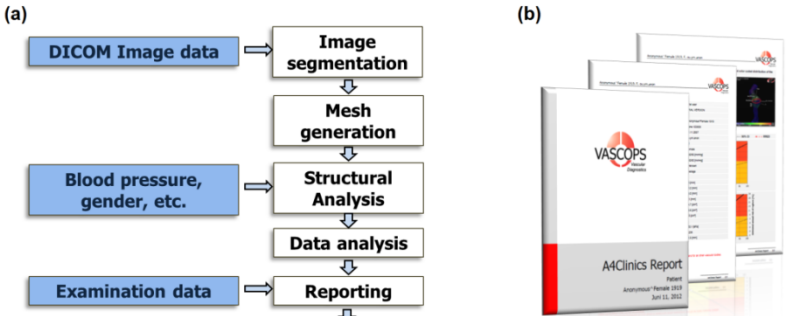


Figure 4: A4clinics simulation pipeline (a) and diagnosis report (b) for clinical decision making.

developed software of this kind that successfully has been CE approved as a class 2b medical device for the European market. The software has been used by almost 20 hospitals to collect information for the next step, the routinely integration in the clinical workflow of AAA patients.
Given a training session of four hours, clinical users without any prior experience in engineering modelling are able to use the software. Aside from direct distribution to the hospitals, ARTEC Diagnosis AB (supported by the VINNOVA innovative start-ups program) has been installed to push a service centre-based model towards bringing this technology into routinely clinical application. The service centre-based business model is more flexible in the adaptation to clinical needs. Aside from these actions, ongoing engineering developments aim at integrating ultrasound follow-up images, considering time aspects of aneurysm disease, and enriching our decision support system with machine-learning-based techniques.

Table 11: List of clinical contacts related to the development of A4clinics.

United States
Stanford: *Stanford University, California, USA* **Prof. Ronald L. Dalman (**Chief of Vascular Surgery at Stanford University, elected vice president of the Society for Vascular Surgery**)**
Australia
Townsville: James Cook University **Prof. Jon Golledge**(Professor of Vascular Surgery and Head of the Queensland Research Centre for Peripheral Vascular Disease)
Belgium
LIEGE: Cardiovascular Surgery Department, University Hospital of Liège,Belgium **Prof. Dr. Natzi Sakalihasan** (Organiser of the International Meeting of Aortic Disease)
Denmark
ODENSE: Elitary Research Centre of Individualized Medicine in Arterial Disease (CIMA) Department of Cardiothoracic and Vascular Surgery, University Hospital of Odense **Prof. Dr. Jes Lindholt** (Editorial board member of the European Journal of Endovascular Surgery)
France
PARIS: Departments of Vascular Surgery and Vascular Imaging, Henri Mondor Hospital, University Paris Val de Marne, Paris **Prof. Dr. Jean-Pierre Becquemin** (Founder of the Controversies and Updates in Vascular Surgery meeting, Board Member of the European Journal of Vascular and Endovascular Surgery, Member of 7 national and international Vascular Societies)
LILLE: Department of Vascular & Endovascular Surgery, Aortic centre, Hôpital cardiologique, CHU Lille, France

