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Panel 8

Panel 8 Mathematics and Engineering Mechanics

Research Assessment Exercise (RAE) 2021, self-evaluation

Coordinator: Prof. Anna-Karin Tornberg
Vice-coordinator: Prof. Sebastian Stichel

Organisation

Organisation schedule

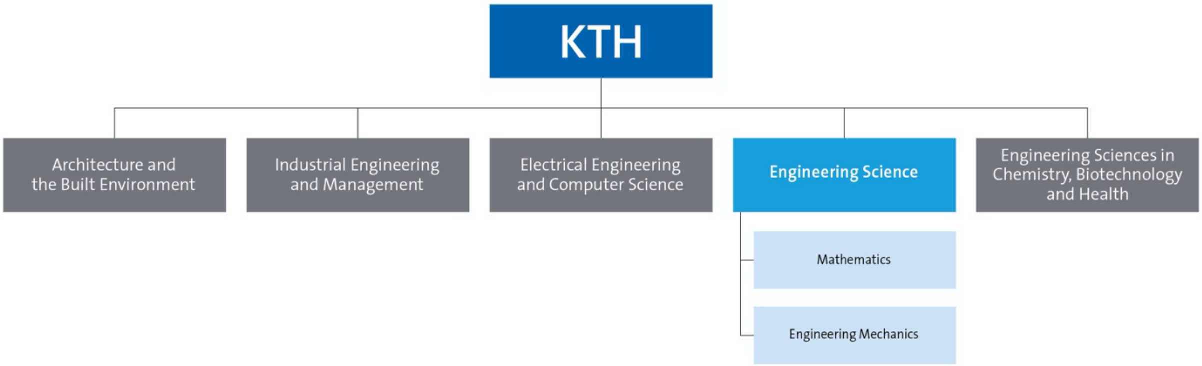


Figure 1: Panel's position in KTH's organisation

Involved units

School of Engineering Sciences, Head of School: Sandra Di Rocco

- **Department of Mathematics**, Head of Department: Mats Boij
  - Division of Mathematics, Head of Division: Mattias Dahl
  - Division of Mathematical Statistics, Head of Division: Jimmy Olsson
  - Division of Optimisation and Systems Theory, Head of Division: Xiaoming Hu
  - Division of Numerical Analysis, Head of Division: Anna-Karin Tornberg
  - Division of Mathematics of Data and AI, Head of Division: Johan Håstad
- **Department of Engineering Mechanics**, Head of Department: Fredrik Lundell
  - Division of Vehicle Engineering & Solid Mechanics, Head of Division: Malin Åkermo
  - Division of Fluid Mechanics & Engineering Acoustics, Head of Division: Lisa Prahl Wittberg

Table of Contents

Part A: Introduction of panel

Description of the research field 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, 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 the department is a large user of computational resources.

Description of the self-evaluation process for the research panel

The Department of Mathematics saw a larger organizational change around the time of RAE 2012, when the Division of Numerical Analysis joined the department (with the actual physical move taking place in August 2013).

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 preconditions for the two departments going into the self-evaluation process were hence quite different when it was initiated in 2020. The Division of Numerical Analysis was well integrated into the Department of Mathematics, whereas the Department of Engineering Mechanics was in the initial phase of effectuating the merger. Both department chairs were however new on their posts. Due to the pandemic, RAE 2020 became RAE 2021, but this was naturally not known when the work started.

RAE 2021 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 one-and-a-half-day workshop in March 2020.

Different key persons were asked 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 strengths, weaknesses and development areas, together with 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.

Shortly after, the pandemic hit, and the work with the self-evaluation was essentially put on hold. An internal version of the report was finished, on which some feedback was given in August and October 2020. With the full process postponed for a year, there was more time to work on the report and to further involve the faculty. Both departments had four on-line seminars open to all faculty in the beginning of 2021, focusing on different topics to get feedback and improve on the 2020 report version. In March 2021, both departments organised writing workshops where the input from the four seminars was incorporated in the text. After that the two coordinators and the department chairs performed some further alignments of the text in the different chapters. The initial idea was to once again have a joint workshop, but this was changed since a digital format had to be used.

In summary: we have had discussions about the ideas in this report during e.g., workshops and seminars as described above, involving many of the faculty members of the departments and several of them have also contributed to the text.

Identified research panel synergies

Within the Department of Engineering Mechanics, physical experiments as well as numerical simulations are used to learn more and hence drive the knowledge within the specific field forward. When analysing 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 Department of Mathematics. 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 catalyse such collaborations. Research networks or centres can be certainly be one way. Here one example is the Linné FLOW centre for fluid mechanics research that started in 2007, which for ten years was funded by the Swedish Research Council (VR) as a centre of excellence. Researchers in numerical analysis from the Department of Mathematics have been active in this centre together with researchers specializing in fluid mechanics and acoustics. Collaborations have continued within the more recently established centre INTERFACE (a VR research environment).

Overall, the number of synergies becomes larger in broader collaborations, where also other departments take part. This is true for the centre INTERFACE mentioned above, as well as for SeRC (the Swedish e-Science Research Centre). Other possible future topics include medical imaging and traffic planning or in more general terms the strategic research areas energy, transport, material design and machine learning/AI.

Part B: Report for each department

Department of Mathematics

Self-evaluation
Head of Department: Professor Mats Boij

Included divisions:

Division of Mathematics
Division of Mathematical Statistics
Division of Optimization and Systems Theory
Division of Numerical Analysis
Division of Mathematics of Data and AI[1]

[1] This division was formed in 2020

Department of Mathematics

1. Overall analysis and conclusion; strengths and development areas

a. Limited SWOT-analysis

The Department of Mathematics has seen a substantial development since RAE 2012. The following gives a brief summary of the current major strengths and weaknesses that have been identified, both considering research and organisation.

	Strengths	Weaknesses
Research	Bulleted list, in order of magnitude. 1. Excellence of the department. 2. Recruitments with highly competitive applicants. 3. External collaboration. 4. Positive atmosphere and genuine willingness to increase collaborations within the department. 5. Consolidated mathematical sciences within one department.	Bulleted list, in order of magnitude. 1. Dependence on external funding. 2. Terms of employment. 3. PhD students recruited to specific projects. 4. Internal expertise not used to its full potential for multidisciplinary collaborations.
Organisation	Bulleted list, in order of magnitude. 1. Research active faulty. 2. Increase in female faculty 3. Group and division structure that creates belonging. 4. Efficient local administration. 5. Promotion through tenure track.	Bulleted list, in order of magnitude. 1. Slow recruitment processes. 2. Gender imbalance among senior faculty. 3. Regulations for assistant professorships. 4. Lack of support in the tenure track process. 5. Group and division structure that can create cementation.

The items listed in the table are explained briefly below.

Research - Strengths

Excellence of the department. The department has many excellent researchers as exemplified by awards and prizes. Several of the faculty members are members of the Royal Academy of Sciences (KVA). The researchers in the department are successful in grant applications for VR, ERC and KAW. The increasing amount of external funding has made it possible to increase the number of postdocs in the department, leading to an even more research-intensive environment. Several rankings show that the department has a very strong international reputation (e.g., no 26 in Shanghai ranking 2020 and No. 49 in QS ranking 2021). Recent awards to the faculty members include the EMS prize (Sara Zahedi 2016) and the Knuth-prize (Johan Håstad 2018). Five members of the faculty have been invited speakers at the International Congress of Mathematicians (ICM)[2]. Some members of the faculty have

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

key assignments in international boards. One faculty member (Lenells) has an ERC consolidator grant and one faculty member has an ERC consortium grant (Chachólski together with KI).

Recruitments with highly competitive applicants. There has been a large number of highly competitive applicants for each announced position in the department. During the last decade international candidates have filled many of the positions.

External collaboration. Most faculty members at the department have long term collaborations with mathematicians at other universities. There are also extensive collaborations with scientists in other fields and industrial partners.

Positive atmosphere and genuine willingness to increase collaborations within the department. Over the last decade there has been an increase in the collaborations within the 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. Many members of the faculty express appreciation for the positive atmosphere that they experience at the department including the notion that all branches of mathematics are important and respected.

Consolidated mathematical sciences within one department. The range of mathematical subjects covered by the department is very broad, including mathematical statistics, numerical analysis, optimisation and systems theory, unlike at many other universities.

Research - Weaknesses

Dependence on external funding. In principle all PhD students are financed with external funds and thus the size of the PhD programs strongly depends on such funding. The research time allowed for each individual faculty member also fluctuates depending on current external grants.

Terms of employment. The starting package and salary that the department can offer new faculty is not always competitive. Another weakness is the uncertainty in long term conditions regarding expected allowed research time etc.

PhD students recruited to specific projects. As a consequence of the dependence on external funding for the doctoral programs, each PhD student is recruited to a specific project from start.

Internal expertise not used to its full potential for multidisciplinary collaborations. New multidisciplinary collaborations require initial efforts, and it is often difficult for individual faculty members to make this a priority. Some systematic factors are short time horizon of result-oriented research, individual research record prioritized and busy agendas.

Organisation – Strengths

Research active faculty. A large proportion of the faculty of the department 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.

Increase in female faculty. Since RAE 2012 the department has hired 27 faculty members among which 11 are female. This has led to a significant increase in female faculty members. This can be seen as an effect of an active search process and priorities of the department for each recruitment. This could also have been included as a strength under research, as this enriches the research environment.

Group and division structure that creates belonging. These structures emphasize subject identities and has a positive effect on the working environment as they create social belonging among the faculty members.

Efficient local administration. Even though some of the administration has been centralized, there are still local key administrative staff in the department. This allows for very efficient administrative support and is highly appreciated by the faculty.

Promotion through tenure track. KTH has a functioning tenure track system and the department mainly recruits on the assistant and associate professor level. The clear path for promotion to full professor increases the attractiveness of the department as an employer.

Organisation – Weaknesses

Slow and cumbersome recruitment processes. The regulation for hiring has a built-in inertia that can be valuable in order to maintain high standards, but the process is heavy from an administrative point of view. This creates problems for applicants during all stages of the process, from the unusually complicated requirements on documents in the applications to the unpredictable and silent waiting time before the decision is taken.

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

Regulations for assistant professorships. The 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. Local KTH regulations stipulate that assistant professors can perform teaching duties only up to 30% of their working time during the full six-year period. This low level makes it difficult to recruit as desired on the assistant professor level while meeting the teaching needs of the department.

Lack of support in the tenure track process. The department does not have a sufficiently strong support system for the junior faculty during the first 5-10 years of employment which is a stressful part of the career with many different types of demands. This might be extra important to retain female faculty.

Group and division structure that can create cementation. While organisational units based on traditional research subjects are good for providing a subject identity and a fruitful working environment, they can become obstacles for development by creating artificial boundaries within the department. Moreover, when an organisational unit becomes too small, it will be vulnerable since it will have difficulties in adjusting to change.

As is apparent from the above discussion, some themes are discussed both in the context of strengths and weaknesses. The large recent increase in external funding is very beneficial for the department, as it gives the opportunity to build a more research-intensive environment, with more PhD students, postdocs, and more research time for faculty. On the other hand, the dependence on external grants, or lack of internal funds, for example leaves one of the central missions of the department vulnerable, since the doctoral programs would be essentially non-existent without external funds. For discussion of other effects, see also *4d. Strategies for high quality* on page 37.

When it comes to gender, it is considered a strength that 40% of the faculty members recruited since 2012 have been female, but the overall situation still leaves a lot of room for improvement. This is further discussed under 3c Current faculty situation and *3d. Recruitment strategies* on page 31, and is an important consideration in the development are concerning recruitment practices listed below.

While the group and division structure help to create a sense of belonging, there is also a risk of creating artificial boundaries within the department, which can potentially lead to non-optimal use of expertise and neglected recruitment in certain, possibly new, subject areas. To mitigate this effect, the departments has e.g., worked both with faculty positions shared between divisions and to increase internal collaboration. The latter continues to be a development area, as listed below.

Development areas

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

Increased internal collaboration. Successfully meeting challenges in pure and applied mathematics rests to a great extent on combining several areas within mathematical sciences. It is therefore essential to promote collaboration with both external and internal partners. Faculty at the department already have extensive international collaborations, whereas internal collaborations could be further strengthened. This will not only be beneficial for the overall quality of research, but also contribute to an improved working environment at the department that promotes exchange and gives a sense of being part of a greater whole. This will also address two of the weaknesses listed, namely *group and division structure that can create cementation* and *internal expertise not used to its full potential for multidisciplinary collaborations*. Furthermore, many of the present and future large calls/initiatives require research teams or consortia. Internal collaborations will facilitate the participation in such calls and will allow us to build on the strength with more *research active faculty*, as well as the broad expertise of that faculty, due to the *consolidated mathematical sciences within one department*.

Further development of recruitment practices. In order to continue recruiting excellent candidates with a significant proportion of women, the department will continue to improve on the internal recruitment process. This has to start by implementing a search procedure that is even more systematic and also continuous. This search procedure should also be used for identifying excellent external candidates to be nominated for the Wallenberg Academy Fellow program and other similar opportunities that arise.

Improve on faculty development support. To optimize the chance of retaining successful recruitments, the department will consider how to improve the support of the faculty members in their development in general, and specifically assistant professors through their promotion process. For this, a mentor system will be developed on the basis of input from those who have recently been promoted. In addition, the department will work for an improvement of the promotion process at KTH, since this has been experienced to be unnecessarily cumbersome. Another consideration is how to better support the faculty, and in particular those new to Sweden, in their efforts to apply for grants. Specifically, since relatively few applications have been submitted for ERC grants, the faculty should be encouraged to apply in the future. For this, support for those who are in a suitable stage for applying needs to be developed.

Increase faculty mobility. There is a recently initiated centrally financed program for sabbatical research visits, but so far, few of the faculty members have applied. The department needs to identify and eliminate obstacles in order to enable future sabbaticals for a larger part of the faculty.

Development strategy for the area Mathematics for AI and Data science. With financial support from the Wallenberg AI, Autonomous Systems and Software Program (WASP), four assistant professors have recently been hired. The department needs to work out a development strategy for this field, in order to also optimally leverage the expertise within the department. This includes keeping the possibility open of recruiting a well-established professor with a strong international standing if and when an opportunity arises.

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 the control of the department. This includes the slow recruitment process and the regulations for assistant professorships. The limit on teaching for assistant professors is a KTH specific regulation, and the department will lobby for a change in this respect, in order to be able to recruit more frequently at this level. The PhD students are almost all paid by external grants and, unlike at many other mathematics departments internationally, are therefore recruited to a specific project from the start. This is an effect of available internal resources which also determines the initial and long-term conditions that can be provided for faculty.

An attractive working place provides good working conditions, including sufficient time for research. The size of the faculty is primarily dimensioned based on the educational needs. The department has prioritized to use internal research funding for faculty salaries to do what can be done in order to provide more stable conditions. Despite this, the research time for the tenured faculty still varies depending on the external funds available for each faculty member, as the base level that the department is able to offer is not as generous as one would wish for. The insecurity regarding long-term conditions is a disadvantage in the recruitment process, especially when it comes to high-profile international candidates.

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

Impact and engagement in society that comes from research conducted at the department is primarily in the form of collaborative research projects with external stakeholders. As can be seen from the impact cases (cf. Appendix 1: Impact cases), these collaborations have been going on for an extended time period and they also involve developing new mathematical theory, some in mathematical fields traditionally labelled as pure mathematics. Broader societal impact comes in the longer term from the importance of sustaining and developing educational programs in science and engineering, which requires having access to a strong and active research environment in mathematical sciences. The department also leverages on this research environment for organising outreach activities that aims to improve on mathematical literacy (numeracy) among young people and decision makers.

The aforementioned collaborative research is mainly initiated and led by individual faculty members at the department. One source for new such collaborations is master thesis projects, of which the department has about 100 per year with industrial partners. The department has complemented this bottom-up approach with strategic top-down initiatives, which this far focused on industrial mathematics, life sciences, and AI. Two of the impact cases are results of these strategic initiatives. In order to improve the ability to support new external collaborations, the department will explore various options for establishing a sustainable platform for such initiatives. The precise form and funding for this are yet to be determined.

Finally, contribution from research in mathematical sciences to sustainable development is in general indirect, but nevertheless significant as pointed out in several reports cited in the section *c. Sustainability and the United Nations' Sustainable Development Goals* (SDG) on page 45. Overall, less than 20% of the research at the department is directly related to SDGs, but those that are affected are SDG 8 (decent work and growth), SDG 3 (good health well-being), SDG 9 (industry innovation and infrastructure), SDG 13 (climate change and its impacts), and SDG 4 (quality education).

2. Research profile

a. General information of the department

The Department of Mathematics is one of the four departments in the School of Engineering Sciences. The department has five divisions where four of the divisions were present in the department throughout the period 2012-2021. The Division of Mathematics of Data and AI was created in the beginning of 2020 in order to gather the members of the department associated with the Wallenberg AI, Autonomous Systems and Software Program (WASP). Since 2017, the Brummer & Partners MathDataLab is a centre on the departmental level.

The department has around 160 employees, including 21 professors, 29 associate professors, 5 assistant professors, 12 researchers, 20 postdocs and 47 PhD students. The Division of Mathematics is the largest division and it corresponds to about half of the department. The Divisions of Mathematical Statistics and the Division of Numerical Analysis are of similar sizes and the sizes of the Division of Optimization and Systems theory and the Division of Mathematics for Data and AI are about half of that.

b. Central research questions and themes, knowledge gaps addressed, main research activities

Mathematics is an essential and ever-present part of our attempts to understand the world around us. Increasingly, research and development require sophisticated mathematics. It is the vision of the department to work to actively strengthen this central role of mathematics, both at KTH and in society, and to make fundamental contributions to the subject.

The research themes present in the department are described according to the organisation into divisions. To some extent this is artificial since research in some themes is performed in several divisions. Examples of such themes are data science, probability and stochastic modelling. As the Division of Mathematics of Data and AI has operated under a limited time its members are included under the Division of Mathematics in this section.

Division of Mathematics

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, Kathlén Kohn[3], David Rydh, Martina Scolamiero[3], 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. The research in algebraic geometry is focused on moduli spaces and moduli stacks, Hilbert schemes, modular forms, moduli spaces and their cohomology, toric geometry, tropical geometry, applied algebraic geometry and algebraic

[3] Member of the Division of Mathematics of Data and AI

statistics. The research in algebraic topology is focused on homotopy theory and applied topology including applications to AI, in particular in the form of topological data analysis (TDA). Research in commutative algebra focuses on homological properties of graded algebras and modules.

- Combinatorics and complexity theory (Petter Brändén, Johan Håstad[3], Katharina Jochemko[3], Svante Linusson, Liam Solus[3]). 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), AI (causality in networks) 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). The area of 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, Anders Szepessy, 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 integral geometry, partial differential equations (PDE), free boundary problems, and potential theory, applications to imaging and also connections to random models and machine learning. Another direction is towards integrable PDE:s.
- Random matrix theory and stochastic models (Maurice Duits, Håkan Hedenmalm, Kurt Johansson, Kevin Schnelli, Anders Szepessy, 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. One research theme 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 central 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, Sigrid Källblad, Pierre Nyquist, Kevin Schnelli). Probability theory provides mathematical tools for modelling and analysing random phenomena and describing the random nature of data. The group conducts active research in stochastic analysis, especially mean-field theory, reflected differential equations and martingale optimal transport. Other research areas in probability covered by the group are random matrix theory and extreme value theory for time series.
- Stochastic simulation (Henrik Hult, Pierre Nyquist, Jimmy Olsson). A plethora of quantitative problems in science, engineering, and finance are solved using Monte Carlo simulation methods. The research of the group is devoted to the understanding and development of such methodology—especially importance sampling, sequential Monte Carlo methods, and Markov chain Monte Carlo methods—as well as applications of the same to rare-event analysis, population genetics, machine learning, and high-energy physics simulation.
- Statistical learning and data analytics (Joakim Andén-Pantera, Henrik Hult, Pierre Nyquist, Jimmy Olsson, Tatjana Pavlenko). Generative models (GM) are paramount in artificial intelligence and unsupervised learning, and the group conducts research on variational auto encoders and online statistical learning in general hidden Markov models and dynamic Bayesian networks. Another research direction is towards statistical inference and machine learning for high-dimensional data and signals. The group is also working on applications of GM in bioelectronics and the development of machine learning methods for medical image segmentation, radiation dose prediction, and *cryo-electron microscopy*.
- Financial and insurance mathematics (Boualem Djehiche, Henrik Hult, 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 research of the group revolves around systemic risks, network-information-based credit modelling and rating, and modelling and valuation of life insurance contracts. Questions related to model risk are addressed using martingale optimal transport techniques and different types of extremal dependence structures in financial data are explored using extreme value theory. Finally, ongoing research develops GM 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. The research at the division includes 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 encompasses development, analysis and implementation of algorithms. The division can be divided into three areas.

- Partial and ordinary differential equations (Michael Hanke, Patrick Henning, Olof Runborg, Anna-Karin Tornberg, Sara Zahedi). This is a main focus area, with applications e.g., in multiphase flow and micro fluidics, wave propagation, quantum mechanics, micro magnetics and neuroscience. 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 stochastic differential equations, 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.

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. The central research questions can be divided into two areas.

- Optimization and optimal control (Per Enqvist, Anders Forsgren, Xiaoming Hu, Johan Karlsson). Research in this area focuses on nonlinear optimization, optimal transport, scheduling and inverse optimal control. A particular area in nonlinear optimization is within so-called quasi-Newton methods. Optimal transport is aimed at solving resulting optimization problems utilizing duality theory tensor computations. Different topics within scheduling are studied within several application scenarios. Inverse optimal control aims at finding efficient methods to reconstruct the objective function from data. The research is tied to applications such as radiation therapy (industrial partner: Raysearch Laboratories) and flight scheduling (Aviolinx).
- Mathematical systems theory (Xiaoming Hu, Johan Karlsson). Research in this area focuses on multi-agent systems and interpolation problems. In multi-agent systems emergences beyond consensus have been studied, with particular attention to crowd dynamics and formation control. In interpolation, the focus is on theory for rational multidimensional interpolation problems and model reduction for multidimensional systems. The group is also working on applications such as autonomous systems and medical imaging.

Multi-disciplinarity

Results from mathematics research are often important tools for solving problems in applied fields and other areas, and demanding challenges in applications can also require and inspire new mathematical theory. Collaboration with other departments and between subfields in mathematics is therefore essential. One important role of computational mathematics is to tailor and transfer knowledge of numerical methods from one application area to another. Some examples 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).

Examples of multi-disciplinary research involving statistical methods are research in financial mathematics (Djehiche, Hult, Källblad), a subject that is inherently multi-disciplinary, the development of clustering techniques for monitoring inflammatory diseases (Hult), and the design of Monte Carlo techniques for simulating the final states of high-energy collisions at the CERN large hydron collider (Olsson).

Mathematical physics is a subject which is by its very nature multi-disciplinary. Some examples of subjects in physics that connect with the research carried out are statistical mechanics and random growth (Duits, Johansson, Viklund), quantum-chaos (Kurlberg), non-linear waves (Lenells), and general relativity (Dahl, Lenells, Ringström).

Two research fields where multi-disciplinarity is inherent are life sciences and data science. There are several research groups working in these fields as discussed in the section *Impact and engagement in society*. Specifically, three of the impact cases described in the appendix concern modelling and optimisation of radiotherapy (Forsgren), topological data analysis of life science data (Chachólski, Scolamiero), and scientific machine learning for image reconstruction in medicine (Öktem).

c. 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. This does not at all cover all research done at the division but serves to paint a picture of the activity and give some highlights.

- The Division of Mathematics has a strong group working in random matrix theory and related stochastic models like random growth and random tilings. Important recent contributions include the first computation of the two-time distribution in the KPZ universality class starting from certain last-passage percolation models by Kurt Johansson together with co-authors, and the computation of the inverse Kasteleyn matrix for the two-periodic Aztec diamond by Maurice Duits and collaborators, and the analysis of its asymptotics at the liquid-gas boundary by Kurt Johansson - the first rigorous analysis of a random tiling model with a gas phase. Other important developments are the proofs by Maurice Duits and collaborators of central limit theorems for linear statistics of determinantal point processes based on recurrence coefficients, and work by Kevin Schnelli and collaborators on local laws for various ensembles of random matrices. Important results on the Stochastic Loewner Equation (SLE) have been obtained, e.g., on the almost sure multifractal spectrum for the tip of an SLE curve by Fredrik Viklund and Gregory Lawler. Håkan Hedenmalm and Aron Wennman have 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 Pär Kurlberg and co-authors has been proofs and disproofs 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 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 around John Andersson and 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 by Henrik Shahgholian and his co-authors is a complete proof for dimensions greater than five.

- Since 2016, Jonatan Lenells has led an ERC project on boundary value problems for nonlinear integrable equations. He and his group members have developed new tools for the analysis of the asymptotic behaviour of solutions. Among other things, they have used these tools to obtain detailed asymptotic formulas for the Boussinesq equation. The derivation of such formulas had been an outstanding open problem in the field for at least 30 years.
- 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 David Rydh and collaborators that says that 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 looks 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, Martina Scolamiero and their 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 by Michael Benedicks[4] and collaborators, the proof of existence of Arnold diffusion in a pendulum lattice by Maria 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 by Danijela Damjanovic and collaborators.
- One research project to which Hans Ringström has devoted several years is the stability problem in cosmology. This project culminated in a research monograph in 2013 in which he demonstrated future global non-linear stability of the models of the universe currently preferred by physicists. The monograph also contains a proof of the fact that, with the current preferences, it is not possible to determine the topology of the universe on the basis of observations. In a follow-up article with Håkan Andréasson, he also demonstrated that the current preference for a positive cosmological constant can, dynamically, lead to the elimination not only of spatial anisotropies, but also of significant spatial inhomogeneities.
- In combinatorics, Petter Brändén and June Huh (Stanford University) 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

[4] Professor emeritus

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.
- Ozan Öktem has developed a framework for integrating elements of harmonic analysis, integral geometry, geometric analysis, and microlocal theory with statistical decision theory and deep learning. This led to pioneering work in 2016 on using deep learning for reliably solving large-scale ill-posed inverse problems arising in tomographic imaging. Later developments based on deep generative models and optimal transport allowed for the first computationally feasible usage of Bayesian inference on such large-scale inference problems.

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 were established by Boualem Djehiche and his collaborators: new approaches to modelling 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.
- Martingale optimal transport problems is an emerging line of research in applied probability to which Sigrid Källblad has made several contributions. Recently, she and her collaborators provided 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.
- Kevin Schnelli and his collaborators extended recent results on the universality phenomenon of spectral statistics to sparse sample covariance matrices and established a local law for the eigenvalue density up to the upper spectral edge. Under a suitable sparsity condition, it was shown that the GOE Tracy–Widom law describes the limiting distribution of the rescaled, shifted extremal eigenvalues.
- Jimmy Olsson and his collaborators established several results on the consistency and numerical stability of marginal- and path-space SMC methods, including the tightness of the asymptotic variance of the standard bootstrap particle filter under close to minimal assumptions being satisfied also for models with a non-compact state space. The latter yields the most general time-uniform convergence result for particle filters obtained so far.

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

- Patrick Henning and Olof Runborg have developed and analysed multiscale methods for problems where small scale features need to be simulated over large scales. 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.
- Anna-Karin Tornberg and Sara Zahedi have developed numerical methods for multiphase flow and micro-fluidics with complex and evolving geometry involving for instance deforming droplets and moving particles in Stokes flow. 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/particles.

- Mattias Sandberg and Anders Szepessy have derived methods and error estimates for Born-Oppenheimer molecular dynamics based on deterministic and stochastic models in the linear case of the Schrödinger equation. In the non-linear case finite element methods have been developed and analysed for Bose-Einstein condensates by Patrick Henning.
- Elias Jarlebring has developed 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.

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

- Xiaoming Hu and his collaborators have developed new approaches for modelling and intervention of multi-agent system. This includes the discovery of new connections between agent formations and graph topology that explore the topological structure of communication to generate a desired formation.
- Anders Forsgren has developed new approaches for dynamic modelling 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 elementary flux modes as the problem is being solved.
- Johan Karlsson and his collaborators have discovered new connections between multimarginal optimal transport problems and hidden Markov chains, which allow for development of new efficient algorithms for solving certain multimarginal optimal transport problems.

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

Highlighted publications

The following 10 publications have been selected 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. Authors that are members of the faculty of the department are written in boldface.

- Alper, Jarod; Hall, Jack; **Rydh, David** *A Luna étale slice theorem for algebraic stacks*. Ann. of Math. (2) 191 (2020), no. 3, 675–738.
- **Andersson, John** *Optimal regularity for the Signorini problem and its free boundary*. Invent. Math. 204 (2016), no. 1, 1–82.
- 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
- **Brändén, Petter**; Huh, June *Lorentzian polynomials*. Ann. Of Math. (2) 192 (2020), no.3, 821-891
- **Di Rocco, Sandra**; Eklund, David; Weinstein, Madeleine *The bottleneck degree of algebraic varieties*. SIAM J. Appl. Algebra Geom. 4 (2020), no. 1, 227–253
- **Djehiche, Boualem**; Tembine, Hamidou; Tempone, Raul *A stochastic maximum principle for risk-sensitive mean-field type control*. IEEE Trans. Automat. Control 60 (2015), no. 10, 2640–2649.

- Douc, Randal; Moulines, Éric; **Olsson, Jimmy** *Long-term stability of sequential Monte Carlo methods under verifiable conditions*. Ann. Appl. Probab. 24 (2014), no. 5, 1767–1802.
- Gaaf, Sarah; **Jarlebring, Elias** *The infinite bi-Lanczos method for nonlinear eigenvalue problems*. SIAM J. Sci. Comput. 39 (2017), no. 5, S898–S919.
- Hansbo, Peter; Larson, Mats G; **Zahedi, Sara** *A Cut Finite Element Method for a Stokes Interface Problem*. Appl. Numer. Math. 85 (2014), 90–114.
- Zhang, Silun; Ringh, Axel; **Hu, Xiaoming**; **Karlsson, Johan** *Modeling collective behaviors: A moment-based approach*, IEEE Trans. Automat. Control 66 (2021), no. 1, 33–48.

Reflection on the department's publication strategy

A part of the culture of the mathematical community is to always aim for publication in the most important journals. In the international community there is a consensus concerning the prestige and impact of different journals. The strategy of the department is to trust everyone to be ambitious and to do their best to disseminate and publish their research. The department sees a need for exploring new channels to spread information concerning research activities and results to a broader audience. Most researchers do not have the means to achieve this on their own.

Reflection on the department's bibliometrical performance

Below follows three figures with bibliometric data for the department. From checking the underlying data for some individuals, it is has become clear that some key publications are missing, but it is not known to which extent this may affect the overall numbers.

The number of publications registered in DiVA (fractional count) are displayed in *Figure 1*. This number has not seen a steady trend over the years 2012-2019 shown in the figure, but there has been an increase over the last years. Increasing the number of publications is, however, not a primary goal of the department, but rather a natural consequence as e.g., the number of postdocs has increased lately.

In *Figure 2*, the publication and journal impact are shown. The world average is 1 for both numbers. One can note that the average impact numbers for the journals are quite steady over the period, both from WoS and Scopus. These numbers probably indicate that the publication pattern of the faculty has not really changed over the evaluation period. One can, however, note an improvement in the field normalized citations for the actual publications, i.e., the publication impact. It looks like a positive trend over the last years, more so based on the WoS data than on Scopus. For the last window of data provided, 2016-2018, the average Cf number for citations from WoS is 1.19. The share of top 10% publications is now also above average, with a noticeable positive trend, increasing to 14% for the period 2016-2018 according to WoS (not shown in figure). The strategies outlined in this document, including recruitment and faculty support, should be helpful in sustaining this trend and further improve on these numbers.

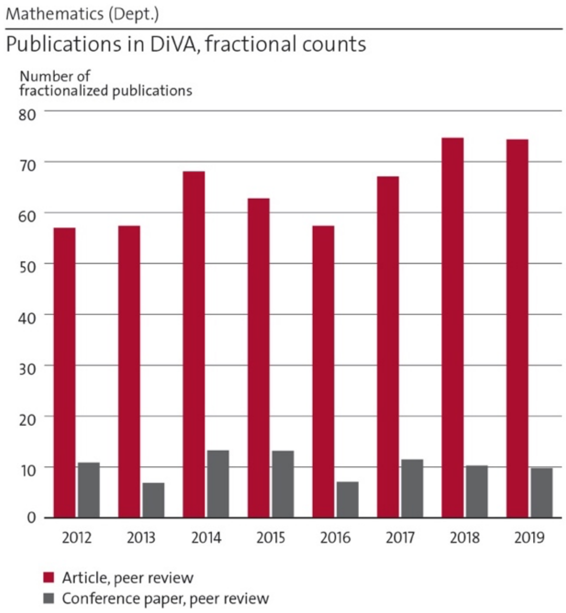


Figure 1: Publications in DiVA, fractional counts

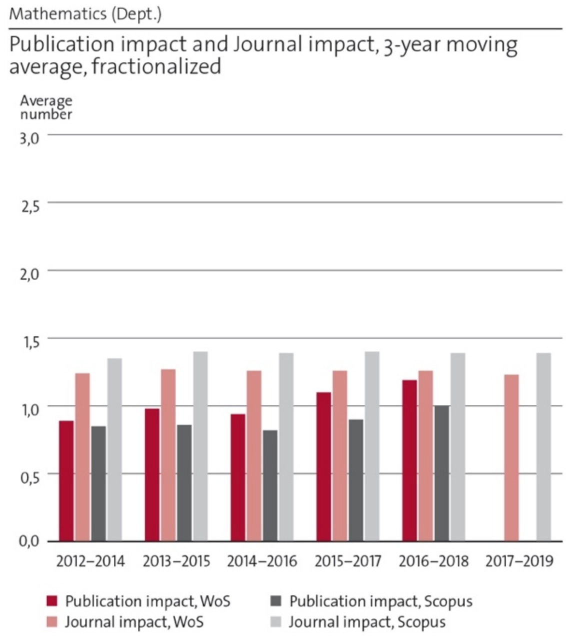


Figure 2: Publication impact and Journal impact

In *Figure 3: Co-publication*, data concerning co-publications is shown. Here, it can be noted that while the share of Swedish non-university co-publications is low, the share of international co-publications is high. Many faculty members have long term international collaborations, and the number of publications with an international co-author is larger than for those without. Moving averages from 2014 and forward based on data from WoS and Scopus both show over 60% international co-publications.

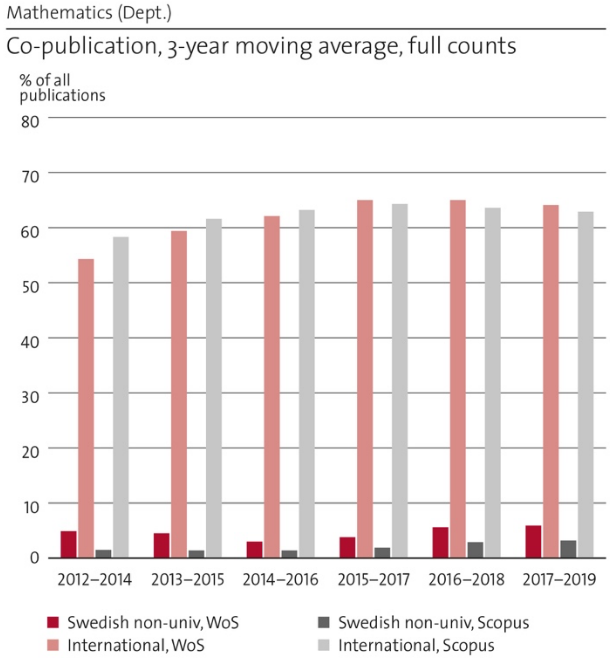


Figure 3: Co-publication

e. 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 mostly recruited internationally, and they all have established networks. This makes the research environment at the department truly international, open to new influences, and constantly updated 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. For more details, see *Guest researchers at KTH* on page 28.

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

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

- 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.
- The VR centre INTERFACE (with Department of Engineering Mechanics and Department of Fibre and Polymer Technology at KTH),
- The Linné centre FLOW, with Department of Engineering Mechanics at KTH,
- 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,
- WASP – the KAW financed program for AI, Autonomous Systems and Software.

In addition, the department is a partner in the EU COST action network EU-MORNET on model reduction methods.

The Brummer & Partners MathDataLab is a centre at the department focusing on complex data and supports a number of postdocs. Activities include seminars, mini-courses, study groups, workshops and conferences.

The Stockholm Mathematics Centre (SMC) is a centre in which KTH and Stockholm University collaborate around common interests in mathematics. It started in 2011 and includes common seminar series, colloquia, summer schools, master classes and outreach activities.

The faculty members of the department participate in, and organise, conferences and workshops of many kinds. Particular examples are research semesters at Institut Mittag-Leffler. The past years there have been several such programs co-organised by members of the division. Further, programs at MSRI and other research institutes have been co-organised by faculty members. For more details about this, see section *3b. Academic culture* on page 26.

f. Follow up from previous evaluations

In the RAE 2012 each division within the department was a separate unit of assessment and therefore the follow up is presented 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 Doctoral program and to ensure that the associate professors have sufficient time to develop their research program. Unfortunately, the division has not been able to secure stable funding for the Doctoral program with the result that is more than ever dependant 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 the faculty members of the department 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 launched the five-year program in *Engineering Mathematics* that will be further described in the section *Interaction between research and teaching at all three levels (BSc, MSc, PhD) of education.*

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*". Getting the group to grow has indeed been a challenge in the light of a number of faculty resignations (mostly retirements) in recent years, and the recruitments that have been made have largely served to compensate for this faculty loss. Therefore, the size of the division is about the same size as 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. Further associate professor positions were announced in the beginning of 2021. It was also suggested that the division should "*formulate a clear and realistic strategy for its future development*". In the era of massive and complex data, the subject of mathematical statistics is undergoing major changes. This poses a challenge to every statistics department in the world. In this development, the division's intention is to distinguish itself from other actors in the data science field by keeping a clear focus on the mathematical — or inferential — aspects of complex data analytics. When it comes to the activities of the department, this is not only visible through the recruitment of expertise in data science (most recently Joakim Andén-Pantera, who focuses 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. One new assistant professor was recruited in 2013. In 2016 there was 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 is now finished and hopefully this is the first step in remedying this problem.

3. Viability

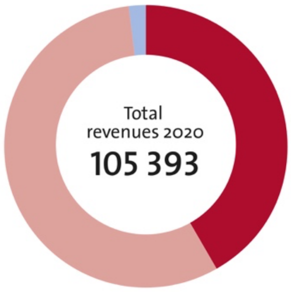
a. Funding; internal and external

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 was twice as high in 2020 as it was in 2013.[5] It is expected to increase even further. Thereby, the balance between internal and external funding has been switched in favour of the external funding. See *Figure 4: Sources for research income* below. New developments that have strongly contributed 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.

[5] The amount of external funding used in 2020 was expected to be even higher, but due to the pandemic it was reduced because of postponed starting dates for several positions as well as temporary teaching increases.

Mathematics

Sources of research income (2012, 2016, 2020)



Research income, kSEK	2012	2016	2020
Government grants for research and doctoral studies	45 340	41 620	44 200
Research grants	32 894	39 041	59 683
Contract research funding	468	0	0
Other revenues	1 594	1 700	2 056
Financial income	0	0	0
Total revenues	80 297	82 361	105 939

Figure 4: Sources for research income

The largest single source for the external funding in 2013-2020 has been the Swedish Research Council (VR). In 2021, the funding from the Knut and Alice Wallenberg Foundation (KAW) is expected to become the largest contribution. See *Table 1 - Five most prominent external sources for research* below. Observe that some external funding is missing from the top-five list during 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 2020.

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020
VR	21.1	17.2	18.8	19.6	27.7	25.4	26.0	21.8	21.3
KAW	5.1	5.0	5.4	5.4	6.3	8.2	10.2	18.2	19.6
SSF	2.3	1.3	0.8	2.2	1.5	2.2	5.0	6.5	2.8
EU					1.3	2.7	3.0	4.6	6.1
GG	1.6	2.8	2.9	1.9	1.9	3.9	3.0	3.4	2.1
SU	1.2	0.7	0.9						
Total	32.9	27.0	28.7	29.0	39.0	42.4	47.2	54.5	59.7

Table 1 - Five most prominent external 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 is on-going in collaboration with KTH Fundraising in order to explore if there are other similar opportunities for research funding in the future.

b. Academic culture

The research in mathematics is performed in an international context where meetings are essential for the development. The following meeting places and structures that are important for the academic culture in the department have been identified: research seminars and reading groups, conferences and workshops, research programs at international research institutes, guest researchers, research platforms at KTH and the doctoral programs. In addition, there are several informal meetings such as discussions in the coffee breaks. The absence of these informal meetings has been apparent during the pandemic.

Research seminars, reading groups etc

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

- Algebra and geometry
- Analysis
- Random matrix theory
- Number theory
- Combinatorics
- Numerical analysis
- Mathematical statistics
- Optimization and systems theory
- Applied Combinatorics, Algebra, Topology & Statistics

In the most active seminar series, there has been 30-40 seminars per year. In 2020, there has been a shift, due to the pandemic, from local seminars to more international online seminar series.

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*.

Colloquia and the Göran Gustafsson Lectures in Mathematics

The Stockholm Mathematics Centre (SMC) organises a colloquium series which has featured many prominent mathematicians since the start in 2011. With the support from the Göran Gustafsson foundation, the department is able to organise the *Göran Gustafsson Lectures in Mathematics* which is a distinguished lecture series where the speakers in the period 2012-2018 have been Gigliola Staffilani (2018), Avi Wigderson (2017), Gerhard Huisken (2016), Amie Wilkinson (2015), Claude Le Bris (2014), Aise Johan de Jong (2013) and Gregory Margulis (2012). In 2019, the *Göran Gustafsson Symposium* was organised on three themes together with Jean-Pierre Eckmann, Gérard Ben Arous, and Martin Hairer. This year (2021) the speaker will be Alessio Figalli, postponed from 2020 due to the pandemic.

Conferences and workshops

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

Research programs at international research institutes

There are several international research institutes where members of the faculty take part in longer or shorter research programs. Some examples are BIRS, ESI, IHP, MFO, MSRI, ICERM and the Fields Institute. Several members of the faculty have spent sabbaticals or longer research visits at such institutes and some faculty members have been part in organising 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

Every year there are several long-term visitors to the department. In particular, during the last six years ten guest professorships have been financed by the KAW Mathematics program:

- Professor Masatoshi Noumi, Kobe University, Japan (2020)
- Professor Robert Bruner, Wayne State University, Detroit, USA (2020)
- 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

As a result of RAE 2012, 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 deputy 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 faculty members have been part of the leadership at the institute. Hans Ringström is currently the deputy director and previously, Ari Laptev, Anders Björner, Dan Laksov and Lennart Carleson have been directors. Kurt Johansson is currently the chair of the board of the institute. Several of the semester long programs have had faculty members from the department on the organising committee with the most recent examples the program on *Algebraic and enumerative combinatorics*[6] during spring 2020 with Petter Brändén and Svante Linusson as two of the organisers and the program on *Number theory*[7] during spring 2021 with Pär Kurlberg and Lilian Matthiesen as two of the organisers. In relation to these programs there have been some conferences organised at KTH. The institute also have summer workshops since a few years and many of them have had organisers and participants from KTH.

Doctoral programs

Within the doctoral 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 doctoral 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 organise the graduate student seminar, which is a weekly seminar where PhD students

[6] This program did, however, unfortunately have to terminate early due to the pandemic

[7] This program had to be held digitally due to the pandemic

present their field and their research to other PhD students with no faculty attending. This is organised in collaboration with the PhD students in Mathematics at Stockholm University.

c. Current faculty situation

The department has had several retirements during the past 10-15 years in the categories of lecturers, associate professors and professors. In addition, several members have left to move to other universities or to industry. Recruitments to faculty positions have been done at the assistant and associate professor levels only. In *Figure 5: Staff headcount* it can be seen that the number of faculty positions has decreased in the last period and compared to the figures for 2020 four faculty members will be lost in the count for 2021. The department is currently in the process of recruiting one assistant professor and eight associate professors as a response to the understaffed situation. In the meantime, some temporary positions are used. Close to 70 faculty members including lecturers are needed in order to maintain the teaching in the department. There is a clear positive trend in the gender balance distribution among the faculty even if there still is a long way to go, in particular at the professor level. Future promotions and retirements will improve the situation at the senior level. Successful recruitments will be essential to reach an overall better gender balance.