Prof. Dr. Stephan Haulon (Co-director of the European Vascular Course, Member of the Society for Vascular Surgery) **Associate Prof. Jonathan Sobocinski**
Germany
HEIDELBERG: Hospital for Vascular & Endovascular Surgery, Heidelberg, Heidelberg, Germany **Prof. Dittmar Boeckler** (Board Member of the German Society for Vascular Surgery, Editorial Board Member of 5 medical journals, Member of the European Society for Vascular Surgery and the International Society for Endovascular Specialists)
MUNICH: Klinikum rechts der Isar of the Technical University Munich, Department of Vascular and Endovascular Surgery, Munich, Germany **Prof. Dr. med. Hans-Henning Eckstein** (President of the UEMS Board and Section of Vascular Surgery, formerly president of the German Vascular Society, honorary member of 3 national Vascular Societies, Secretary of the Zeitschrift für vaskuläre und endovaskuläre Medizin and Organiser of the Munich Vascular Conference)
AUGSBURG: Universitätsklinikum Augsburg, Klinik für Gefäßchirurgie und endovaskuläre Chirurgie, Augsburg, Germany **Prof. Dr. med. Alexander Hyhlik-Dürr,** chair of the vascular and endovascular surgery department
Greece
ATHENS: University of Athens Medical School, Attikon University Hospital, Vascular Surgery, Athens, Greece **Prof. Dr. Christos Liapis** (Director of Vascular & Endovascular Clinic at Athens Medical Center, formerly Secretary of the UEMS, President of the European Society for Vascular Surgery and President of the International Society for Vascular Surgery) **Dr. Konstantinos G. Moulakakis**
Italy
PERUGIA: Università degli Studi di Perugia, Cardiothoracic Surgery and Surgery, Perugia, Italy **Prof. Dr. Fabio Verzini** (Task force responsible for European guidelines for aorta treatment)
Poland
BYDGOSZCZ: Department of Vascular Surgery and Angiology, Collegium Medicum, University of Nicolai Copernicus, Bydgoszcz, Poland **Prof. Dr. Arkadiusz Jawien** (Chairman of the Department of Vascular Surgery and Angiology, former President of the European Society of Vascular Surgery)
Portugal
PORTO: Angiologia e Cirurgia Vascular, CUF Porto Hospital, Porto, Portugal **Prof. Dr. Armando Mansilha** (Chairman of the Annual Conference of the European Society of Vascular Surgery)

Serbia
BELGRADE: Clinic for Vascular and Endovascular Surgery, Serbian Clinical Center, Faculty of Medicine, University of Belgrade, Belgrade, Serbia **Prof. Dr Lazar Davidović** (President elect of the European Society of Cardiovascular and Endovascular Surgery) **Dr. Igor Koncar** (Advisor to the Board of the ESCVES; Member of the Guideline committee of the ESVS)
Spain
BARCELONA: Department of Cardiovascular Surgery, Institut of Cardiovascular Diseases, Hospital Clínic, University of Barcelona, Barcelona, Spain **Prof. Dr. Vincente Riambau** (former President of the European Society for Vascular Surgery and Vice President of the International Society for Vascular Surgery)
Sweden
Stockholm: Karolinska Institute and Hospital **Prof. Dr. Ulf Hedin** (Head of the vascular surgery unit at Karolinska Hospital) **Prof. Dr. Rebecka Hultgren** (Vascular surgeon and co-founder of the Stockholm Aneurysm Research (STAR)) **Dr. Joy Roy** (Vascular surgeon and co-founder of the Stockholm Aneurysm Research (STAR))
Switzerland
BERN: Dept. of Cardiovascular Surgery, Bern University Hospital, Bern, Switzerland **Prof. Dr. Jürg Schmidli** (Former president of the European Society of Vascular Surgery)
The Netherlands
EINDHOVEN: Department of Vascular Surgery, Catharina Hospital, Michelangelolaan 2, 5623 EJ Eindhoven, The Netherlands **Dr. Marc van Sambeek** (Board Member of the European Association of Percutaneous Cardiovascular Interventions congress, Board Member of the European Association for Percutaneous Cardiovascular Interventions)
United Kindom
LONDON: St. George's Vascular Institute, London, United Kingdom, NHS Foundation Trust, London, UK. **Dr. Alan Karthikesalingam**
LEICESTER: Department of Cardiovascular Sciences and the NIHR Leicester Cardiovascular Biomedical Research Unit, University of Leicester, Leicester, UK **Prof. Dr. Matt Bown** **Dr. Athanasios Saratzis**

Impact case3:
Curl simulation toolbox: a way to reduce paper waste

The computational toolbox developed by KTH is being used in creation of a new generation of large-scale digital printers by Océ Canon meeting "Zero Waste" requirements.

KTH has developed a computational module enabling the simulation of the response of fiber networks to water application at both the micromechanical and continuum level. The tool is packaged and transferred to Océ Canon in two training sessions. Océ Canon is a world-leading company specializing in high-speed inkjet printing, which is a modern way of delivering flexible printing solutions, fully digitalized and customizable in every print. Paper is exposed to water-based inks during such a printing process. Due to the absorption of the ink, the fibres composing the paper swell, causing global deformation of the paper sheet. The challenge of inkjet printing system designer is to maintain the printing quality and control the undesired deformations. The paper sheet that does not pass the dimensional stability control after printing has to be dismissed together with a number of already printed sheets that follow it. Therefore, successfully addressing the underlying problem effectively reduces undesired waste and contribute to a sustainable development in printing.
Purely experimental research has been very valuable to characterize the existing paper grades, their performance and to identify the problems. However, due to the complexity of the problem and many parameters involved, a number of factors related to the paper structure cannot be accurately controlled. The computational tools include implemented constitutive modelling routines and accompanying fitting methods. They are currently used to improve the design of the drying unit in high-performance printers.

The major contributions to this research come from Professor A. Kulachenko, Dr H. R. Motamedian (graduated in 2018), Dr R. Mansour (Researcher), A. Brandberg (PhD candidate) and M. Alzweighi (PhD candidate). The developed tools are unique and are used in collaborative research with VTT Research Institute of Finland, Technical University of Darmstadt (Germany), Technical University of Graz (Austria). The work has been conducted between 2017 and 2019. The result of the work has been published. Two more papers are under preparation and will be submitted during Spring 2020.

[1] Motamedian, H. R., & Kulachenko, A. (2019). Simulating the hygroexpansion of paper using a 3D beam network model and concurrent multiscale approach. International Journal of Solids and Structures, 161, pp. 23-41 (https://doi.org/10.1016/j.ijsolstr.2018.11.006).
[2] Brandberg. A, Motamedian, H. R., Kulachenko, A., & Hirn U. (2020). The Role of the Fiber and the Bond in the Hygroexpansion and Curl of Thin Freely Dried Paper Sheets. International Journal of Solids and Structures (online since February 19, 2020 https://doi.org/10.1016/j.ijsolstr.2020.02.033).

Company references: Louis Saes (louis.saes@cpp.canon)
Ern Clevers (ern.clevers@cpp.canon)

Training sessions: https://www.youtube.com/watch?v=PvENwmiY7Sw
https://www.youtube.com/watch?v=2bU3_dJGI_4

A consequence of the favourable accomplishments of the *Fibre Based Materials and Packaging Technology* research group, both in science and in industrial impact, is a noticeable increased interest from industry to work jointly and directly contribute research funding, e.g. in the form of master thesis and post-doc projects.

Impact case 4:
Hydrodynamic assembly of exceptional nanostructured materials

Summary

Fundamental fluid mechanic research at the department has been instrumental to develop a patented technology for assembly of nanostructured biomaterials with exceptional mechanical properties. The results were published in Nature Communications 2014 (continued efforts were published in a paper that was the most downloaded paper in ACS Nano during 2018). The key to the scientific achievement was to combine fundamental understanding of (i) flows in channels and (ii) the behaviour of elongated particles in flows with state-of-the-art regarding cellulose nanofibrils (CNF) available through participation in Wallenberg Wood Science Center.

The case and its impact

The starting point for this impact case is a paper in *Nature Communications*[1], which reports that cellulose nanofibrils (CNF) can be assembled into strong filaments utilising flow-focusing. The high impact of this work stems from the fact that it combines (i) preparation of a cellulose material with exceptional properties, (ii) use of flows to achieve a material with aligned nanofibrils and (iii) characterisation of the dynamics of the fibrils in-situ using synchrotron X-ray radiation and polarized optical microscopy. In other words, the work includes a breakthrough in material science achieved through innovative application of fundamental fluid mechanics. The work reported in the paper was a result of transdisciplinary work within the Wallenberg Wood Science Center.

The publication [1] was reported in Swedish as well as international media and was included as a highlight in the annual report of the research centre DESY in Hamburg, where the synchrotron measurements where performed. The work was even used on the DESY Christmas card for 2014! The technology as such is patented[2] and process development efforts that aim at turning the scientific discovery into a useful and more sustainable alternative to e.g. cotton or glassfibres (in textiles and composites) are presently underway at RISE AB.