In *Figure 5: Staff headcount* it is also shown statistics for other categories of staff. Considering the gender balance for different categories of employees or for different divisions, there are some variations. The Division of Mathematics still has 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.

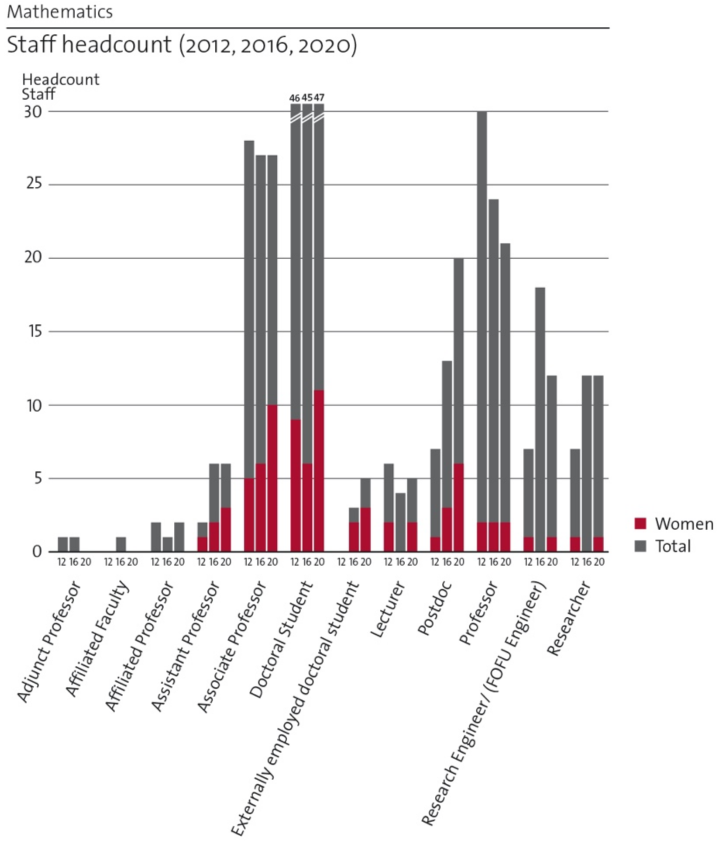


Figure 5: Staff headcount[8]

KTH has a tenure track system, which is valued as the most appropriate way for recruiting emerging talents and fostering their development within KTH. As the department has a need for teachers a balance has to be found between assistant professorships, where the amount of teaching is limited (for a maximum of six years) and associate professorships. In this context, possible recruitments of permanent lecturers[9] also need to be considered. With such positions it is possible to cover the needs from the teaching side without requiring more internal funding for research. However, this is not in line with the aim to maintain a research active faculty and there is no possibility for promotion since lecturers are not part of the tenure track system.

In the near future, there will not be a large number of retirements, but the department will have to be prepared that some of the faculty members can move to other universities. It seems that there is a somewhat increasing trend in this respect. The more international recruitments that are made, and the more excellent researchers the department attracts, the harder it gets to retain all the faculty. The balance in terms of age and career stage is sound and, in order to sustain this, a constant pace in recruitments is needed to keep up with retirements and other losses. The gender balance distribution is far from perfect and in order to improve on it, the department will need to continue working actively in the recruitment processes.

[8] It is worth noting that in addition to the category Postdocs, the category Researchers mainly consists of short-term positions that would be categorized as Postdocs in many other universities.
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d. Recruitment strategies

The recruitment strategies of the department of mathematics have several priorities. One of the 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, collaborations and interdisciplinary research are considered to be 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 the department. It is both a necessity and a strength that all faculty members are involved in teaching at engineering programs and master's 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 for the recruitment strategy of the department; luckily this need not be the case as these competences are often strongly correlated. In past recruitments the department has been remarkably successful in fulfilling these separate priorities.

In recent years, all recruitments of faculty members, postdocs, researchers and PhD candidates have been done internationally with a large number of applicants. It has been a strategy to give faculty positions a broad profile in order to achieve high competition. The faculty members have very active international networks, which are used to find and encourage female mathematicians to apply to the open positions. This is also formalised in the work of search committees that are formed for each faculty position that is initiated. In order to increase the number of female faculty members, there has been three cases where the department has been able to hire two faculty members instead of one in the same call, in order to hire more women. The department has been successful in achieving a relatively good gender balance among new faculty recruitments over the last decade. The department will continue working along KTH's guidelines on gender equality, diversity, and equal opportunities for this positive development to endure. In particular, the continued development of the recruitment practices has been identified as one of the development areas discussed in *1a. Limited SWOT-analysis*.

An example of recent recruitments is the hiring of four assistant professors initially funded by the WASP[10] initiative. They are now 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 assistant professors 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 in 2018. The department was able to hire two exceptionally strong mathematicians. Unfortunately, after less than a year, both of them had left due to competing offers from other universities. With the international competition for the most excellent researchers, it is inevitable that situations like this will sometimes occur. The department needs 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.

e. Infrastructure and facilities

During the last decade, the size of the department has grown. Since the Division of Numerical Analysis moved in, the mathematics library has been rebuilt into office space and one seminar room. The remaining two seminar rooms have been transformed into office space for postdocs. Part of the teaching administration has moved to join the central administration at the school level. Still, there is trouble finding enough office space. This has, for example, led to that the emeriti professors had to

[10] Wallenberg AI, Autonomous Systems and Software Program (wasp-sweden.org)

move into offices that are not suitable as working spaces for any longer periods of work. In order to continue to be an attractive department the availability of office space has to be improved. This problem will become even more critical if the external funding continues to increase.

Regarding computing resources there are five 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[11] and PDC[12]. The five compute servers have slightly different characteristics; one with a high core count, one with a large memory, and three that are GPU accelerated. The three 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 the faculty. The current estimate is that upgrade costs will be fairly minor, say 100 000-200 000 SEK per year, but increased demands on computational resources could of course change this significantly.

4. Strategies and organisation

a. Goals for development 5–10 years ahead

Overall visions

In 5-10 years, the department aspires to

- be a research environment that continues to produce excellent research within a broad range of the mathematical sciences, with an internationally leading role in an increasing number of research areas.
- have an even stronger international visibility that together with a reputation as an excellent working environment makes the department a top choice employer.

In order to work towards these overall visions, more concrete goals are formulated in three categories: research environment, faculty development and international visibility. How to reach these goals and how they relate to the development areas identified in the first section, *1. Overall analysis and conclusion; strengths and development areas*, will also be discussed.

Different research areas are not specifically discussed here, with one important exception, which is mathematics for artificial intelligence and machine learning. Last year, a new division was initiated at the department to further accelerate developments in this field. Being this recent, this new division is not included in the description of the research activities at the department during the evaluation period. This is however a field with a recent growth that is also expected to continue to grow. It involves not only the new division but many sub-disciplines in the department and is a great opportunity to increase the collaboration within the department, as was highlighted in the first section. Hence, it is warranted to outline a few specific goals for this research field.

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

The goals of the department are to be

[11] Swedish National Infrastructure for Computing (www.snic.se)

[12] PDC Center for High Performance Computing (www.pdc.kth.se)

- 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 fundamental basic research to multidisciplinary collaborative projects.
- a department that has maintained a high level of external funding, contributing to a research-intensive environment.

Faculty development

The goals of the department are to be

- a department that is constantly hiring excellent faculty with a balanced gender distribution.
- an attractive and inclusive working place that provides an environment where each individual can develop and thrive.
- a working environment based on open-mindedness, curiosity and respect.

As has been described earlier, the department has seen a substantial development since RAE 2012. Many excellent hires have been made, including a large number with an international background and a good proportion of women. A rapid increase in external funding, unprecedented in the history of the department, has allowed the department to become even more research intensive, including also a large body of postdocs.

These goals are based on the development areas identified in the first section. More precisely, in the development area *Increased internal collaboration,* measures are outlined that will be important for reaching the goals related to research environment. In addition, the development area *Improve on faculty development support* includes measures that intend to increase the number of successful grant applications. Specifically, the department aims to increase the number of applications for ERC grants.

The development area *Further development of recruitment practices* relates to the first faculty development goal above. The two softer goals are partly also targeted through research, as discussed in the development area *Increased internal collaboration*. Under *Organisational strengths* (see page 9) the division structure was pointed out as having some positive effects on the working environment. diversity is enriching the department. Based on, for example what has come out from the development dialogues with the faculty members, it is clear that the working environment already now, to a large extent, is inclusive and based on open-mindedness, curiosity and respect. Still, the department needs to stay constantly alert and work towards further improvements. As the department becomes more heterogenous with new hires, it is important to make sure that these new faculty members receive the support they need to be well integrated into the department. Here, the leadership at the department needs to take an active role.

To recruit well and to continue being an attractive working place, the department also needs to be able to continue providing good terms of employment, including time for research. The limitations of the possibility to provide internal funding for research were discussed in Section 1, and the department works hard to mitigate its impact.

International visibility.

The goals of the department are to be

- a department that has an even higher visibility for its research.

- a strong partner in local collaborations in the Stockholm area, which is highlighting the research strengths of the region, hereby yielding a joint visibility.
- a research environment with a large mobility, both in terms of an increased number of sabbatical visitors as well as an increased number of shorter and longer sabbatical visits abroad for the faculty.

International visibility can be achieved in many different ways. Highly cited publications and keynote lectures at international conferences are two important contributions, prestigious prizes yet another. The base for this is of course to produce excellent research, where the goals are set high.

The QS World Ranking by Subject ranks the department as number 49 in the world this 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 the department has a strong international reputation today and the aim is to enhance it even further.

International PhD students and postdocs are important for the international reputation and visibility, as they function as ambassadors for KTH when 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, most from outside of Sweden. Hence the goal listed under *Research environment* to maintain a high level of external 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.

The visibility of research results depends on factors other than the excellence, and it is important to draw attention to publications. Here, networks of individual faculty members are important both to spread the publications and to generate invitations to give key-note lectures that will make the results more widely known. The department will encourage the faculty to be even more active within their networks and to work towards extending them further.

With the focus to maintain high visibility promoted by fruitful interactions, the department aims also to extend the long-term collaboration with Stockholm University (SU) and Institut 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. Faculty members are regularly involved in organising research programs at Institut Mittag-Leffler. Those research programs are important to introduce Stockholm in general, and KTH in particular, as a strong mathematical environment.

International visibility as well as research quality benefit also from mobility of more senior researchers. As indicated in the development area *Increase faculty mobility,* it is desirable to increase the number of sabbatical visits made by the faculty. Another important aspect is visitors to the department, both short and long term. For long term visitors it is possible to establish a deeper research connection with the local community, for example by giving doctoral courses and working in the local research groups, that will establish a basis for many further interactions with the network of the visiting professor. In recent years a number of guest professors have visited the department funded by the KAW mathematics program (see Guest researchers at KTH on page 28). The department plans to encourage a larger part of the faculty to apply for this kind of funding.

Mathematics for AI and Machine Learning

The goals of the department are to have

- an internationally leading group within the mathematical foundations of AI.
- more and deeper collaborations that include the development of new mathematical theory for AI and data.
- an enhanced mobility between academia and industry, e.g., in the form of industrial graduate students, summer internships, Master's thesis projects, and affiliated faculty from academia/industry.

Methods from artificial intelligence (AI) in general, and machine learning (ML) in particular, are increasingly deployed to base decision making on the enormous amounts of data that is being collected. This calls for new exciting research at the intersection of mathematics, statistics, numerical analysis and computer science. The department has since 2014 worked systematically towards promoting such mathematical research, initially through specific projects, followed by the establishment of Brummer & Partners MathDataLab in 2015, and most recently further expanded through recruitments in 2019 made possible within the WASP AI initiative. The department has since 2020 a Division of Mathematics of Data and AI, which together with Brummer & Partners MathDataLab constitutes a dynamic and growing research environment.

Data driven modelling is a dynamic and highly competitive area. Currently, much of the large-scale challenge driven research is pursued within industry. There is, however, an increasing interest in offering a deeper understanding of the limits and possibilities with these data driven models, a quest that will require mathematical research. This will be an important research area for the coming decade(s). For these reasons, the department plans to continue to expand upon its activities related to AI and data driven modelling and build an internationally leading group within the mathematical foundations of AI. This is directly related to the development area *Development strategy for the area Mathematics for AI and Data science*. In order to have a leading role in this dynamic area, it is particularly important to have close collaborations with industrial partners. In this sense, the third goal listed above will be an integral part in achieving the first.

The field is highly dynamic, and it is difficult at this stage to predict what mathematics that will be required for future breakthroughs. Still, the department has outlined a scientific profile that is believed to be highly relevant and that leverages upon the strengths of the department. This profile is based on 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. Hence, the second goal listed above relates to the development area of *Increased internal collaboration*.

b. Congruence with university-level goals for "A leading KTH" as set out in KTH´s "Development Plan 2018-23" (page 5)

The congruence with the university-level goals will be commented on with a focus on internationalization, gender balance and digitalization, starting with a quote from *A Leading KTH*, the development plan for 2018-23:

"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."[13]

It is indeed impossible to predict when and where research breakthroughs will occur, but the vision formulated by the department is an enabler for ground-breaking research: to have many excellent researchers in a thriving and open research environment, involved in a range from fundamental basic research to multidisciplinary collaborative projects. This will clearly contribute to the KTH goal to have "application-oriented research that is deepened by curiosity-driven basic research and interdisciplinary collaboration". One specific goal listed under the headline of "Mathematics for AI and Machine Learning" is to promote collaborations that include development of new mathematical theory for AI and data, which aligns perfectly with this cited KTH goal as the interdisciplinarity will be enhanced by an increased mobility between academia and industry.

The research at the department is strongly characterized by internationalization. Research results are produced in international collaborations, results are disseminated in international journals and at international conferences and workshops, the department recruits at an international market, and both incoming and outgoing shorter research visits and sabbatical terms enhance the research at the department. Visions and goals concerning increased internationalization are found under the overall visions as well as listed under the headline of international visibility in the previous subsection.

In the overall vision, one important component for succeeding in making the department a top choice employer for international mathematicians is to have a reputation as an excellent working environment. A starting point for having that reputation, is to be such a workplace. Hence the department strives to continue to improve on the research environment, and one fundamental ingredient is to hire faculty with a balanced gender distribution. All the goals listed under faculty development applies to gender equality as well as the broader concept of diversity and equal treatment.

Mathematics for AI and Machine learning, discussed in the previous section, is essential for digitalisation. The department also have two specific projects within the Digital Futures research centre, on *Digitizing brain data for health and disease* and *Decision making in critical societal infrastructures*. The department goal to increase local collaborations in the Stockholm area will further increase the participation in interdisciplinary projects, and thereby in projects that are central both to digitalization and sustainability.

c. Leadership structure and collegial structure

The formal leadership structure consists of

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

The department has a management group consisting of the people listed above together with the director of studies, the administrative head and one student representative.

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

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 organisation 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 head of department 2012-2019 and Boualem Djehiche was the deputy head of department 2014-2019. It is a temporary situation that Anna-Karin Tornberg is remaining as the head of division for the Division of Numerical Analysis while being deputy head of department. The leadership structure of the department is under revision and there is a plan to come up with a new structure that will start in late 2021 or early 2022. A working group with representatives from all divisions has been appointed and is expected to present their suggestions in the spring of 2021. Before a decision is taken, there will be collegial discussions at the division and department levels. This self-evaluation report and the work that has led to it can be used as input for these discussions.

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

Many important issues are discussed in collegial meetings on division or department level before decisions are taken. Examples of this are profiles for new faculty positions and suggestions for external experts in the recruitment process. The Division of Mathematics has a reference group, consisting of a few members from the faculty, that discusses matters of interest for the division with the head and deputy head of division before decisions are made. The reason for this construction is the size of the division and there is no need for it in the other divisions.

There are research groups within the department that are formed around common research interests, collaborations and research seminars, but with no formal leaders. In these groups, questions about for example joint grant applications, invitations of guest researchers and issues related to the doctoral programs are discussed.

In most research activities the leadership has a more supporting role and initiatives are taken by individual researchers or groups of researchers. As an example of the opposite, the formation of the Brummer & Partners MathDataLab was initiated by the department leaders. In the applications for the WASP assistant professorships mentioned in Development areas on page 11, there was a mix of bottom-up and top-down. Possible research areas were discussed in the department management group, and divisions or research groups were then responsible for writing applications with feedback from the management group.

d. Strategies for high quality

The most important factor for high quality research is excellent faculty. The department's success with recruitments is hence very important and it is instrumental to make the uttermost to hire excellent researchers with a strong capacity of producing high quality research. However, for the best output, it is necessary to also create something greater than a set of individuals; a research environment where everyone, faculty, postdocs, PhD students, can develop and thrive. As previously described, the research environment is already considered as a strength of the department. Nevertheless, continuous work to further improve and also to increase internal collaborations is needed. Since a number of years, prizes awarded and external grants obtained are announced to the entire department by the head of department. This can be extended to also include other activities, such as important publications and keynote lectures. This can hopefully enhance the pride of the department and at the same time work as an incentive to strive for the highest quality.

There are several external incentives for each individual to set their goals high. Importantly, 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 the faculty. All members of the faculty are encouraged to apply for external funding both nationally and internationally. In order to be competitive in their applications, the faculty members need to maintain a high-profile research program with publications in prestigious journals. One strategic priority at the department is to use the internal funding for research time for the faculty instead of, e.g., financing PhD students. This enables faculty to stay research active also during years without individual external funding.

While it is widely acknowledged that the competition for external grants can keep researchers at their toes, this situation might make them a bit near-sighted. The department trusts the faculty to determine which problems in their respective areas that are most important to work on and feasible to tackle, but it can be harder to take the risk to work on a really challenging problem where the outcome is uncertain. The competition for external grants can therefore tend to steer us towards problems that more certainly will render publications within a shorter time horizon. There is no definitive answer to what the right prioritization is, but it is evident that more internal research funding would allow more flexibility in this respect.

Regarding dissemination of research, an important part is done through journal publications as mentioned above. A key factor is to draw attention to the research results, and one important mean is presentations at international conferences and other universities. International networks are important to obtain invitations. Hence, the faculty is actively encouraged to organise workshops, conferences and longer research programs. For the latter, there are excellent opportunities through Institut Mittag-Leffler, which maintains a very strong international reputation. Organising such a program results in increased research output of high quality and extended international research collaboration and invitations.

Large funding agencies, such as VR, demand that all research is made available through open access. Most papers can now be published with open access through the KTH library. For the few journals where there are no such agreements with the library, there are also specific funds at the school level that can be used to pay for open access publication. It is also in the interest of the individual researcher to spread their work as much as possible already at an early stage. Mathematicians have a tradition of publishing their papers as preprints before they are accepted, currently primarily on arXiv.org. Hence, there is a long tradition of making the research results freely available.

Dissemination towards industry is mainly achieved through collaborations with industrial partners and through PhD students that graduate and start working in industry. For this latter part, the program committees continuously work with the quality of the Doctoral programs. One major change that enhanced quality was when the three applied divisions started the joint Doctoral program in applied and computational mathematics in 2011.

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

The department strongly believes 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 a stated goal, which is mostly fulfilled, to have active researchers as teachers in all courses. All members of the faculty are expected to participate in undergraduate teaching. Furthermore, it is important that mathematics courses are, with few exceptions, given by the Department of Mathematics. This is mostly the case at 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 also 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 the master program in *Applied and computational mathematics* that is tightly connected to the research programs. The high-level understanding of researchers is also important in the construction of new programs to get a good mix of courses. The new five-year program, *Engineering Mathematics,* that started receiving students in the fall of 2020 has been designed as an entirely new program for KTH. Many members of the faculty have been active in the work leading up to this. The department is very proud of the program and also confident that it will become a flagship program for KTH. The launch of this new program has been an extremely successful with over 300 first-hand applicants for 30 places.

Our mathematics education at a glance

The main contribution of the 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 the five-year engineering programs. The department has over 1500 new students yearly on these programs and about one semester of their curriculum consists of courses from the department.

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.
    - This new program started in the fall 2020 and highlights the connection of research and education at the department. The broad scientific competence of the faculty has been used to design a program of high relevance and quality. It will be a key task for the department to continue to develop this program.
- The master program in **Mathematics** in collaboration with Stockholm University started in 2011 and currently has 15-30 students yearly.
    - The master's Program in Mathematics is a joint initiative of the Department of Mathematicss of Stockholm University (SU) and KTH. The aim of the program is to allow students to deepen as well broaden their knowledge in mathematics. After initial mandatory courses in Analysis, Algebra & Geometry, Topology and Discrete Mathematics the students are given significant freedom to choose their own specialisation.
- The master program in **Applied and Computational Mathematics** started in 2011 and has an increasing number of students, currently with close to 100 students yearly.
    - This master's program was created when the Division of Numerical Analysis joined the department. After the basic mathematical courses (30 ECTS credits) the students specialize in one of the four tracks Computational Mathematics, Financial Mathematics, Optimization and Systems Theory, and Mathematics of Data Science.

- The doctoral program in **Mathematics** with 5-6 new students yearly.
    - The course requirement for the program is 60 ECTS credits (8 full courses), of which 2 courses have to be taken in each of the areas Algebra/Combinatorics/Logic, Analysis, and Geometry/Topology (the "breadth requirement"). All courses are offered 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.
- The doctoral program in **Applied and Computational Mathematics** with 5-6 new students yearly.
    - The doctoral program in applied and computational mathematics was started in 2011 to give a well-defined alternative to the doctoral program in mathematics. In this new combined program, the PhD education of the three divisions Mathematical Statistics, Numerical Analysis and Optimization and Systems Theory is unified with the aim to provide a broader education that better suits modern applied mathematics.