With time, the scientific reach and significance of the work has grown further and this is probably best illustrated by a paper recently published in ACS Nano[3] where continued developments are reported. Now, even better understanding of the coupling between the properties of the raw material, the process and the final filament has been developed, together with even better mechanical properties of the filament. The later paper (which was published after the program period but is used

to demonstrate the exceptional significance and reach of the work presented in the impact case) is the most downloaded paper in ACS Nano during the last 12 months and its outreach is measured by its Altmetric score of 785 (this score puts it among the 0.1% top papers tracked by Altmetric so far). As mentioned, the attention given to the later paper[3] further supports the impact of the first[1].

The societal impact for this case comes from the widespread media coverage, and the fact that the work and results serves as an inspirational example how multidisciplinary knowledge makes it possible to develop novel materials from a widestread source (trees). This impact continues and recently the organisation "Swedish Forest Industries" produced a film that is meant to be used in Swedish schools, where the novel material and research behind it is explained.

Underpinning research

The impact case[1] is underpinned by research in fluid mechanics as well as preparation and colloidal chemistry of cellulose nanofibrils. We will here shortly describe and give some examples of the enabling fundamental fluid mechanics research at the department.

The research leading up to the impact case originates from our interest in papermaking[4]. The first aspect we have investigated thoroughly is the motion of elongated particles (e.g. fibres) in different flows. Different aspects of this problem have been studied experimentally, theoretically and numerically for a long time at the department. Some selected examples are fibres in shear near a wall[5], the effect of particle inertia on an ellipsoid in infinite shear[6] and the combined effect of fluid and particle inertia on an ellipsoid in shear[7].

The second papermaking-related fluid mechanical research critical for the impact case is the behaviour of jets and wakes in different configurations, e.g. a flapping liquid sheet with coflowing air[8] or the stability of jet and wake flows in confined geometries[9].

The impact case came into being as the fluid mechanical insights from these and similar works met state-of-the-art regarding the colloidal behaviour of charged cellulose nanofibrils (they were brought together as a part of the Wallenberg Wood Science Center). Further on, the work on hydrodynamic assembly[1] was performed in parallel with more detailed work on the behaviour of nanofibrils in flows[10].

Key factors

The impact case is a perfect example of successful implementation of the overall strategy of the department: to perform excellent disciplinary research *and* aim towards application of the knowledge towards different applications, in this case material science. The formulation and execution of this strategy is a key factor for the impact case. The impact case also benefitted from a number of activities with the explicit aim to understand what is needed to go from publication in good disciplinary journals to higher impact journals of more general scope.

References

[1] Håkansson, K.M.O. *et al*. (2014) "Hydrodynamic alignment and assembly of nanofibrils resulting in strong cellulose filaments" *Nature Communications* **5**, 4018

[2] Söderberg, L.D. *et al.* (2018) "Method of spinning fibres or extrusion, and the products obtained" *US Patent* 10132005.

[3] Mittal, N. *et al.* (2018) "Multiscale control of nanocellulose assembly: Transferring remarkable nanoscale fibril mechanics to macroscale fibers" *ACS Nano* **12** (7), 6378-6388.

[4] Lundell, F., Söderberg L.D. & Alfredsson, P.H. (2011) "Fluid mechanics of papermaking".
Annual Review of Fluid Mechanics **43**, 195-217

[5] Carlsson, A., Lundell, F. & Söderberg, L.D. (2007) "Fiber orientation control related to papermaking" *Journal of Fluids Engineering* **129** (4), 457-465.

[6] Lundell, F. & Carlsson, A. (2010) "Heavy ellipsoids in creeping shear flow: transitions of the particle rotation rate and orbit shape" *Physical Review E* **81** (1), 016323.

[7] Rosen, T. *et al.* (2015) "The dynamical states of a prolate spheroidal particle suspended in shear flow as a consequence of particle and fluid inertia" *Journal of Fluid Mechanics* **771**, 115-158.

[8] Tammisola, O. *et al.* (2011) "Stabilizing effect of surrounding gas flow on a plane liquid sheet" *Journal of Fluid Mechanics* **672**, 5-32.

[9] Tammisola, O., Lundell, F. & Söderberg, L.D. (2012) "Surface tension-induced global instability of planar jets and wakes" *Journal of Fluid Mechanics* **713**, 632-658.

[10] Håkansson, K.M.O. *et al.* (2016) "Nanofibril alignment in flow focusing: Measurements and calculations" *The Journal of Physical Chemistry B* **120** (27), 6674-6686.