The department supervises more than one hundred master theses yearly. There are academic projects done fully at KTH, some of which lead to publications in journals, while a majority of the projects are initiated by outside stakeholders where the students have one advisor at the external company/organisation and one academic advisor at KTH.

The department also supervises about one hundred bachelor thesis projects yearly. These students come primarily from Engineering Physics, Vehicle Engineering and Industrial Engineering. Many of these projects are formulated either by faculty members or graduate students, often related to their current research interests.

Some examples of research and teaching interaction in the programs

The new program in Engineering Mathematics has a seminar series where invited researchers give presentations about their research for the students in the program. This seminar series provides the students with an opportunity to interact with researchers at the department as well as external experts. The program also includes the basic course SA1006 *Ingenjörsfärdigheter i Teknisk matematik*, where different companies are invited to give lectures on how they use mathematics and programming outside academia. Students within the course also conduct smaller research projects that relate to the research done at the invited companies.

In the joint master's program in mathematics, there is a strategic choice of having one teacher from SU and one from KTH in all the core courses. This brings the students into direct contact with more researchers which in particular gives the benefit of extra potential advisors for the degree projects. In addition to the core courses there are also more specialized courses that are designed to reflect the research interests and activities at the two departments. A few such courses are offered bi-annually, others are offered as "Topics in Mathematics" where the content varies from year to year. Many students find their degree project through these courses and hence do a research-oriented master thesis.

Some students are allowed to take PhD courses as part of the master's program. Despite the risk that some students may overestimate their backgrounds this is overall a positive challenge for ambitious students. 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. In a survey distributed amongst the students in the fall of 2019 more than 50% of the students in the program stated that they were aiming to continue on the PhD level.

In the master program in Applied and Computational Mathematics, there is a strong connection to research outside the department and also KTH. In several courses, including SF2561 Finite Element Method, SF2863 Systems Engineering and SF2980 Risk Management, external lecturers are used and there is a Program Council consisting of representatives of companies with strong ties to the research in the department. Most of the program's teachers are active researchers often with close connections to outside stakeholders. This leads to a large number of master thesis projects carried out at companies, research institutes and public authorities.

The basic principle in constructing the curriculum consists of providing all students a broad and thorough mathematical basis and to enable them to delve into one subject in detail. In this way future experts are educated to be able to bridge the gap between research and its applications in real life problems.

During the last years, the program has modified its structure by incorporating important new developments in research and society at large. In particular, the creation of the Brummer & Partners MathDataLab as well as the hiring of WASP-financed faculty has resulted in a new study track, namely Mathematics of Data Science, as well as changes in some existing courses.

The Doctoral program in Mathematics has, obviously, a very tight connection to research. On top of the breadth courses mentioned above there are also more specialized courses. These usually reflect the interests of the faculty members or are given by visiting researchers. The collaboration with SU is here important and makes it possible to give courses in a wider spectrum of mathematics.

As mentioned before, PhD students in the applied program are encouraged to help formulate and supervise bachelor thesis projects 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 this practice increases the interaction with research at the undergraduate level.

The creation of the applied Doctoral program out of three separate programs as mentioned before, had had a benefit of bringing the faculty closer together and creating a larger, more dynamic, research and teaching environment.

Finally, the PhD students sponsored by WASP should be highlighted. Such external programs are applied in nature but has nevertheless attracted students in both Doctoral programs and supervisors from many groups in the department. This has increased the flow of information and interaction within the department.

6. Impact and engagement in society

a. Relevance of research to society at large

Collaborative research projects with external stakeholders have a clear relevance to the involved parties. In the longer term, such projects also contribute towards building up domain specific knowledge within the department, which in turn has a broader societal relevance. Another long impact to society comes from activities at the department that leverage upon the research to improve on mathematical literacy (numeracy) among young people and decision makers. Finally, as outlined in section 5, a strong and active research environment is essential for sustaining and developing educational programs in science and engineering.

The interplay between research and education along with its societal relevance is discussed in section 5. Focus here is therefore on societal relevance of collaborative research projects and activities for improving upon the mathematical literacy.

Collaborative research projects

Collaborative research projects are typically initiated and led by individual faculty members at the department. Many are pursued jointly with stakeholders from industry involving industrial PhD students, postdocs, and adjunct professors. They are also diverse in the sense that they involve a broad range of mathematical fields, including some usually seen as part of pure mathematics (like algebraic topology, algebraic geometry, geometric analysis, and combinatorics).

Some of these collaborations originate from the extensive set of master thesis projects (about 100 each year) that the department has with industrial stakeholders. The department has also increased its involvement in externally hosted research infrastructures. As an example, there are currently four projects pursued within the Swedish e-Science Research Centre (SeRC); three in Data Science MCP (Hult and Olsson, Jarlebring, and Szepessy) and one in Brain/IT (Nyquist). There are also two projects within the Digital Futures centre: Digitizing Brain Data for Health and Disease (Chachólski) and Decision-making in Critical Societal Infrastructures (Karlsson).

An overall ambition with the applied mathematical research is not only to provide means for addressing specific problems from applications, but 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, see case studies section for examples. Such applied mathematical research often requires combining expertise from multiple areas of mathematics. To explore and further develop new application areas for mathematics that has 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. Key industrial stakeholders related to CIAM were Ericsson, ABB, AstraZeneca, General Motors, Saab, Volvo, Handelsbanken, Swedbank, Comsol, and RaySearch Laboratories. 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.

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.

Societal impact from such joint 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 outcomes from the research that materializes into a product/service as such information is often not publicly available. An indirect measure of impact is to see whether the industrial partner continues to participate in collaborations over a longer period of time. Another aspect of societal impact relates to improving the mathematical literacy among decision makers. The industrial partner typically employs some of the PhD students or postdocs that were involved in the collaboration after the completion of the project. These individuals tend to act as ambassadors for mathematics and thereby improve the mathematical literacy among decision makers within their organisations.

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 require notions/tools from a wide range of mathematical fields where the department has strong scholarly traditions.

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, Koski, and Di Rocco) for analysis of chemical reaction networks and genomics data. Likewise, it contributed to opening up for research in the intersection of analysis, differential geometry, optimization, machine learning, and numerical analysis 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 the Brummer & Partners MathDataLab (MathDataLab), a centre that focuses on mathematics of complex data.

MathDataLab currently engages about 15 faculty from all divisions at the department. It has supported several workshops with industry participation (Nov 2017, June 2018, Jan 2019, June 2019, Oct 2019), it hosted study groups on specific topics. An international conference on "Mathematics of Complex Data" was planned to be organised in June 2020 but has been postponed and will take place when travel restrictions allow for it. Developing mathematical theory and methods for AI motivated by challenges in life science and medicine is a reoccurring theme in several of the larger applied research projects at the department. For example, the Director of MathDataLab (Hult) was recently appointed as Research Director for the second strategic research area at MedTechLabs (see section *Platform for collaboration* on page 46). Other examples are topological data analysis applied to genomics data (Chachólski) and for diagnosis, prognosis and more effective treatment of brain diseases (Chachólski), deep learning for optimal scheduling and treatment planning in radiotherapy (Forsgren), and deep learning for image reconstruction in medical and biomedical imaging (Öktem).

The next thrust 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 (with a postdoc and a PhD student each) was made possible thanks to funding from WASP/AI.

Mathematical literacy (numeracy)

The ability for citizens and decision makers to understand and critically judge quantitative arguments based on modelling is becoming increasingly important in the society. A clear indicator is the ongoing debate around modelling the spread of covid-19 and assessing efficiency of various counter measures. Improving upon the mathematical literacy is therefore an important part of the societal relevance.

One approach is to showcase selected parts of mathematical research, and in particular stress that mathematics is primarily a way of structured reasoning rather than computations. The public image of the subject (of the science, and of the profession) is not only relevant for the support and funding it can get, but it is also crucial for the talent it manages to attract - and thus ultimately determines what mathematics can achieve, as a science, as a part of human culture, but also as a substantial component of economy and technology. The department therefore organises outreach activities towards schools. Jointly with Stockholm University (through Stockholm Mathematics Centre), the department organises 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). Faculty from the department are also active in outreach activities towards the general public, e.g, as part of the Sonja Kovalevsky days and the Pi-day, the latter organised by Stockholm Mathematics Centre.

Summary and analysis

The strategic initiatives for collaborative research at the department are based on the view that applications often require combining a broad spectrum of mathematical techniques, including some that are considered as pure mathematics. This is in particular the case for life sciences and AI where challenges relate to research areas within mathematics where the department has a strong track record. An example is mathematical theory and methods for complex multi-scale phenomena (dynamical systems, random matrix theory, multiscale numerical methods, large deviations theory), another is combining first principles modelling with data driven approaches to infer models from patterns/causalities in highly noisy heterogeneous data (algebraic geometry, algebraic topology, combinatorics, algebraic statistics, geometric analysis, machine learning, inverse problems). There are also large investments that are now being made in AI and life sciences.

The department will therefore continue to actively highlight relevance of its research within life sciences and AI, and whenever possible initiate activities for catalysing collaborations in these areas. The department will also continue to showcase mathematics research for improving mathematical literacy among decision makers.

b. Research dissemination beyond academia

Research with non-academic stakeholders is an important part of disseminating research beyond academia. The department utilizes on-going collaborations and puts particular emphasis on cases that involve multiple areas of mathematics and/or use cases that are easy to understand for the layman. These collaborations also improve the mathematical literacy since project members (typically MSc or PhD students) act as ambassadors for mathematics.

Another form of dissemination relates to taking part in public debates and writing briefing and policy papers. An example of this 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. In that role, he wrote KTH response to various briefing and policy papers and took part in high-level meetings with KTH strategic partners active in life sciences. Another example is the report written in April 2020 by Hult on uncertainties in the SIR-model for Covid-19 spread. The report was part of KTH's response to a direct query from Region Stockholm (which governs all hospitals in Stockholm region). A final example is the report written in April 2019 by Linusson (together with a professor at Uppsala University) on weakness in the law that allowed for political parties to manipulate the election of members in municipal subcommittees and in practice steal seats from other parties. They presented a solution and also wrote an op-ed article and contacted members of parliament to bring attention to the problem. A public inquiry that started in February 2020 was commissioned to review the matter. In March 2021 it presented its conclusion, which is to follow the suggested mathematical solution.

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

Several reports[14] show that mathematical sciences have a significant impact on the economy. As such, an active mathematical research community indirectly contributes towards SDG 8 (decent work and growth). The connection is more explicit 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 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").

Overall, less than 20% of the research at the department is directly related to SDGs. Research at the department that applies to life sciences is directly related to SDG 3 (good health well-being). 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 SDG 8 (decent work and growth). Furthermore, industrial mathematical research relates to SDG 9 (industry innovation and infrastructure). Likewise, research in theory and methods for modelling and simulating multiscale phenomena and for uncertainty quantification relate directly to SDG 13 (climate change and its impacts). Finally, outreach activities that target mathematical literacy are also directly related to SDG 4 (quality education).

e. Structure for increased impact

Mathematical literacy

Outreach activities at the department for improving mathematical literacy (numeracy) have been paused during the covid-19 pandemic, but they will be resumed once restrictions are lifted. These activities are highly prioritized and come with sustainable funding through Stockholm Mathematics Centre. An option that is being considered is to allow for "summer internships" in which selected students (undergraduate or high school) take part in a project with researchers at the department.

[14] 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

Platform for collaboration

The department has until recently pursued a strategy where traditional bottom-up approach for collaborations is complemented with strategic top-down initiatives with focus on life sciences and AI. 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 a successful strategy in the sense that the focus on life sciences and AI is not only scientifically motivated, but it also aligns well with large initiatives within these fields. As an example, SciLifeLab in Stockholm was in 2013 upgraded to a national infrastructure for molecular biosciences. This was followed by the opening of BioMedicum (2018), MedTechLabs (2018), and BioClinicum (2019), all new research infrastructures for life science and medicine. For AI, a major thrust came in 2017 when the Wallenberg foundation extended the WASP program to include AI research. The latest line of development came in 2020 when the Wallenberg foundation announced the Data-driven Life Science initiative that will offer SEK 3.1 billion over 12 years.

An issue of concern is that there is currently no infrastructure for catalysing new collaborations. This has been a key component in the above strategic initiatives towards life science and AI. Life science related activities were initially done as part of CIAM, the industrial mathematics centre that was closed in 2016. This also paved the road for further initiatives in life science and AI, like MathDataLab, WASP AI recruitments, and the projects "Topological Data Analysis of Genomics Data" and "Image reconstruction in medicine" mentioned as impact cases. 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 centre for applied mathematical research.

Discontinuing existing centres is part of the natural evolution of academic research, but much is gained from having some degree of continuity. The department will therefore explore various options for establishing a platform for external collaboration. The aim is to something similar to the platform offered by Stockholm Mathematics Centre for collaboration with Stockholm university on outreach activities and on master's and doctoral programs in (pure) mathematics. The precise form and funding for such a platform are yet to be determined and there are here several options, but it is natural to build this on MathDataLab. One approach is to explore possibilities within the existing Research Platforms at KTH, alternatively actively work for establishing a new Research Platform on "Modelling and Simulation" (or something similar). Another is to team up with an external stakeholder, similar to how Chalmers/University of Gothenburg and Fraunhofer Institute jointly established the Fraunhofer-Chalmers Centre for Industrial Mathematics. One could here consider exploring the possibility to let RISE take a more active part in developing MathDataLab, e.g., by integrating AI with other areas of mathematics and computational sciences. RISE is making large investments into digitisation related research, and applied AI research in particular. An example is the Digital Futures research centre that was established 2020 by KTH, Stockholm University and RISE, based on significant long-term support of a Strategic Research Area by the Swedish Government.

Shared positions

Positions that are jointly shared with an external partner is a proven way to strengthen collaborations. Overall, there are no legal obstacles that prevent one to have such positions, even though some formal matters need to be resolved regarding forms of recruitment if the position is a permanent faculty position.

The Division of Mathematical Statistics has had adjunct professors from industry and one associate professor at the Division of Mathematics is half time in industry. One can here further expand on hosting adjunct professors. Another venue is to consider “shared” positions with another department at KTH, e.g., this can be with a suitable department (say Department of Intelligent Systems) at the School of Electrical Engineering and Computer Science for AI and/or optimization and for numerical analysis, it could be with Department of Mechanics. Along the same lines, one can also consider a shared position with a suitable department at Karolinska Institutet (KI). This is indeed possible since there are examples of such shared positions between KTH and KI. A concrete option is to leverage on the SciLifeLab Fellows program and the forthcoming positions that will be announced as part of the Data-driven Life Science initiative. KTH has, as a founding partner, the mandate to specify profiles for candidates to such career programs at SciLifeLab and it would be natural to have at least one such position focusing on mathematical theory. To summarise, the department will explore possibilities for shared positions.

Department of Engineering Mechanics

Self-evaluation
Head of Department: Professor Fredrik Lundell

Included divisions:

Division of Vehicle Engineering & Solid Mechanics
Division of Fluid Mechanics & Engineering Acoustics

Department of Engineering Mechanics

1. Overall analysis and conclusion; strengths and development areas

a. Limited SWOT-analysis

The starting point for the self-evaluation 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 are presented and commented. This analysis is followed up by presenting key development areas for the department.

	Strengths	Weaknesses
Research	Bulleted list, in order of magnitude. 1. From high to low TRL: strong in a wide range from fundamental research (ERC) to applied work with direct industrial relevance. 2. International presence and influence (keynotes, state-of-the-art papers key references, collaborations, sabbaticals) and industrial collaboration (industrial PhD students, EU-projects, centra). 3. Culture of publication in top journals of the discipline(s) in parts of the department. 4. Resilient to the funding landscape and attracting research funding from various sources. 5. Systematic and strategic work to identify and engage in multi-disciplinary research questions. 6. Excellent access to high quality experimental and computational resources in house and externally.	Bulleted list, in order of magnitude. 1. The extent of efforts to develop truly transformative research questions is less developed. Too little focus to read, as well as publish in, high-impact multi-disciplinary journals. 2. Often possibly related work at high and low TRL does not interact. 3. Faculty has too little time to perform own research due to administrative tasks and engagements in different tasks at KTH. 4. The different publication cultures within the department lead to a lower overall citation score than potentially possible (cf. Strength 3). 5. Demands on co-funding make resources for free research and infrastructure development very limited.
Organisation	Bulleted list, in order of magnitude. 1. Internationally recognised teachers and researchers. 2. New departmental structure with increased access to state-of-the-art experimental and numerical infrastructure. 3. Significant roles in national and international commissions of trust and many external relations and interactions. 4. Systematic and continuous improvement of education and research on all levels. (Leading CDI and Kaizen.) 5. Many commissions within KTH.	Bulleted list, in order of magnitude. 1. The economic burden of maintaining laboratories takes focus from developing them. 2. Due to retirements, we risk losing important competences. 3. Faculty structure: many professors but few assistant professors. 4. Informal leadership structures can dominate and have a conservative effect.

Development areas

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 the cross-departmental structures already existing and that we will extend are necessary in order to fully 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. In order to have resources for this, it is important to keep the number of faculty balanced given the basic funding.
- *Working environment with special focus on equality and diversity (JML)*
  Quite often, issues regarding 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: Maintaining and developing labs and computational resources*
  A continuous discussion on needs and possibilities must be maintained, while continuously matching the needs to funding opportunities. This requires a strong and continuous commitment from the faculty.
- *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 we will strive for continuing to be that. Furthermore, it is important that the administrative support is efficient and accessible in a transparent manner.

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

Research results from the department are brought to direct use as can be seen in the eight impact cases from Engineering Mechanics in the Appendix. Furthermore, a large number of clinical, industrial and societal collaborations are ongoing that have a continuous but more qualitative impact on best practices and future developments. Transfer of knowledge to industry and other actors takes to a large extent place through alumni and, in particular, industrial PhD students and affiliated faculty and our life-long learning activities. By conducting disciplinary work of very high quality, we are leading several research fields. We also contribute to 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:

We maintain and develop an extensive experimental infrastructure (the Odqvist Laboratory, which is a KTH infrastructure) and numerical codes for scientific computing. We have a leading role on the national level in using and developing computational resources. We use and contribute 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. The main contributions when it comes to sustainability are that we contribute to the development of future sustainable transports with a holistic perspective from the components of vehicles, via the vehicles as a system (including humans interacting with it) to the function of the vehicle in the overall transport system. We are also contributing to development of the energy system, e.g work on wind turbines and improved efficiency of combustion engines. Improved health will be a direct result of our research 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, transfer to biological sources and/or development of novel functions such as structural batteries.

2. Research profile

a. 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: 31 professors, 21 associate professors, 3 assistant professors, 21 researchers, 21 postdocs, around 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 categorized 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 and underwater technology
- Aeronautics engineering
- Space technology
- Solid mechanics
- Composites and lightweight design
- Sound and vibration
- Fluid Mechanics
- Biomechanics

We have a long tradition of cross-disciplinary research, both within department, as well as with other academic and industrial partners. The laboratories maintained by the department are:

- The Solid Mechanics laboratory
- The Lightweight Structures and Maritime Robotics laboratory
- The Aeronautics laboratory
- The Space technology lab (part of)
- The Fluid Physics laboratory
- The Vehicle Engineering laboratory

- The Marcus Wallenberg Laboratory for Sound and Vibration Research (MWL)
- The MoveAbility laboratory

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

Through our engagement in different centra, we carry out multidisciplinary research. Research groups at the department are or have been responsible for or leading the following long-term research centres (collaboration partners):

- CCGEx – Competence Centre for Gas Exchange (Swedish Energy Agency, Scania, Volvo Cars, Volvo Powertrain, Borg Warner))
- Centre for Sustainable Aviation (Trafikverket, Swedavia, Transportstyrelsen, Luftfartsverket, Chalmers, LiU)
- ECO2 Vehicle Design Centre (VTI, AB Volvo, Volvo Cars, Bombardier Transportation, Scania, and SMEs) (Vinnova Centre of Excellence, 2006 – 2016, 2017 – 2022)
- KTH Railway Group (Trafikverket, Alstom, SJ, Sweco, Atkins, WSP ,Dellner, Green Cargo)
- SMaRC Swedish maritime robotics centre (SU, GU, FMV, SAAB...)
- Standup for Wind (UU, LTU, SLU)
- Swedish e-Science Research Centre (KI, SU, LiU)
- Linné Flow Centre (VR Linné Centre of Excellence 2007-2017)

b. Central research questions and themes, knowledge gaps addressed, main research activities

The research performed at the department is broad, ranging from system behaviour on a global level to microscale dynamics and their effects on macroscopic modelling. In general, the research questions and the approach to research at the department are 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 challenge whose solution is anyway strongly dependent on and enabled by the tools developed). In the following, we provide details of the different areas and present concrete examples.

Many of our activities are connected to one or several of our four thematic areas:

- Advanced computing and machine learning
- Biomechanics, bioengineering and health
- Energy, transport and sustainable mobility
- Materials and structures: processing, functionalizing, characterizing and utilizing

The holistic perspective with thematic areas has recently been established. Thanks to an investment from the School of Engineering Sciences, eight postdocs related to the thematic areas have recently been announced. Each postdoc project was chosen from proposals from teams of senior researchers from at least two of the three merged department. 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.

Below the research groups at the department with their respective research activities are presented.

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 Vehicle Design group (see below) are also how to translate societal needs and goals into sustainable vehicle and transport system solutions. Trends of automation, electrification and connectivity is clearly re-shaping the road bound vehicle industry with new types of vehicles emerging. The Road Vehicle group has strategically focused on innovative over-actuated vehicle concepts and how these types of vehicles can be designed, configured and controlled to reduce energy consumption, increase comfort as well as become safer. For drivers and operators, aspects such as feedback and connection to the vehicle as well as comfort and communication of vehicle character are important. Within the area of driver-vehicle interaction, methods have been developed using machine learning to classify and predict objective and subjective assessments of vehicle dynamics that have been adopted in vehicle industry. Further, using a model-based human-centred approach, objective development of moving base driving simulators as well as prediction and minimisation of motion sickness in autonomous vehicles using optimisation-based motion control strategies are explored. With increasing complexity of new vehicle designs and transportation tasks it is important to evaluate how to optimise the vehicle operation and its control with respect to aspects such as energy, safety, performance and comfort. Here, comprehensive knowledge of vehicle dynamics aspects when developing control strategies becomes increasingly important, especially in safety critical manoeuvres. The Road Vehicle group focuses as well on understanding how the interaction with the surrounding environment impacts the operation of vehicles, e.g., crosswind stability, rolling resistance and tyre wear. A significant effort is made to combine cross-disciplinary fields, simulation tools and methods to analyse the vehicle system and environment interaction.

The *Conceptual Vehicle Design research group* focuses 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 behaviour, 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 behaviour of the contact partners is predicted, and the system optimized. An important subsystem for our research is the dynamic interaction between rail vehicle pantographs and catenary where research questions are reduced contact force variation and less wear and fatigue. Another 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 consumption and CO_2 emission labelling can be mentioned as example. Together with the lightweight structures group studies on replacing conventional steel structures like bogie frames with composites are ongoing. The group has extensive collaboration with universities around the world and many industry partners.

The research of the *Naval Research group* is addressing questions specific for Swedish industry needs as well as more basic research with no immediate end user. The group has an excellent collaboration with Swedish industry, government bodies and other universities. A typical signum of the group is the strong link between theory, simulations and experimental verification. The Naval group has extensive international collaboration. Among the more traditional topics are 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.

The *Aeronautical research group* aims to contribute to sustainable aviation covering a wide range of applications from a technical and system perspective including novel aircraft configurations, integrated urban air mobility, and optimal air transport. Today there exists three subgroups: Flight Dynamics, UAV Design, and Sustainable Air Transport. The multidisciplinary inherent to these research areas fosters collaborations within KTH departments as well as international partners. Most recently a project on aircraft Trajectory analysis for Reduced EnVirOnmentaL impact (TREVOL) has been commenced, as well as the design of a fuel-cell powered and battery powered, hybrid/electric unmanned air vehicle (UAV). Project TREVOL focuses on the operational side of aviation, with an emphasis on the reduction of the environmental impact of aviation in terms of gas emissions and noise through flight procedure analysis. Results from this project are expected to be beneficial for operators and regulators for reduction of the environmental impact of air traffic, and for the public health. The UAV design project, dubbed “Green Raven,” is a multidisciplinary effort in sustainable aviation through the perspective of system integration. The main objective is to develop a technology demonstrator with a configuration and manufacturing optimized for the use of hybrid/electric propulsion.

The *Space Technology research group* is focusing on developing different deployable structures technologies for small satellites, e.g., CubeSats, for scientific instruments and low-thrust propulsion, i.e. solar sailing. The research involves understanding the time- and temperature dependent material properties of very thin composites subjected to high strains under several months of storage before spaceflight. The use of shape-memory polymers in the composites open up new possibilities to thermally control the deployment speed and to overcome viscoelastic strain energy dissipation effects. This work involves development of theoretical models verified by experiments in simulated zero-gravity environments. Deployable structures are required for accurate scientific sensors measurements of, e.g., the Earth magnetic and electric fields, by placing the sensitive sensors sufficiently far away from the spacecraft-generated magnetic fields. Hence, the research on deployable structures is performed in close collaboration with the space and plasma physics group at KTH. Another research direction being pursued within the group is the mechanical shock testing of spaceflight hardware. As part of the KTH Space Technology Laboratory, equipment for high-acceleration-level mechanical shock testing (a shock table and a powder-actuated bolt gun) is since 2020 available at the Marcus Wallenberg Laboratory for Sound and Vibration Research. During launch into space, the separation of launch vehicle stages creates mechanical shock waves with acceleration levels up to several thousand times the gravity at sea level. It is difficult to reliably model mechanical shock because of the high frequencies and short duration of the shock. By having access to a facility for experimental shock testing of spaceflight hardware at qualification acceleration level research on shock mitigation spacecraft design has been initiated. 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.

Acoustic and vibration phenomena in fluids and solids are studied at the *Marcus Wallenberg Laboratory for Sound and Vibration Research* (MWL) research group, spanning from fundamental to applied research. The research on mechanical wave generation and propagation originates from a need for low noise and vibration design, environmental noise abatement and improved sound quality, with the main focus on sound in the audible frequency range and vibrations down to a few Hertz, including source, system response and exposure at the receiver point, be it a human or vibration load on structures. Thus, research on source mechanisms, transmission and absorption properties of various geometries and materials, measurements of sound and vibration fields are combined with subjective aspects like perception and sound quality. The subject is inherently multi-disciplinary often requiring a systems analysis approach, implying multiscale considerations. The research activities range from fundamental studies of waves, materials and signal processing to studies of complex systems and applications on system level. The research team combines experimental work, numerical simulations, and physical modelling to tackle a broad range of research questions. Lately, methods benefiting from machine learning and sparse sensing have led to promising developments already receiving attention from the MWL partners and its scientific community. In addition, new research is emerging due to increased adaption of digitalization, availability of cheap, distributed and powerful CPUs and sensors together with novel and efficient data driven algorithms which all have increased the potential of using sound and vibration signals for new application areas. The MWL has well established connections and cooperation with industry and close collaboration with international institutions and universities as one of the largest and most influential centres for sound and vibration research in Europe.

Flow acoustics, in particular acoustics of confined complex flows related to rotating machines and sound in ducts is a field where MWL has a strong tradition and international recognition for its research. The work focuses on experimental as well as numerical studies of acoustic sources, and linear and non-linear aero-acoustic properties of duct elements. Acoustic liners used in aircraft engines and automotive silencers, heat exchanger tube banks, other duct elements and even straight ducts are often exposed to complex loads such as high amplitudes, temperature gradients, grazing and bias flow, and the research at MWL has led to improved understanding of the effects of these externalities on the acoustic properties of the system components. Sound sources in fluid machines, such as turbo units and fans are also not fully understood, and a continued subject of research. The team at the MWL on *material acoustics* is among the leading groups in the field, combining experimental and theoretical research enabling inverse estimation of the elastic, anelastic, acoustic properties of real materials with frequency and direction dependent properties. A number of original works on anisotropic modelling, simulation and characterisation of poro-elastic materials have been published, including microscopic modelling of visco-thermal dissipation in poroelastic media, and design and characterisation of the dynamics of anisotropic cellular materials including visco-elastic dissipation, recently using machine learning in order to address the associated complexity and growing level of detail under investigation. The activities within *vibro-acoustics* span structural vibrations and source quantification, damping treatment, building acoustics and the transmission and radiation of sound due to vibrations of solid surfaces. Recent activities include research on high-cycle fatigue of energy generating turbines, influence of surface roughness on rolling contact for metal-metal (wheel/rail) and rubber-asphalt (tyre/road), and sound source separation in ground transportation, specifically the application to rail vehicles, the fundamental problem of sound field analysis and source separation in confined spaces. Excellent research is conducted on novel design of hydrogel, filled and magneto-sensitive elastomer elements by constitutive modelling, including effects of chemical and physical ageing, and on the design of locally resonant acoustic metamaterials.

The MWL is an active partner including leadership roles in several KTH based research centres, such as ECO2, CCGEx and CSA, and is involved in EU projects for quiet transport and clean energy, all involving multi-functional and multi-disciplinary aspects where engineering acoustics is a key. Examples of recent multi-disciplinary research in the vehicle context are multi-functional panel and noise shield design and compact silencer design for road vehicles, enabling noise and vibration reduction simultaneously allowing for reduced weight or space, aiming at achieving optimal solutions on a system level. The research on novel metamaterial design for improved sound transmission properties of periodic flat panels, curved panels and sandwich structures, using distributed embedded resonators for vibro-acoustic applications has received much attention. Recently, research related to *environmental noise modeling and assessment* has grown through the centres and EU projects, for instance focusing on the impact and perception of noise from transport and wind turbines, involving the implementation of long-term outdoor noise measurements around airports and roads for the study of sound propagation in the atmosphere, and the development of assessment methods for internal and external noise exposure from ground transport. The research guides initiatives for noise mitigation through optimized take-off and landing procedures at airports, and cost and psychoacoustic assessment of the effects of new propulsion systems in road vehicles. The outcome of recently concluded EU projects has led to ongoing reconsiderations and reformulations of requirements associated with night-time delivery related traffic in the city of Stockholm.

Very recently, we have inaugurated the new *KTH MoveAbility Lab research group*. 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 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 as described below.

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 *Reliability and fatigue research* group deals with modeling of fatigue and its variation. Several models for the probability of fatigue have been developed and implemented in codes. Some of them are unorthodox and show good correlation with experiments. These models are a prerequisite for probabilistic design, in which "all" contributing reasons for scatter are included: Material behavior, loads and stochastic design variables, assembly variations, heat-treatments, etc. In this setting, optimization is studied. An objective is minimized, such as weight or cost, under the constraint that the probability of fatigue failure must be less than a required value. This procedure defines RBDO, Reliability Based Design Optimization. Both parametric optimization and topology optimization is studied. The group has since long studied contact fatigue, in particular rolling contacts and fretting. The strategy is to understand the basic underlying mechanisms of the damage processes and based on the understanding propose design improvements and solutions. The work is a long-term commitment which has also led to extensions into general fatigue, material mechanics, crack growth and environmentally controlled damage. The newest addition in fatigue research concern Additive Manufacturing of metal.

The *Fibre-based Materials and Packaging Technology* research *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 group* 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 modelling; finite element modelling; micromechanics; testing of materials and parameter estimation by inverse modelling; 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 *research group on Soft Biological Tissues* 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.

The vision of the *Lightweight Structures research group* is to perform high-class research towards lighter, multifunctional and resource efficient materials and structures, thereby strengthening the industry and society at large while targeting the UN sustainability goals. The focus is 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. Examples of on-going research include methodologies for design, fabrication, and quality assurance of welded lightweight metallic structures with focus on durability and structural integrity, see Impact cases for research outcome. Mechanics and strength of multi-material interfaces where anisotropy in combination with discontinuous stiffness, shape, thermal expansion etc. generate detrimental or beneficial performance. The application area in focus is multi-material joints and inserts for mechanical fasteners.

3D textile reinforcement for composite materials is a unique technology that allows for unprecedented textile architectures that are utilised in structural applications. In collaboration with a SME with a flexible and patented 3D weaving process, the research involves mechanical characterisation, strength predictions and resin flow during manufacturing.

Sandwich structures, their integrity and damage tolerance are within the expertise of the group. Recent work includes analysis of impact scenarios in cold climate and further development of new test methods for characterisation of constituent materials. Except for new research findings, this has led to improved experimental techniques and a patented test rig. Examples of ongoing research towards the vehicle industry covers material models for accurate simulation of forming processes of novel formable metallic sandwich structures, multifunctional topology optimisation, prediction of fatigue properties in composite materials and novel running gear concepts for rail vehicles using composite materials.

Technical cost modelling frameworks are being developed to enable studying true design for circularity towards meeting the target on sustainability. Research on cost efficient manufacturing of structural composite components includes process simulation of multi-layer forming, heat transfer modelling, analysis of shape distortions and residual stresses. The research has resulted in new design guidelines for wrinkle free forming and process settings for local heating resulting in improved quality and significant reduction (80%) of forming times for aerospace applications. Composite structures with embedded multi-wall carbon nanotubes or graphene for integrated temperature and strain sensing is an example of research at low TRL within the group.

Another example of innovative research is on structural batteries, a carbon fibre composite material that can also store energy as a Li-ion battery. This multifunctional material can provide substantial mass savings on system level, in e.g., electrically powered vehicles, and thereby reducing energy consumption. The work has led to several spin-off ideas for utilizing electrochemical activation of carbon fibre composites to include even more functionalities like sensing, shape morphing and energy harvesting.

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.

The fluid mechanics activities are performed under the umbrella of the FLOW community (FLOW is a research environment that originates from the Center of Excellence Linné FLOW Centre, which was active 2007-2017). This community assembles several research groups and activities.

One of the main topics of the *Stability, Transition, Turbulence and Control* group is 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. Within a number of EU-funded research projects, both as coordinators and partners, we have developed tools for optimal design of wings with natural laminar flow or hybrid laminar-flow control. We have developed numerical tools which are used by aircraft manufacturers. Our latest simulations aim at producing a high-quality database, both using simulations and experiments, to describe the high Reynolds number turbulent flow around wings, using novel adaptive numerical methods. Our FLOW database for various turbulent flows is already widely used in the research community as reference data. We have also developed our activities in emerging areas, including machine learning and uncertainty quantification. In both areas we have published fundamental contributions, pioneering the predictions of turbulent flows using neural networks, and assessing the impact of artificial intelligence on sustainability. We have also applied concepts from the field of dynamical systems to turbulent flows and used modern mathematical approaches from optimisation theory for topology optimisation, an area with tremendous technical potential. Building on our turbulence research we have been able to develop high-fidelity turbulence models with low empiricism, which have gained attention in the CFD and aeronautics communities, enabling participation in EU and Clean Sky projects, also as coordinators. In addition, we collaborate closely with MISU (Stockholm University) on developing large-eddy simulation and RANS approaches for the simulation of atmospheric boundary layers of relevance for climate and weather models. Simulations of wind parks and analysis of the wind-turbine wake instability, contributing to knowledge required for efficient design of parks, are also part of our research activities. Our work in the unit relies heavily on large-scale computational resources, provided both from SNIC (Swedish National Infrastructure for Computing), but also from Europe (mainly PRACE - Partnership for Advanced Computing in Europe). During the last years, we have had the largest allocations of computer time in Sweden (5 million hours per month) and were regularly allocated PRACE projects (on the excess of 200 million hours). We are also having leading roles in the Swedish e-Science Research Centre (SeRC), where we for instance develop GPU-accelerated versions of our research codes.

Another part of the FLOW environment is the *Fluid Physics Laboratory*, with activities relating to all thematic areas. The work related to energy and transport is renown turbulent boundary layer measurements in the MTL (minimum turbulence level) wind tunnel. This work ranges 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 also active in a basic research campaign on high Reynolds number turbulent flow in the pipe flow facility CICLoPE in Italy. The work on turbulent and transitional measurements also include experiments related to gas turbines and wind power. When it comes to materials and structures, we investigate the assembly of biomaterials, primarily the flow of elongated “particles” from millimetre sized fibres 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 fibres or assembling of molecules and supramolecular building blocks into macroscopic materials. This work utilizes 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. The third activity in the fluid physics laboratory group is shock waves, a traditional research area that was revitalized with a faculty recruitment in 2018. 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. The fluid physis laboratory is also host to the Cicero lab, in which flow related to gas exchange of internal combustion engines, e.g. performance of turbo chargers under transient conditions.

The overall goal of the *Biofluid* research within FLOW 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 complications 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.

The *Complex fluids group* has recently addressed the challenging problem of 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.

A new direction of FLOW research initiated with the multidisciplinary research initiative 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.

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 centres 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.

c. 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 believed to be best suited to give a good picture of our contributions. 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 CO_2 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. We have proposed a European scheme on energy labelling of rail vehicles.
- 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). These methods can be used to enhance the life of key components, optimize maintenance planning and thus significantly reduce cost.
- contributed to the advancement of the usage of active suspension systems in rail vehicles together with Swedish rail industry. The research results are today implemented in commercial vehicles from Alstom (former Bombardier Transportation), one of KTH's strategic partners, in Italy and Switzerland.

- 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 evaluation 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.
- contributed to understanding the human-boat interaction onboard high-speed craft and performed ground-breaking work on large sailing vessels.
- designed and manufactured very thin high-strain composites, investigated their visco-elastic time-dependent and temperature-dependent behaviour 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 carried out.
- developed acoustic models and improved the understanding of the acoustic or vibrational behaviour of e.g., micro-perforated plates and wind-turbine blades.
- developed methods for inverse estimation of the elastic, anelastic, acoustic properties of real materials with direction and frequency dependent properties. These methods have been applied to design and characterise anisotropic cellular materials, where we have shown that we can continuously control the anisotropy by manipulating the micro-structure, including visco-elastic dissipation and introducing machine learning methods in order to address the associated complexity and growing level of detail under investigation.
- 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.
- 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 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 turbulent boundary layers 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.

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

We have an established tradition of contributing to the body of scientific knowledge through publications in “listed in Web of Science” journals and contributions to international well-established peer-reviewed conference contributions. We are also active in well-established international networks, resulting in journal editor assignments, scientific conference committees, and expert evaluations in an international context. An important aspect is that we, along with the disciplinary research activities, perform inter-disciplinary research. This forms a basis for collaborations resulting in emerging new research fields and enable development of disruptive technologies, which is reflected by the appended References. A measure of good quality is the ability to attract larger grants in high competition, that enables strategic development of the research activities and focus. Thus, we contribute to the body of scientific knowledge on all levels from fundamental phenomenological research to research on a higher system level close to applications, on all length scales. Applications span from the bottom of the ocean to space. These measures of quality and quantity are further elaborated below.

Journals

One measure of quality is publications in highly ranked specialized disciplinary journals in our respective disciplines. The last years, we also strive towards publishing in more general journals (e.g., Physical Review Letters, ACS Nano) and in multidisciplinary journals (e.g., Nature Communications, PNAS). All research groups are aligned with the traditional publication landscape and have a long history of considering publication in peer-reviewed journals as one of their main sources of dissemination. In addition, some research groups with close collaboration with industry also aim at impact through other means as can be deduced from the impact section. The bibliometric performance varies for different parts of the department. This variation reflects differences in publication culture between different research areas.

Conferences

Faculty members are regularly invited to give keynote lectures and organize sessions at the most important conferences in our research fields, and we also organize conferences regularly. Researchers are regularly participating in relevant conferences in their respective discipline, as well as conferences with a broader system perspective.

Research Grants

As indicated above, another good measure of our contribution is our ability to secure very competitive funding like ERC grants, Wallenberg fellows and – not least - large research centres. The high level of our scientific contribution is illustrated by the fact that one of the research centres from the department, the Linné FLOW Centre which was active 2007-2017, was evaluated as one of the top three research centres in engineering sciences in the final evaluation of the prestigious Linnaeus program. Two other examples of successful centres are the Vinnova Excellence centre for ECO2 Vehicle Design, which after 10 years of funding secured funding for another 5 (or even 10) years period, and the "Swedish Maritime Robotic Centre, *SMaRC*", funded by the Swedish Strategic Research Council. Several other centres could be mentioned here, cf. for example with lists in Section 2.a or below in 2.e.

Reflection on the department's bibliometric performance and publication strategy

The number of publications (fractional counts) has not changed significantly since 2012 according to our own database DIVA, cf. *Figure 6*. The publication impact, however, has decreased in Scopus from 1.16 (2012-2014) to 0.87 (2015-2017) for to rise a bit again to 0.92 (2016-2018), *Figure 7*. We do not know yet, whether this is a lasting reversion of the downward trend. When interpreting the impact numbers, it must be remembered that the variations across the units of the department are substantial. The publication impact between different units varies between roughly 0.6 and 1.25. For the same three-year periods the share of top 10% publications has decreased from 14.4% (2012-2014) to 7.9% (2015-2017) and then slightly increased to 8.2% (2016-2018). The share of international and corporation co-publications has increased from 47.3% (2012-2014) to 56.9% (2017-2019), see *Figure 8*, which to our opinion is a satisfying development that most probably will continue. We feel that we have strong international networks in our research activities.

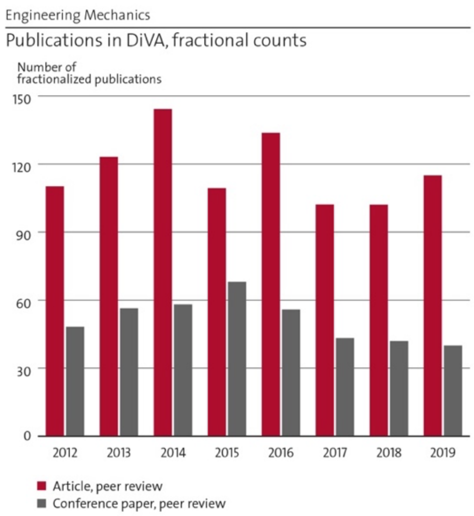


Figure 6: Publications in DIVA, fractional counts.

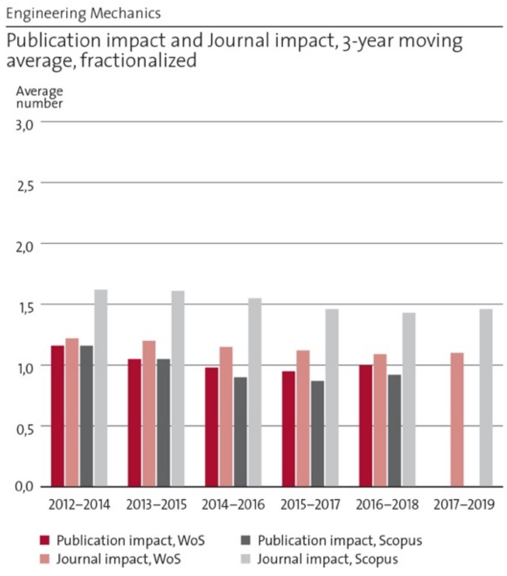


Figure 7: Publication impact and Journal impact

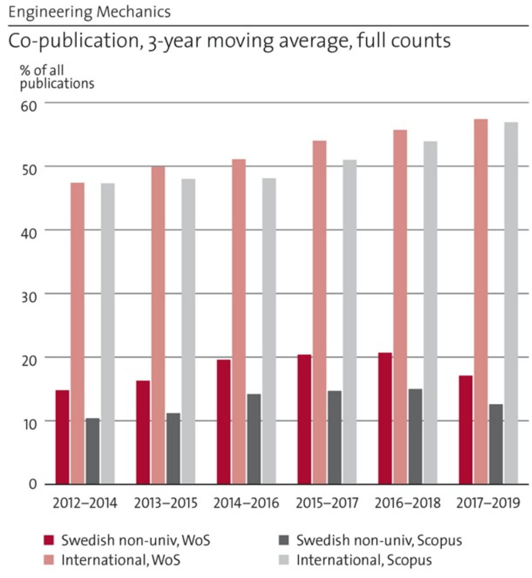


Figure 8: Co-publication

Our analysis of the bibliometric data is that the competition has increased. We believe that the following measures will help us to improve the bibliometric data:

- Encourage more people to submit manuscripts to higher ranked journals. Those that have succeeded can coach others in how to structure manuscripts for those journals. One strategy is to organize a seminar series on this topic.
- We should continue to strive for publishing more journal papers from applied research. There is no contradiction between more applied research in collaboration with industry and good bibliometric performance.
- We should have internal discussions about how many papers are needed to publish for a successful PhD defense. As supervisors today we might coach our students to too many publications instead of prioritizing quality.
- We have lacked a common strategy to publish open access, but as most journals are now by default open access that should improve the visibility.
- We must improve the visibility for our publications in social media, such as LinkedIn, Twitter and ResearchGate.

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 over the whole period covered by the RAE. Authors that are members of the faculty of the department are written in boldface and other authors affiliated to the department at the time of publication are marked with an asterisk.

- **T.C. Gasser**, S. Galinetti, X. Xing*, C. Forsell*, J. Swedenborg & J. Roy**.** *Spatial orientation of collagen fibers in the abdominal aortic aneurysm's wall and its relation to wall mechanics.* Acta Biomaterialia 8, 2012.
- **J. Faleskog**, I. Barsoum*. *Tension–torsion fracture experiments—Part I: Experiments and a procedure to evaluate the equivalent plastic strain.* International Journal of Solids and Structures 50, 2013.
- M. Shahzamanian Sichani*, R. Enblom* & **M. Berg**. *A novel method to model wheel-rail normal contact in vehicle dynamics simulation.* Vehicle System Dynamics 52 (12) , 2014.
- **M. Nybacka**, X. He*, G. Gil Gómez*, **L. Drugge &** E. Bakker. *Links between subjective assessments and objective metrics for steering*. International Journal of Automotive Technology 15 (6), 2014.
- P. Costa, F. Picano, **L. Brandt** and W.-P. Breugem. *Universal Scaling Laws for Dense Particle Suspensions in Turbulent Wall-Bounded Flows*. Physical Review Letters 117, 2016.
- Z Liu*, R Rumpler*****, **L Feng.** *Broadband locally resonant metamaterial sandwich plate for improved noise insulation in the coincidence region.* Composite structures 200, 165-172, 2018.
- P. Yadav, S. Shefelbine, E. Pontén & **E.M. Gutierrez-Farewik.** *Influence of muscle groups' activation on proximal femoral growth tendency*. Biomechanics and Modeling in Mechanobiology 16 (6), 2017
- G. Fuchs*, N. Berg*, L.M. Broman, & **L. Prahl Wittberg.** *Flow-induced platelet activation in components of the extracorporeal membrane oxygenation circuit.* Scientific Reports 8, 2018.
- N. Mittal*, F. Ansari, K. Gowda*, C. Brouzet*, P. Chen, P. T. Larsson, S.V. Roth, **F. Lundell**, L. Wågberg, N.A. Kotov & L.D. Söderberg*. *Multiscale Control of Nanocellulose Assembly: Transferring Remarkable Nanoscale Fibril Mechanics to Macroscale*. ACS Nano 12 (7), 2018.
- J. Canton*, E. Rinaldi*, R. Örlü* & **P. Schlatter.** *Critical Point for Bifurcation Cascades and Featureless Turbulence*. Physical Review Letters 124, 2020

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

A large portion of the research activities during 2012-2020 has been carried out through research centres and researchers at our department often have leading roles in these centres. In most cases, these centres serve as a basis for academic and industrial collaboration. Some are with only KTH participation, but most of them involve several Swedish universities, institutes and also industry partners. Among others, the department is or has been involved in the following centres that include national partners outside KTH and, in many cases, international cooperations. The centres in italic are centres where the department can be said to be the leading partner:

- *Swedish e-Science Research Centre* (KI, SU, LiU)
- Wallenberg Wood Science Center (Chalmers, LiU)
- Bolin Centre for Climate Research (SU, SMHI)
- *Standup for Wind* (UU, LTU, SLU)
- Swedish Aerospace Research Centre (Chalmers, LiU, LTU)
- Transport Research Environment with Novel Perspectives TRENoP (LiU, VTI),
- *ECO2 Vehicle Design Centre* (Univ. of Graz, Wageningen University, Univ. of Eastern Finland, Univ. of Le Mans)

- *KTH Railway Group* (Univ. of Illinois (UIUC), Beijing Jiaotong University, Bandung Institute of Technology, RWTH Aachen, Politecnico di Milano, Chalmers, LTU)
- SEC (LiU, UU, LU, Chalmers)
- LIGHTer
- NFFP-MIAU (LiU, Chalmers)
- Vehicle Dynamics Competence Area (Chalmers, SAFER)

A strength of the department is also the involvement in a large number of EU projects and also in large EU Joint Undertakings like Clean Sky or Shift2Rail with budgets of 1 billion Euros or more. Examples include:

- Excellerat Competence Centre (Uni Stuttgart)
- EU-ALLEGRA (Trinity College Dublin)
- EU-MorphElle (TU Munich, University of Bristol)
- EVERSAFE (TU Chemnitz, Fraunhofer-Gesellschaft, VTI),
- Clean Sky (a large number of European stakeholders in the Aerospace sector)
- 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)

The added value of working via these centres or programs cannot be overestimated. Broader and often multidisciplinary research questions can be addressed that need competences also outside the engineering mechanics field and the centres also have a formative effect on future research. Furthermore, these cooperations also give our researchers the possibility to benchmark against the way of working in other departments or universities which improves the quality of our research. It is difficult to assess in detail, but we believe that at least 60-70% of our research output can be linked to a research cooperation. We believe in this model and will continue to work for participation in and leadership of research cooperations.

In addition to the structured collaborations in the centres and networks listed above, there are also smaller scale and less formalized collaborations with a large number of academic institutions inside and outside of Sweden, e.g. Heidelberg University, Karlsruhe Institute of Technology (KIT), 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. Some of us are guest professor at partner universities, for example at the Aeronautics Institute of Technology (ITA) in Brazil, Bologna university, NTNU Trondheim, or at Beijing Jiaotong University. 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.

In order for the department to be a successful partner in different constellations, and for individuals to develop and maintain a strong engagement in centres without having an unacceptable working situation, it is important that adequate and flexible low-level administrative support is available and that decisions can be taken in an efficient manner. We see a risk that increased bureaucracy leads to decreased engagement in formal collaborations.

f. 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: Applied Mechanics as a whole.

- *The Applied Mechanics UoA's should pay particular attention to the creation and definition of a consistent research strategy for the future in close collaboration with each other.*
  The challenge has been taken on by the merger of the three departments in the beginning of 2020 as mentioned above. Since then, we have been working on a common research strategy. On example are the thematic areas we have defined (cf. section on research profile), and which involve faculty and researchers from all three former departments.
- *It was clear from a number of impact case studies that industry is applying and using academic output for business purposes KTH and the academic staff do not derive full value of this. KTH should therefore reappraise processes for identifying research output that is worth commercialisation and assisting the academic to realise the full commercial potential for themselves and for KTH.*
  In the contracts especially with our centra it is regulated how to handle inventions. So, sometimes our innovations get patented by our industry partners. Furthermore, several of the impact cases demonstrate how research results from the department have been commercialised in start-ups since RAE2012.

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, we intend to continue recruiting externally educated candidates.
- *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 area*s.
  The particular area of naval architecture has grown beyond subcriticality, as illustrated by the establishment of the SMaRC research centre funded by the Swedish Foundation for Strategic Research SSF. Efforts are presently being made to strengthen the faculty also in other potentially subcritical areas such as space technology. We want to maintain research groups in all vehicle areas since KTH is one of few universities in the world with that breadth.
- *Focus on enhancement of publication quality and consequential scientific impact.*
  Scientific publication has been emphasized and some of the outcomes are among the journal papers listed above.

Unit of Assessment: 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 (even on a national level) 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, and that it is one of our thematic areas, 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 are 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. A particular example is a soon-to-be advertised position as assistant professor with specialization in nanostructured biobased materials.

- *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 significantly recently. The age structure at the unit is such that a considerable number of faculty positions will be recruited in the coming years and efforts are being made to utilize these opportunities 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 be 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 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 response 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.

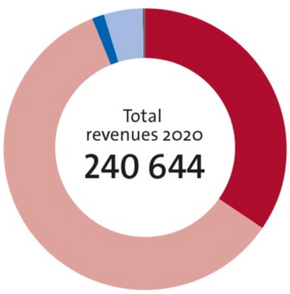
3. Viability

a. Funding; internal and external

The total turnover of the department is 298 MSEK out of which 158 MSEK are external grants and missions. More about research funding can be found in *Figure 9*. It can be seen that the total amount of research funding was basically constant between 20212 and 2016 but had increased with 20% in 2020. 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. An important aspect of the funding is that different parts of the department attract external funding from different sources (research councils, foundations, governmental agencies and industry). When striving for increased external funding, it must be remembered that internal competition for the same resources is necessary to some extent but can be detrimental.

Engineering Mechanics

Sources of research income (2012, 2016, 2020)



Research income, kSEK	2012	2016	2020
Government grants for research and doctoral studies	81 862	73 265	82 975
Collaborative research funding	105 245	98 780	143 150
Contract research funding	2 485	11 877	3 704
Other revenues	9 206	11 128	10 792
Financial income	989	85	23
Total revenues	199 786	195 134	240 644

Figure 9: Research funding

b. 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 factors to create and sustain a promotive and positive atmosphere. For academic staff it is important to feel included and to have fora to have oneself heard. A good psychosocial environment must be built from the base, i.e., locally in the organization, with willingness among colleagues to take responsibility.

In an international comparison, we have a rather flat organizational structure, with students on all levels having a quite direct access and close contact with the academic personnel. Most meeting-places for research have been created and developed locally on unit level over many decades. Overall, the culture can be characterized as friendly, open and non-hierarchic. Daily discussions and ad-hoc meetings are still the most frequent arenas where research is discussed. The informal climate with an open-door philosophy makes this efficient. However, from time-to-time, both faculty and students are under high pressure, which makes it a challenge to create relaxed academic meetings despite active efforts. The non-hierarchical academic structure is, despite its upsides, exposed to the risk for informal power structures to appear. Such structures can, and have in the past, caused conflicts and exclusions. In order to avoid detrimental effects on quality, awareness and continuous discussion are necessary.

Locally, on unit or division level, the 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 unwillingly lose priority by the faculty due to the number of administrative tasks that are being carried out very dutifully. As a consequence, 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 part of collegial cooperation and loyalty. Discussions of this loyalty also address the term academic housekeeping, which is a term that assembles the whole set of precautions that are necessary for the academic workplace to run efficiently and qualitatively but usually not being recognised in the academic career. Gender studies show that the distribution of the academic housekeeping is clearly non-uniform and for an unjustified larger extent performed by women. In our context, with mostly men; women faculty, administrators, PhD-students, researchers and research engineers tend to do most of the housekeeping. 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, there seems to be a cultural acceptance for unequal participation in the diversity of university activities.

There are both formal and informal meetings in large and small fora, and the meetings impact on quality is both direct and on longer time perspective. Below, examples of the most important meeting places for researchers at the department are presented,

Large formally organised meeting places:

- Scientific seminars organised by the research environments, centra and thematic areas
- Scientific workshops and reference group meetings, sometimes with industrial partners, 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, KTH Space centre… (etc.)
- The Strategic Innovation Programmes launched by VINNOVA give 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.

Small formal meeting places are primarily 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. Some examples of formats beyond the "typical" group meetings are:

- 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.
- "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.
- "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.
- "Journal clubs", where a group meets and discuss a jointly read paper
- "Defence debriefing", where a group meets after a Thesis defence and discusses the questions asked and answers given.

There are also informal meetings, or meetings that are organized without direct supervisor or management action:

- In some environments, PhD and postdoc meet in self-organized groups. This is a meeting format where they present and discuss their own research topics, without the presence of supervisors.
- "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.

c. Current faculty situation

The total faculty of 56 persons consists of 31 (5 female) professors, 21 (4 female) associate professors, 3 assistant professors (2 female), cf. *Figure 10*. 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.

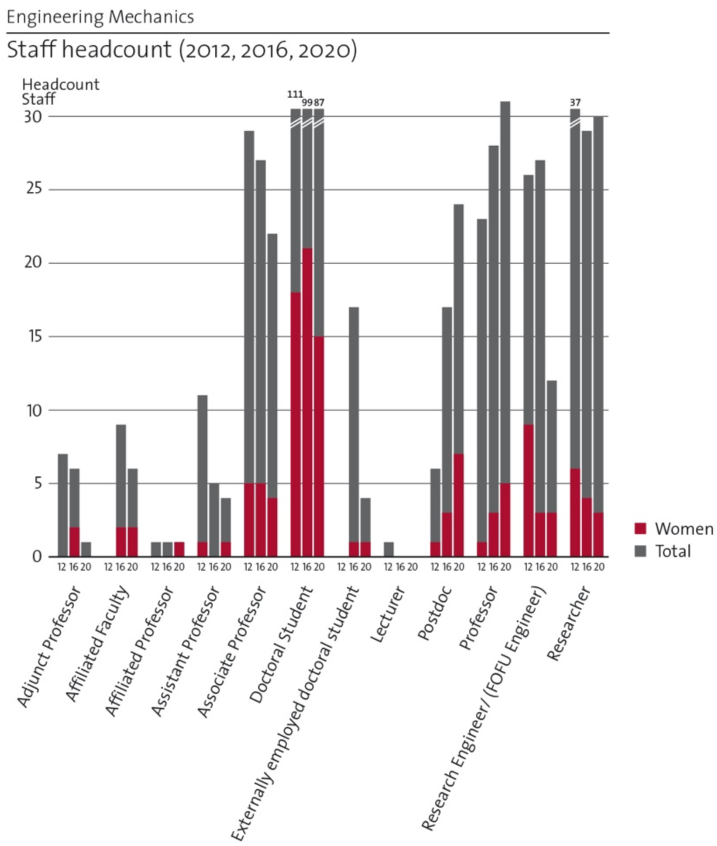


Figure 10: Staff headcount

d. Recruitment strategies

While detailed faculty development plans exist for the three former departments the new Engineering Mechanics consists of, a composed plan for the new department is yet to be created. Still, the need for new recruitments is significant since several faculty members are retiring within the coming 5-10 years.

When recruiting new faculty, we either see a need to safeguard the teaching and research ability within an existing group or pursuing research areas identified as strategic for the department development. However, occasionally we may also employ excellent researchers rewarded large personal grant.

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. We are striving towards gender diversity, wherefore high focus is on the preparation phase in order to write attractive announcements (for all genders), invite female candidates to the department and actively look for/contact good female candidates as traditionally have been done for male candidates. 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 anymore 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 maintaining 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 and develop as 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. Also, an international Postdoc brings her/his network with her/him. The experience of working with postdocs varies between the units of the department and this is a cultural difference we want to work on in the future.

PhD student recruitment is typically done by a PI who has received a grant. We believe that we can become even more strategic in our recruitment strategy. 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 could be wise to provide a structure for “second opinions” from colleagues regarding candidates that are highly ranked by the PI. In some parts of the new department different kinds of test are used to distinguish in-between candidates. Such test can be discussion of a research paper provided 2 day before the interview and/or a request for a short and spontaneous presentation in English in a subject that is well known for the candidate, e.g., his/her Master thesis work.

e. 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. Apart from those classical areas there are new emerging ones like fluid-structure interaction in biological systems, such as the human body (blood and air flow in soft tissue), mechanics of living cells, swimming of bacteria and algae, micro-fluidic devices for biotechnology, fluid dynamics and mixing of melted metals, atmospheric flows, fibre suspension flows for paper making or composite manufacturing etc. 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 provides measurements and characterization for model input, analysis and verification. Other activities are focused on experimental method development, new manufacturing technologies and innovative material production.

The Laboratory comprises 4500 m^2 of test facilities and the majority of the labs are coordinated through the centre *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 Laboratory is since 2018 acknowledged as one of KTH's prioritised infrastructures for research. Several of the department's labs are also involved in larger national and international research centra and international collaborations where research groups at the department are active.

In an evaluation of basic research within the area of Mechanical Engineering in Sweden made by The Swedish Research Council (SRC) 2013, the research within fluid mechanics, acoustics, solid mechanics, composite materials and biomechanics at KTH, was specifically acknowledged and rated as excellent to outstanding. All these areas have a strong experimental research presence at the Odqvist Laboratory.

The laboratory resources at the department are used in parallel for research, education and collaborative projects with other universities, industrial partners and research institutes. There are several installations and equipment that constitute national or international state-of-the-art and many of the laboratories have been developed for decades to support research and education. The lab units are well equipped and renowned for advanced experimental capabilities and excellent competence, in Sweden and in internationally, and they are 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 (where the department was part of the original initiative) as well as vitalised experimental research activities. The lab provides about 10 000 person-hours of laboratory activities for more than 800 students every year.

The second aspect, namely personnel and competence development, is handled somewhat differently in different labs. Some labs are maintained by lab supervisors, who also assist and have expertise in many if not all equipment used in the lab. Other labs depend more on continuous competence transfer between PhD students and postdocs to maintain their experimental expertise. Such a setup is of course more vulnerable, but sometimes necessary when a wide spectrum of quite specialised competencies need to be maintained.

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 Odqvist Laboratory has been successful in the internal competition for such means and managed to win about 1 M€ funding during the last three years. 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 must be assured both for continuity and sustainability. Unfortunately, the required level of expertise of such personnel, and thus the associated costs, are also constantly increasing.

In conclusion, maintaining and developing an extensive infrastructure as described above does not come easily. The department merger enables more efficient management of resources such as lab staff and coordination of investments, which could bring substantial synergies. However, it is a challenge to organize such coordination in a manner that encourages collaboration and still satisfies the specific specialised needs of different user groups and sub-disciplines.

Another continuous challenge is the costs for lab premises, since they increase at a considerably higher rate than the basic government funding to the universities. 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 “indirect 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. The KTH infrastructure initiative has helped to ease this problem to some extent, but not completely.

4. Strategies and organisation

a. 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 we have disciplinary excellence in the core areas that also have given the names to our divisions, i.e., Vehicle Engineering, Solid Mechanics, Fluid Mechanics and Engineering Acoustics, and a high level of multidisciplinarity. We produce fascinating demonstrators on both high and low TRL-levels in a collaborative manner and the links between research, industry and education are strong.

In order to reach this ambitious overarching goal, the goals below are identified.

Goal 1: **Maintain and develop an excellent research environment**. Means: providing the best conditions for our faculty, through e.g., stable research funding, access to advanced research infrastructure and encouraging and supporting proposals for excellence grants. Regular benchmarking vs. institutions we have identified as role models, efforts to combine all competence (insights on policy, presence in councils, industrial contacts, etc) at the department for external analyses.

Goal 2: **Identify emerging areas**. Means: Strategic tenure-track hires for new faculty in a structured manner. Improve process to identify faculty profiles.

Goal 3: **Increase internal and external collaborations** and interactions between research aimed at high resp. low TRL, while maintaining disciplinary depth. Means: identify and support cross- trans- and interdisciplinary research questions. Measured by grants obtained, joint publications, affiliations, industrial PhD students.

Goal 4: **Improve citation indices** as measured by the Annual Bibliometric Monitoring (ABM). Means: publication strategy in particular for PhD students, focus on quality rather than quantity, as discussed in the section on our quality and quantity of contribution.

Goal 5: **Maintain and develop research infrastructure** (experimental facilities, software, access to computing and storage hardware, technology platforms). Means: identify needs and possibilities, prioritize and focus on obtaining funding for the identified infrastructures.

Goal 6: **Offer an inclusive working environment** with equal and non-biased opportunities. Means: Increased knowledge and awareness. Unfair situations and structures are identified and acted upon. Proactive action from the management. Workshops at department gatherings.

Goal 7: **Decrease administrative burden** for faculty. Means: adequate administrative support that focuses on the needs of the faculty. Delegate decisions to the lowest possible level and provide efficient procurement support.

b. Congruence with university-level goals for “A leading KTH” as set out in KTH´s “Development Plan 2018-23” (page 5)

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 assist 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. A concrete example are department wide pedagogical seminars during which experiences due to the pandemic and beyond are shared in a collegial context.

An integrated KTH has a robust joint infrastructure that is used for both teaching and research.
All laboratory exercises at the department are performed 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 not missed.

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 have 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 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 for example 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 Centre.

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 group consisting of head, vice head and the two heads of the division is gender balanced and maintains a continuous discussion on gender related issues.

c. Leadership structure and collegial structure

The merger of the three departments gave an opportunity to a new start in defining the formal leadership structure. The new organization was consequently built on the best practices as a start and has developed during this first year.

The department is led by a management group consisting of the head and vice head together with the two division managers, the main director of studies and the head of the administrative support for the department. There is also a department "council" consisting of the management group, three directors of studies, the eight unit leaders, the director of the Odqvist Laboratory, the head of the department administrative support and a representative from the PhD students. The management group meets biweekly and discusses current questions related to the department. The department council meets biweekly. The department council is meant as a forum for information in both directions. The intention is that the council (together with the meetings of the division management groups) 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 process different questions from the department leadership as well as discuss and support each other in daily matters.

The management group has the staff liability and 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 two divisions were considered necessary in the start of the new organisation in order to give the different units space for development without too much interference from units with different challenges. The future plan is to eliminate the division level when the new department organization is fully developed and established.

Each unit typically consists of 20-40 employees belonging to several different research groups. Each research group takes the responsibility to define general goals and directions of their research and supervise the individuals (PhD students, Postdocs, researchers) that are engaged in their research area. The intention of the unit is to create groups of over-critical size, where e.g., no PhD student is totally dependent on one faculty only, while the group size does not prohibit the visibility of each individual. 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 drivers behind this development are both the formal leadership and collegial interactions. 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 were formulated in the start-up of the new department. The initiative came from the formal leadership, but the thematic areas are 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. The fact that we already participate in a considerable number of research centres (cf. 2.e) demonstrate our ability and commitment to such developments.

d. Strategies for high quality

In order to maintain high quality and reach even higher, a combination of formal procedures and continuous informal discussions is 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. Two important elements of such a quality system will probably be

- identification of comparable institutions and regular benchmarking, the result of which is discussed by the management and at department gatherings
- identification of publication channels that would be considered an increase in publication quality followed by discussions on what research questions we should aim for to be able to publish in these channels.

In addition to bibliometric, economic and productivity performance indices, employability of our PhD students, and being an attractive research partner for industry are two other and equally important quality 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 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 (Integrated Transport Research Lab) 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

a. 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 societal relevance in the research work performed. Our work is relevant to, and we collaborate with, a large number of small, medium and large companies in Sweden and abroad in the road vehicle, train, aerospace, naval, material, energy, space, food and medical industries (a complete listing is exhaustive and will not be given). We also collaborate with public authorities and 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 Alstom (former 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 Energy Agency, the Defence Material Administration and the Maritime Administration, is often one of the top five funding sources.

In many of the above-mentioned collaborations, the gender perspective is important. In many areas of engineering mechanics, the gender balance is not satisfactory. Therefore, we work actively with engaging female representatives for example in boards of our research centra or in reference groups for research projects. Gender aspects are also very important for our medically related research, where gender and sex differences must be addressed in order not to miss out on important aspects.

b. Research dissemination beyond academia

By providing highly educated engineers to the industry and other societal actors, we create direct dissemination and also establish a necessary precondition for dissemination and utilization of research results. The educational activities also contribute to dissemination via master theses, where recent research results can be brought to use by different stakeholders. We also strive for having a relatively large number of affiliated and adjunct faculty mainly from industry partners which very much enhances the take-up of research results outside the academic community. We support our faculty participating in mobility programs, for example 20% work at Volvo, Scania and Vattenfall for a few years. There is also some faculty that are part-time employed in industry. The industrial collaborations lead to a substantial number of joint publications.

As mentioned above, we participate in many EU funded projects. In such projects dissemination typically has a high priority. Almost all reports are public and presenting at conferences and publishing papers is expected. In all our research centres industry and public authorities participate. 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). Most of our software development is open source and publicly available.

Our researchers also participate in the public debate through articles and interviews, in particular in transport related issues (two recent examples consider domestic air traffic and the development of the Swedish railway network). We are also regularly part of panels for policy development. Occasionally we contribute with popular science presentations in media or educational material and the department contributes to lifelong learning with regular external courses with up to 50 to 70 participants from industry, authorities, etc.

We are also often consulted as experts and contacted by media (radio, TV and newspapers), for example when it comes to economic, technical and environmental aspects of new technologies and investments in new transport solutions. Although these opportunities typically appear on an ad-hoc basis, media training for younger faculty should be considered in order to ensure that requests from media receives a proper reception. Such training sessions have been performed within the centres ECO2 and FLOW. These sessions have been appreciated.

A dissemination activity that could be considered is increased social media presence. Such activity would benefit from low-level hands-on administrative support.

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

Almost all of our fundamental as well as applied research activities are motivated by sustainable development. Therefore, we believe that 80-100% of our research is related to the SDG. 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 structures. On the vehicle and system level it continues with the design of lighter components and the reduction of air resistance that reduce energy consumption, reduction of noise emissions from transport and investigations into the usability of materials with better recyclability in vehicles. We also develop drones that assist in monitoring our environment. In a recent EU project, we participated in developing an energy labelling system for trains. Obviously, our health-related activities are also strongly connected to the SDG. In summary we probably contribute most to SDG 13 Climate Action by proposing solutions that reduce energy consumption and SDG 3 Good Health and Well-Being with the above-mentioned health related research activities even though many other SDGs are touched upon in the different research projects.

In our work on the sustainability goals our research centres play an important role as well. The ECO2 Vehicle Design Centre (economic and ecological vehicle design) for example has sustainability already in the name. We have also had activities that increase awareness on the relevance of research for the SDG among everyone involved in fundamental research like the fluid mechanics research in the FLOW community (previous Linneaus Centre). An example of how this commitment boils down to actual activities engaging a large number of people is an elaborate group activity during annual meetings of the research centre 2017 and 2018 where everyone was forced to formulate and communicate how their specific research contributes to one or several SDGs. Similarly, the former department of Aeronautical and Vehicle Engineering carried out a department-wide workshop where everyone should pick one of her/his ongoing research projects and describe on one page how they relate to the SDG. Afterwards the results were discussed in groups.

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.

Appendix 1: Impact cases

We provide twelve impact cases for the panel, three old (in the sense that they were mentioned also in RAE 2012) and nine new. The old ones ("Optimization of radiation therapy", "Rational design of social policies" and "active suspension in rail vehicles") are mentioned because they demonstrate still active collaborations with societal actors over a longer time, which in turn is a clear sign that the collaboration is highly valued by both sides.

The two new ones from the Department of Mathematics ("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.

The impact from the Engineering Mechanics is multifaceted. Three of the impact cases from the department are examples of how knowledge from research activities has been commercialized in start-ups or in pre-existing companies and three impact cases illustrate the direct use of research results in technical (vehicle) applications. In these six cases, the link between the research and the impact is very clear. However, often the knowledge produced at the department enters larger companies and an impact case explaining the impact of one of our centres has been included to illustrate this. Finally, one case where the impact is of a more scientific and educational nature has been included since it demonstrates the inspirational power of our science.

1. Modelling and optimization for radiation therapy

Department of Mathematics

This ongoing collaboration between Forsgren at the division of Optimization and Systems Theory and RaySearch Laboratories AB dates back to 2003 and involves a series of industrial PhD student projects. It deals with optimising and automating radiation therapy treatment plans and has this far resulted in several PhD thesis and journal publications. The collaboration was also selected as a showcase when KTH had its 100th anniversary celebrations at campus.

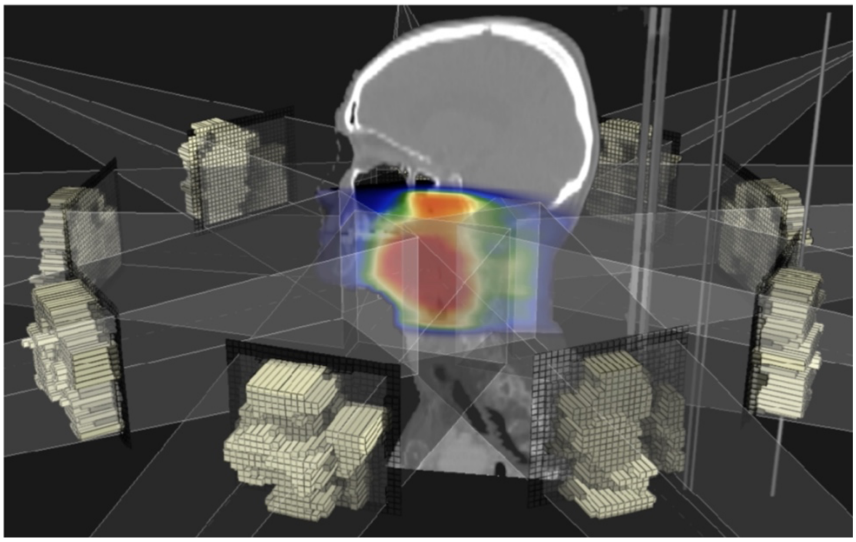


Figure 11: Optimisation is a fundamental tool in intensity-modulated radiation therapy, leading to improved cancer treatment. KTH and RaySearch Laboratories have carried out joint research within this area since 2003. (Image provided by RaySearch Laboratories.)

Summary of the impact

- Intermediate impact: Several of the ideas developed in the PhD theses has made their way into the treatment planning system commercialised by RaySearch. The details remain a commercial secret. The collaboration also served as a valuable recruitment pool for RaySearch. Likewise, several of the research questions considered were closely related to research on fundamental methods for nonlinear optimization, so the collaboration also catalyses applied mathematics research into optimization theory and machine learning.
- Potential Impact: Improving treatment plans means one improve outcome and/or reduce side effects, both directly translating to benefits for patients and society.
- Reach: RaySearch acts on an international market within medical technology. Their clinical collaborations are in north America and Sweden. The collaboration has also catalysed collaboration between mathematics at KTH, Karolinska Institutet, and Karolinska University Hospital.

Underpinning research

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. In 2017, the scope of the joint research widened with the recruitment of two new industrial PhD students, which also involved new advisors from the department. One project deals with scheduling problems related to planning of the clinic's schedule and the other 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 has launched an additional industrial PhD student project in early 2020 related to statistical learning and optimization (Tianfang Zhang), and one related to robust and adaptive optimization (Ivar Bengtsson).

Selected publications:

[1] L. Engberg, K. Eriksson and A. Forsgren, *Increased accuracy of planning tools for optimization of dynamic multileaf collimator delivery of radiotherapy through reformulated objective functions*. Physics in Medicine & Biology 63 (2018) 125012.

[2] M. Böck, K. Eriksson, A. Forsgren and B. Hårdemark, *Towards robust adaptive radiation therapy strategies*. Medical Physics 44 (2017), 2054-2065.

[3] A. Fredriksson, A. Forsgren and B. Hårdemark, *Maximizing the probability of satisfying the clinical goals in radiation therapy treatment planning under setup uncertainty*, Medical Physics 42 (2015), 3992–3999.

[4] R. Bokrantz and A. Forsgren, *An algorithm for approximating convex Pareto surfaces based on dual techniques*. INFORMS Journal on Computing 25 (2013), 377-393.

[5] F. Carlsson and A. Forsgren, *Iterative regularization in intensity-modulated radiation therapy optimization*. Medical Physics 33 (2006), 225-234.

Sources to corroborate the impact

- Reference person at RaySearch Laboratories:

  Kjell Eriksson, CSO (kjell.eriksson@raysearchlabs.com)

- PhD thesis by Michelle Böck (2019), Lovisa Engberg (2018), Rasmus Bokrantz (2013), Albin Fredriksson (2013), and Fredrik Carlsson (2008).
- KTH and RaySearch Laboratories have had an active collaboration for more than 17 years with multiple PhD students fully funded by RaySearch Laboratories, initially through Forsgren but in recent years also through Enqvist, Hult and Olsson. This is a strong indicator for how much the collaboration is valued by both parties.

2.Topological data analysis of life science data

Department of Mathematics

The Topological Data Analysis group led by Chachólski at the division of mathematics is a vibrant research environment with broad interests ranging from fundamental mathematical research, connections to machine learning, and concrete applications in life sciences. The strategic initiative towards life sciences was an important catalyser for starting this group. It currently has funding from several sources, like Vetenskapsrådet and WASP.

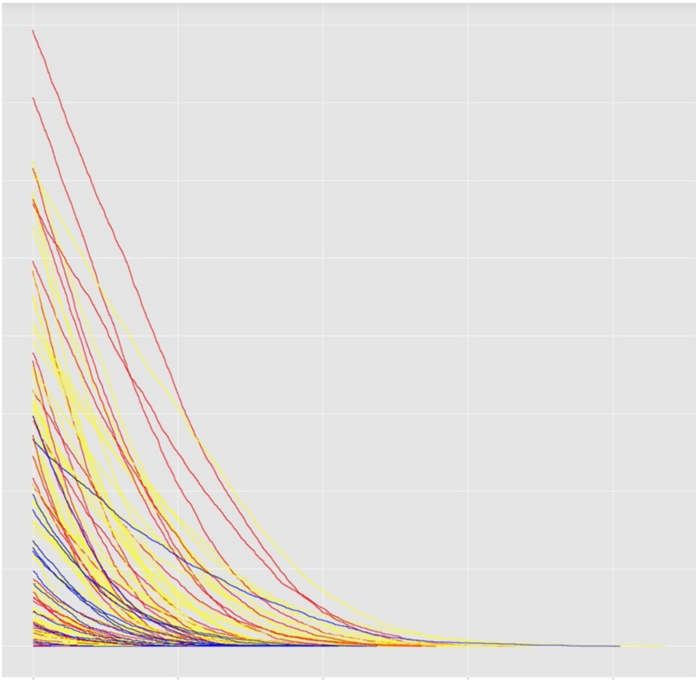


Figure 12: Alzheimer's Disease is diagnosed by symptoms. Since other disorders might have similar symptoms, it is important to find ways of diagnosing Alzheimer based on biological information. In this picture H_1 homology stable ranks (invariants developed by our TDA group) of certain correlation networks extracted from resting state MRI images are illustrated.These stable ranks describe changes of H_1 homological features in the data representing each individual. Red functions are stable ranks of Alzheimer patients without medication, yellow functions are for medicated Alzheimer patients and blue are for controls. This picture illustrates that stable rank invariants are able to identify a sizable group of Alzheimer patients by for example calculating the area under their graphs.

Summary of the impact

- Intermediate impact: The immediate effects of the collaboration is that it catalysed contributions to the mathematical foundations of persistent homology, which in turn has theoretical importance in pure mathematics. It also offered new tools for analysis of genomics data for researchers at Karolinska Institutet.
- Potential Impact: Topological data analysis with symmetry enriched invariants can be used to assemble deep neural network architectures that capture symmetry described by more complicated spaces of transformations. This can have a significant impact on the development of domain adapted neural networks, such as in geometric deep learning, that goes beyond traditional unsupervised learning methods.

- Reach: This work is highly international, e.g., there is extensive collaboration with the CompTop group at Stanford University headed by Gunnar Carlsson and Ayasdi, a machine intelligence software company that tools to build predictive models and/or analyse highly dimensional data sets.

Underpinning research

The first application area was based on collaboration with researchers at the Multiple Sclerosis Research Group at Center for Molecular Medicine at Karolinska Institutet and the pharmaceutical company Novartis. The collaboration involved a postdoctoral fellow and the aim was to develop tools for finding weak patterns in genome wide association data for Multiple Sclerosis. The approach was based on topological data analysis. This is a general framework for analysing data that combines tools from algebraic topology and statistical learning. It has the advantages of being able to extract information from large volumes of high-dimensional data, while not depending on the choice of metrics and providing stability against noise.

The collaboration subsequently led to developing theory and methods for multidimensional persistence [1]. This yields a classifier suitable for repeated measurements that samples from the data space and builds a network graph based on the data topology [3]. The algorithm and software constitute an accurate classifier and a feature selection tool applicable to cases where there are repeated measurements. Currently, these tools are also being used to analyse data from Neuroscience and Psychiatry.

The applied work mentioned above also opened up for pure mathematical research. One was on using combinatorics to present multidimensional persistent homology [2]. 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.

Selected publications

[1] M. Scolamiero et al., *Multidimensional Persistence and Noise*, Foundations of Computational Mathematics 17:1367–1406, 2017

[2] W. Chachólski et al., *Combinatorial presentation of multidimensional persistent homology,* Journal of Pure and Applied Algebra 221(5):1055-1075, 2017

[3] H. Riihimäki et al., *A topological data analysis based classification method for multiple measurements*, BMC bioinformatics 21(1):1-18, 2020.

Sources to corroborate the impact

- Faculty members of the Topological Data Analysis group have also started the company DV Analytics AB to commercialise some of the tools.

3. Scientific machine learning for image reconstruction in medicine

Department of Mathematics

The project is led by Öktem at the division of mathematics, and it was launched in 2014 with an initial grant from SSF. It is scheduled to run until 2022 and with an initial funding in 2014 of 21 MSEK, additional funding was later 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. It involves collaboration with several clinicians at Karolinska University Hospital in Stockholm and Addenbrooke's Hospital in Cambridge and several industrial partners (Elekta, Philips Healthcare, Siemens Healthineers, GE, and Thermo Fischer Scientific).

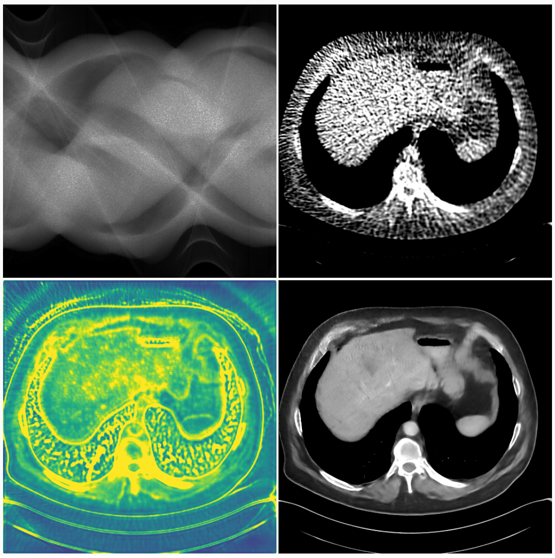


Figure 13: Uncertainty quantification in tomographic imaging. Top right shows image recovered from highly noisy tomographic data shown in top left (2% of normal dose) by the golden standard approach in clinical imaging. Bottom right shows (posterior) mean image obtained using a physics aware trained deep neural network and bottom left shows corresponding point-wise standard deviation (uncertainty).

Summary of the impact

- Intermediate impact: The project established mathematical imaging sciences as an application area within the department. It also established a platform for image reconstruction on clinical data. Finally, the project also spearheaded development of scientific machine learning in its development of physics aware deep learning models for image reconstruction. These are currently being explored by the industrial partners.
- Potential Impact: All clinical challenges translate directly to benefits for patient and have clear societal impact.
- Reach: Much of the impact is international and industrial partners are in medical technology. The project also established a critical mass of expertise in scientific machine learning in the Stockholm region that benefits all involved partners.

Underpinning research

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 infinite dimensional differential geometry (diffeomorphic models 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 [1]. 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 problems [2]. The resulting algorithms are computationally feasible yet significantly outperforms state-of-the-art [3] and allow for uncertainty quantification in large-scale inverse problems [4]. 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 [5]. 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.

Selected publications:

[1] C. Chen et al., *A new variational model for joint image reconstruction and motion estimation in spatiotemporal imaging*, SIAM Journal on Imaging Sciences 12(4):1686-1719, 2019

[2] S. Arridge et. al., *Solving inverse problems using data-driven models*, Acta Numerica 28:1-174, 2019

[3] J. Adler and O. Öktem, *Learned primal-dual reconstruction*, IEEE transactions on medical imaging 37(6): 1322-1332, 2018

[4] J. Adler and O. Öktem, *Deep Bayesian inversion*, arXiv preprint (1811.05910)

[5] H. Andrade-Loarca et al., *Extraction of digital wavefront sets using applied harmonic analysis and deep neural networks*, SIAM Journal on Imaging Sciences 12(4):1936-1966, 2019

Sources to corroborate the impact

- Reference persons from industry:

  Philips Healthcare: Thomas Koheler, (thomas.koehler@philips.com)

  Elekta: Jonas Gårding, Global Director Partner Research (Jonas.Garding@elekta.com)

- The project has this far generated five patents, five PhD dissertations, more than 80 peer reviewed publications.
- Open-source software library that is currently used by several research groups worldwide (https://odl.readthedocs.io/index.html)

4. Rational design of social policies

Department of Mathematics

Linusson at the Division of mathematics has since long been involved in applications of Combinatorics, in particular in the design of voting systems that adhere, as much as possible, to the principle of proportionality.

Summary of the impact

- Intermediate impact: Important expert evaluation on outcome of public elections, like the 2010 elections. Led to a change in the Swedish constitution, which took effect starting with the election in 2018.
- Potential Impact: Usage of mathematically founded social policies will be increasingly important in society, especially given the increasing usage of algorithms for decision making.
- Reach: National

Underpinning research

Linusson published mathematical research papers on theoretical and practical aspects of electoral systems, and he has brought attention to weaknesses in the way Swedish electoral law handles usage of adjustment seats in order to ensure proportionality between parties and different parts of the country. One such weakness was that, unlike was commonly believed, the seats in national parliament might not always be distributed proportionally. It is a key feature in the Swedish electoral system to adhere, as much as possible, to the principle of proportionality between the political parties. The weakness, that Linusson had warned about, played an important role in determining the outcome of the 2010 elections. Linusson was consulted by a parliamentary inquiry on how to change the electoral system and this led to a change in the Swedish constitution, which took effect starting with the election in 2018.

In April 2019, Linusson, together with a professor at Uppsala University, wrote a research paper about another mathematical weakness in the law that allowed for political parties to manipulate the election of members in municipal subcommittees and in practice steal seats from other parties. They presented a solution and also wrote an op-ed article and contacted members of parliament to bring attention to the problem. A public inquiry that started in February 2020 was commissioned to review the matter. In March 2021 it presented its conclusion, which is to follow the suggested mathematical solution.

Sources to corroborate the impact

See https://people.kth.se/~linusson/valsystem.html for a list of publications, reports etc. related to electoral systems.

5. Digitized quality assurance of welded structures - towards industry 4.0

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 comprises both hardware and software.

Winteria AB ® is a start-up company which has received large publicity and funding, including funding for start-ups by Vinnova Vinn Verifiering. Its commercial product is robust inline quality assurance for welded components in serial production. The company is incubated by KTH Innovation and STING. Major Swedish vehicle manufacturers are pilot clients today.

Underpinning research

The research that led to this innovation started in 2010 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). New research projects were started 2013 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. Today several systems are installed at major vehicle 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; These sustainable development goals are achieved 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.

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[3] G. Hultgren, Z. Barsoum, Fatigue assessment in welded joints based on geometrical variations measured by laser scanning, Welding in the World (2020), https://doi.org/10.1007/s40194-020 00962-8.

Sources to corroborate the impact

Users:

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

External (*selected*):

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

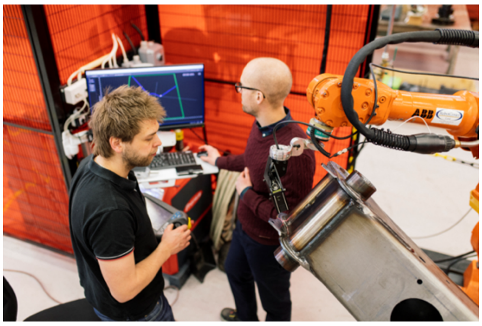

Figure 14: Installation of robotized Winteria ® system at crane manufacturer HIAB

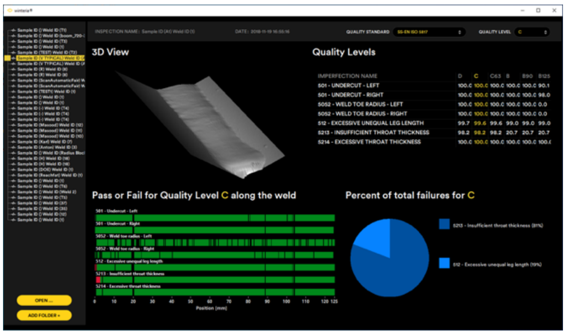

Figure 15: Winteria®: One of the GUI:s in the Winteria system. Determining the quality level of a scanned fillet weld. Green bars indicate that current weld fulfills the demanded quality level (D) for all the imperfections types according to the international weld quality standard ISO5817.

6. Integration of vascular biomechanics simulation in the clinical decision-making of Abdominal Aortic Aneurysm patients.

Department of Engineering Mechanics

Summary of the impact.

To foster the translation of the mechanical modelling of vascular biomechanical research into medical applications, the Soft Tissue Mechanics (SBT) team developed customized software helping vascular clinicians in making a decision whether or not an AAA should be surgically treated. The research initiative led to commercial software that is now used in clinical research in a number of hospitals.

Underpinning research.

Abdominal Aortic Aneurysms (AAA) represents a focal enlargement of the infrarenal aorta, a condition that requires in many cases medical treatment. The SBT group primarily addresses the biomechanical aspects of AAA, research that was funded by a VR Young Faculty grant and then allowed to build a highly effective Pan European network. Given these activities, the group became one of the most well-known groups in Abdominal Aortic Aneurysm (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 16* shows an A4clinics screen shot that illustrates the distribution of a rupture risk index, whilst *Figure 17* 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.

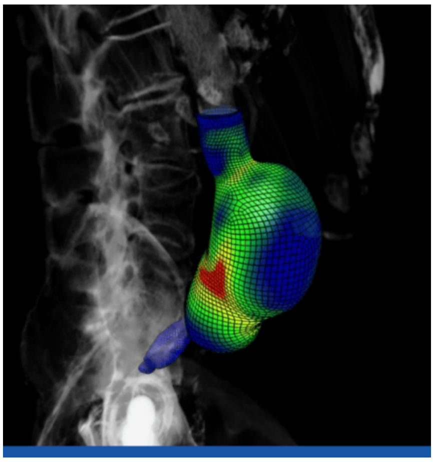

Figure 16: A4clinics scree-shot illustrating the distribution of the wall rupture risk index all over the aneurysm.

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 developed software of this kind that 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 can use the software.

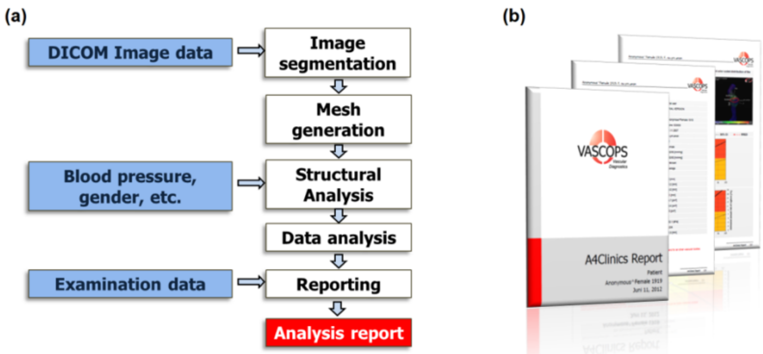

Figure 17: A4clinics simulation pipeline (a) and diagnosis report (b) for clinical decision making.

Aside from direct distribution to the hospitals, ARTEC Diagnosis AB (supported by the VINNOVA innovative start-ups program and EUs EUROSTARS funding) 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.

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[2] Polzer S, Gasser TC, Vlachovsky R, Kubicek L, Lambert L, Man V, Novak K, Slazansky M, Bursa J, Staffa R. Biomechanical indices are more sensitive than diameter in predicting rupture of asymptomatic abdominal aortic aneurysms, Journal of Vascular Surgery, 71, 2020.

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Sources to corroborate the impact

www.vascops.com (with a list of clinical partners)
www.artecdiagnosis.com

7. Modelling as a tool to reduce paper waste during digital printing

Department of Engineering Mechanics

Summary of the impact

Background: 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 the 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, addressing the underlying problem can effectively reduce undesired waste and contribute to sustainable development in printing.

Grand challenge: 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, several factors related to the paper structure cannot be accurately controlled.

Main activities: 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 developed tools are packaged and transferred to Canon in two training sessions. Canon is a world-leading company specializing, among other things, in high-speed inkjet printing, which is a modern way of delivering flexible printing solutions, fully digitalized and customizable in every print. The computational tools include implemented constitutive modelling routines and accompanying fitting methods. The tools are thoroughly verified by Canon and are currently being used in the creation of a new generation of large-scale digital printers by Canon with "Zero Waste" requirements.

Underpinning research

The major contributions to this research come from Professor A. Kulachenko, Dr H. R. Motamedian (graduated in 2018), Rami Mansour (Researcher), August Brandberg (PhD candidate) and Mossab 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 within a project funded by National Foundation for Research, Technology and Development, Austria and participating companies.

The result of the work has been published.

[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.

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[3] Alzweighi, M., Mansour, R., Lahti, J., Hirn, U., & Kulachenko, A. (2021). The influence of structural variations on the constitutive response and strain variations in thin fibrous materials. Acta Materialia, 203, 116460.

Sources to corroborate the impact

Company references:

- Louis Saes (louis.saes@cpp.canon)

- Ern Clevers (ern.clevers@cpp.canon)

Recorded training sessions with company representatives:

- https://www.youtube.com/watch?v=PvENwmiY7Sw
- https://www.youtube.com/watch?v=2bU3_dJGl_4

8. Competence Centre for Gas Exchange

Department of Engineering Mechanics

Summary of the impact

The Competence Center for Gas Exchange (CCGEx) was initiated in 2006 as CICERO (2006-2010), being the third competence center financed by the Swedish Energy Agency in the field of Internal Combustion Engine technology. The present key stakeholders of CCGEx are: KTH (Marcus Wallenberg Lab for Sound and Vibration, Machine Design, Engineering Mechanics, CICERO Lab), the industrial partners namely SCANIA, VOLVO Technology, Powertrain Engineering Sweden, BorgWarner Turbo Systems (Germany), and Wärtsilä (Finland), and the Swedish Energy Agency. The center has a key role in Sweden for educating expert engineers and scientists who are currently developing technologies for sustainable transports.

The overall goal with CCGEx is to enable knowledge-based and efficient design of next generation, energy efficient engines with carbon neutral and sustainable fuels, with focus on advanced gas exchange and turbocharging technologies. The starting point for the formulation of research projects are the challenges with the current propulsion systems for automotive applications. Within CCGEx, a multidisciplinary and integrated research is promoted, which combines dedicated competences, expertise and facilities in gas dynamics, acoustics, and engine technology, and includes both fundamental and applied experiments and simulations.

Since its initiation, 28 CCGEx PhD students graduated with the doctoral degree. Approximately 80% of the educated researchers within the CCGEx are remaining in Sweden, with about 80% of them continuing their careers in the Swedish Automotive Industry (including consulting business), having impact towards higher efficient vehicles with reduced emissions.

Underpinning research

CCGEx promotes research on advancing the gas exchange and turbocharging technologies, heat-transfer quantification for smart thermal-management solutions; thus, to enable knowledge-based and efficient design of next generation clean propulsion systems for vehicle applications. The research efforts are directed towards increasing system's energy efficiency without losing performance, to lower the emissions of hazardous substances, and to manage sound generation and attenuation in the engine gas handling system.

All the applications of combustion engines require a state-of-the-art gas exchange system. The air charging system (the turbocharger) is a key element to enable combustion concepts that generate high efficiency. To get best possible efficiency of the system, the gas exchange and turbocharging processes must be optimized. This includes an exergy analysis, minimizing the losses, and maximizing the performance of the system. Detailed studies of the performance of compressors and expanders are also carried out. The focus on gas exchange processes and turbocharging is the major strength of CCGEx. A combined approach using Computational Fluid Dynamics, reduced order modeling - including model development - and experiments (including developing new experimental methods and sensors) is employed. Optimal control of the valve operation has the potential to further improve energy efficiency of the powertrain system when combined with advanced turbocharging technology.

A powertrain system without proper noise mitigation is not acceptable. Engine noise must be handled and suppressed to a level that is acceptable. The current and foreseen more stringent noise regulations for road vehicles, pressure the automotive industry to achieve lower noise emission levels for powertrain systems. With fast combustion and aggressive valve operation, noise can increase. The requirements of air-charging systems with carbon neutral fuels are higher than for conventional engines. Moreover, in the wide range of engine operating conditions, the turbocharger compressor becomes a very important noise contributor. High fidelity computational aeroacoustics, acoustic modeling, as well as experimental aeroacoustics will focus on enhance understanding of noise generation and propagation. Noise mitigation technologies are proposed and tested. The work can be extended to other components of the engine (e.g., cooling fans, intake and exhaust systems).

Most of the research within CCGEx is conducted by Doctoral students (including Industry PhD students) and postdocs under faculty guidance and supervision, and with support from the industrial partners.

References

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Karlsson M., Åbom M., (2010) Aeroacoustics of T-junctions—An experimental investigation, Journal of Sound and Vibration, 329(10): 1793-1808. 68 citations. https://doi.org/10.1016/j.jsv.2009.11.024.

Sources to corroborate the impact

CCGEx Annual Reports: https://www.ccgex.kth.se/aboutccgex/annual-reports-1.681016
Publications: https://www.ccgex.kth.se/publications/journal-conference-papers-1.368301
SICEC: http://sicec.se/

9. Hydrodynamic assembly of exceptional nanostructured materials

Department of Engineering Mechanics

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 serve as an inspirational example how multidisciplinary knowledge makes it possible to develop novel materials from a widespread source (trees). This impact continues and recently t both 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.

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Sources to corroborate the impact

An information film in English, in which our previous PhD student explains the potential:
https://www.youtube.com/watch?v=a2GD16QJXlk

A film produced by the organisation "Swedish Forest Industries" to be used in schools:
https://www.youtube.com/watch?v=3z7uOxkaLfA

10. Active suspension in rail vehicles

Department of Engineering Mechanics

Summary

In several research projects KTH rail vehicles has investigated the possibility to introduce active suspension in passenger trains to improve ride comfort and to reduce the amount of wheel and rail damage during curve negotiation. Since the very beginning there has been a close cooperation with the train manufacturer Bombardier. The active suspension is now implemented in the ETR 1000 high-speed train from Trenitalia. Research is still ongoing with two PhD students and it is today funded mainly by the European Joint Undertaking Shift2Rail.

The case and its impact

The possibility to further improve the performance of rail vehicles by fine tuning the passive suspension is limited. Active suspensions for railway vehicles have been studied for half a century. Early tests and implementations focused on the lateral acceleration perceived by the passenger when the vehicle travelled at enhanced speed in curves. Introduction of active secondary suspension is considered as an alternative offering better vibration attenuation and became the new focus area when KTH contributed in the GreenTrain project that involved basically all stakeholders in the railway area in Sweden. Together with the supplier Bombardier and the infrastructure manager, i.e. the Swedish Transport Administration, KTH developed and tested active secondary suspension for both lateral and vertical applications. Bombardier implemented the active secondary lateral suspension in the new high-speed train ETR 1000 for Trenitalia that has been in operation for a couple of years allowing performance beyond European standards when it comes to high-speed curving.

KTH has continued the research in the Shift2Rail project RUN2Rail and presently in NextGear with the new focus for active suspensions to reduce vehicle weight and cost by allowing the use of simplified vehicle layouts in combination with active suspensions.

Underpinning research

Anneli Orvnäs conducted research on active secondary suspension in rail vehicles to improve ride comfort during 2007 to 2011. The first part of the work was dedicated to control of active lateral suspension for the test bench Regina 250 together with Bombardier as a part of the GreenTrain project, cf. *Figure 18*. Orvnäs fine-tuned the control algorithms during on-tracks and these were later implemented on the new high-speed train ETR 1000 for Trenitalia built by Bombardier. Orvnäs continued to study more refined control algorithms and started to study active vertical suspension, a work that was continued by Alireza Qazizadeh in 2012 to 2017. The work with active vertical suspension was also part of the GreenTrain project together with Bombardier and included successful on-track tests where Qazizadeh optimized the control of the active system. Qazizadeh continued to study active wheelset steering with the aim to improve the curving performance and thereby reducing the wear on wheels and rails. Failures in active suspension systems may lead to unsafe situations and related homologation issues. Qazizadeh started to study the possible failure modes and proposed a systematic approach to prove safety. This approach was latter accepted as base for the continued work in the area within the Shift2Rail project RUN2Rail 2017 to 2019.

Active suspensions were in focus also in the Shift2Rail projects RUN2Rail and NextGear with the aim to reduce vehicle weight and cost. In RUN2Rail KTH proposed a single axle running gear with only one suspension step, a solution which normally would lead to both poor curving performance and unacceptable ride comfort. Rocco Libero Giossi studied active wheelset steering to improve the curving performance and active dynamic suspension for the ride comfort. The work has been supervised by Rickard Persson and Sebastian Stichel during the entire period.

Key factors

Key factors for successfully taking the research the whole way to implementation in a commercial high-speed train is the long cooperation between KTH, Bombardier, Trafikverket and the operator SJ in the KTH Railway group, a research centre at KTH. This cooperation started already in the late 1980's and built up the trust necessary to openly share information that was needed in the project. KTH researchers had access to quite sensitive data from Bombardier since they knew that we would not misuse it. Another success factor are shared resources where engineers from Bombardier had/have a part time employment at KTH.

Figure 18: The lateral compact actuator installed on the test bench Regina 250

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Sources to corroborate the impact

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Contact person: dietmar.kraft@rail.bombardier.com (dietmar.kraft@alstomgroup.com)

11. Defect free forming of multi-stacked composite aerospace components using tailored interlayer properties

Department of Engineering Mechanics

Summary of the impact

Use of lightweight materials is an important part of aircraft design. A considerable number of structural aircraft parts are therefore built of thin layers of epoxy pre-impregnated (prepreg) Uni-directional (UD) carbon fibres stacked to laminates. Manufacturing these by hand is costly and different methods of automation have therefore been developed. One cost-effective way of manufacturing is Automated Tape Lay-up or Fibre Placement of flat stacks followed by a Hot Drape Forming (HDF) operation [1]. Saab has a long history of HDF of composite wing spars to the Gripen C-D fighter. These spars contained mainly two fibre directions [±45] that made them well suited for HDF. However most modern aircrafts demand for Quasi Isotropic lay-ups (with four fibre direction) required by the load situation. Forming a double-curved geometry with a lay-up with more than two unique fibre directions must invoke both slippage in-between the thin layers as well as shear deformations within each layer in order to end up with a wrinkle free laminate. These wrinkles can, in worst case scenarios, cause a serious strength knock down.

KTH and Saab have performed joint research in HDF of double curved prepreg spars with quasi-isotropic lay-ups during several PhD projects. In particular, the research data is successfully implemented in the majority of all wing spars produced for the Gripen E fighter.

Modern composite designs might also involve several parts co-cured to one integrated part. Such integrated concepts involve delicate composite cure assemblies, which might end up in pressure gradients in the epoxy matrix during the cure cycle. Small undulations in the prepreg lay-ups have a great influence of the pressure gradients and might end up with porosities and voids in the final part laminate. The KTH research of HDF and wrinkling development has also generated knowledge and data that has been implemented in the general manufacturing of civil composite aircraft parts manufactured at Saab, which has had a great effect of the laminate quality of these parts.

[1] Composites World. Automotive Processes for High-Rate Aerospace Composites Manufacturing. 2020 [cited 2020 15th May]; Available from: https://www.compositesworld.com/events/details/f08ec767-7911-4f6d-820c-0d63cb3d161b.
[2] Haanappel S. Thije R. Sachs U. Rietman B. Akkerman R. Formability analyses of uni-directional and textile reinforced thermoplastics. Composites: Part A 2014;56:80-92.

Underpinning research

Larberg and Åkermo [3] investigated the influence of different generations of carbon/epoxy prepreg systems on the interply slippage and developed a method to quantify the interply friction. The developed measurement technology has been widely adopted by both researchers and industry. The research in [3] has currently 66 citations.
Hallander et. al. [4] investigated the influence of stacking sequences on the performance HDF of double curved prepreg spars with quasi-isotropic lay-ups. This research also presented some stacking strategies which were part of the background for the Gripen E wing spar design. The research in [4] has currently 87 citations.
Hallander, Sjölander and Åkermo [5], [6] described that the wrinkling development during the HDF process had both global and local nature. This research continued the explanation of influence of stacking sequence of the forming result. The research results also generated knowledge that improved the laminate quality of integrated co-cured composite parts. The research in [5] and [6] has currently 24 respectively 55 citations.

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Further information can be found in the three PhD dissertations the articles are parts of.

Sources to corroborate the impact

A patent document [7] on the stacking strategies described above can be found on https://worldwide.espacenet.com.

[7] BRPI0823282 (A2) - METHOD OF FORMING A COMPOSITE ARTICLE, HALLANDER PER [SE]; NYMAN TONNY [SE]; PETERSSON MIKAEL [SE]; SAAB AB [SE]; WEIDMANN BJOERN [SE]

12. Extensive studies on over-actuated vehicles and its realization into Research Concept Vehicle (RCV) along with both knowledge and technology transfer to a company

Department of Engineering Mechanics

Summary of the impact

Since 2001 until now the vehicle dynamics group at KTH has conducted research on a novel concept of autonomous wheel corner modules (ACM) i.e. suspensions with individual motors for traction and braking, steering, camber and dampers, which means that each wheel can be actuated individually in all degrees of freedom. The idea originates from a patent by Sigvard Zetterström (US20010030400A1) employed at KTH between 2007 – 2014. Through successive research projects leading to 5 PhD theses as well as a prototype vehicle called RCV, both the knowledge through Johannes Edrén and technology from the RCV was transferred to a start-up company in San Francisco called Zoox Inc. Zoox was started in 2015 by the entrepreneurs Tim Kentley-Klay and Jesse Levinson. Zoox have utilized both the research from KTH and transferred technology in developing their company and product which has recently been demonstrated (https://www.youtube.com/watch?v=RrqV_smolLQ). In 2020 Zoox was acquired by Amazon for $1.2 Billion. Johannes Edrén have during his time at Zoox Inc. filed 5 patent applications out of which three is related to research at KTH. The research at KTH vehicle dynamics group on over-actuated vehicles has been and still is a strategic research area that has gained more interest in society and in the research community in recent years due to the introduction of electrification, autonomous vehicles and by-wire systems.

Underpinning research

The research on over-actuated vehicles, its control and studies of its motion through force allocation started in 2001 by Prof. Annika Stensson Trigell and PhD student Johan Andreasson [1, 2, PhD1], which later was continued by a second PhD student on the topic, Mats Jonasson [3, 4, PhD2]. The third PhD student at KTH on the topic, Johannes Edrén (Currently the Vehicle Dynamics Lead at Zoox Inc.), published several papers on over-actuated vehicles regarding e.g. active camber vehicle performance and safety [5], energy efficient cornering, decreasing braking distance [6], road friction effects on optimal vehicle control strategy and implementation and evaluation of force allocation control, all summarized in [PhD3]. The fourth PhD student at KTH on this topic was Daniel Wanner, his work focused on controlling over-actuated vehicles during failure conditions which included work on fault classification of electric vehicles [7], control allocation strategies during wheel hub motor failures and implementation of the fault handling strategy in the RCV summarized in [PhD4]. The fifth PhD student Mohammad Davari focused the research on energy efficient control using over-actuation [PhD5]. Supervisors involved in the above-mentioned PhD student projects and that are currently employed at KTH are Annika Stensson Trigell, Lars Drugge and Jenny Jerrelind. Since then, the vehicle dynamics group at KTH have continued the research on over-actuation with an additional two PhD students (Peikun Sun and Wenliang Zhang) regarding energy efficiency as well as path following and yaw stability.

In 2011 research was carried out by Mikael Nybacka on how to realise the over-actuated vehicle suspension into a research vehicle, this resulted in a suspension design with individual steering, camber, traction and braking which was incorporated and built on the KTH RCV vehicle [8]. In 2013 KTH researchers who designed the RCV vehicle was contacted by the founder (Tim Kentley-Klay) of Zoox Inc. a start-up with only two people at that time. The contact resulted in a technology transfer between Zoox Inc. and the researchers (Transport Technology Innovations AB) of the RCV design and software including the design and building of a vehicle platform for Zoox by the researchers behind the RCV.

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[1] J. Andreasson, C. Knobel and T. Bünte, "On Road Vehicle Motion Control-striving towards synergy," in Proceedings of AVEC '06 The 8th Int. Symposium on Advanced Vehicle Control, Taipei, 2006 (34 citations).
[2] J. Andreasson and T. Bünte, "Global chassis control based on inverse vehicle dynamics models," Vehicle System Dynamics, 44:1, 2006 (71 citations).
[3] M. Jonasson, J. Andreasson, B. Jacobson and A. S. Trigell, "Global force potential of over-actuated vehicles," Vehicle System Dynamics, 48:9, 2010 (43 citations).
[4] M. Jonasson and F. Roos, "Design and evaluation of an active electromechanical wheel suspension system," Mechatronics, 18:4, pp. 218-230, 2008 (58 citations).
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[6] J. Edrén, M. Jonasson, J. Jerrelind, A. S. Trigell and L. Drugge, "Utilisation of optimisation solutions to control active suspension for decreased braking distance," Vehicle System Dynamics, 53:2, 2015 (13 citations).
[7] D. Wanner, L. Drugge and A. S. Trigell, "Fault classification method for the driving safety of electrified vehicles," Vehicle System Dynamics, 52:5, 2014 (14 citations).
[8] O. Wallmark, M. Nybacka, D. Malmquist, M. Burman, P. Wennhage and P. Georén, "Design and Implementation of an Experimental Research and Concept Demonstration Vehicle," in IEEE Vehicle Power and Propulsion Conference, VPPC 2014, Coimbra, 2014 (24 citations).

PhD thesis projects

[PhD1] J. Andreasson, On generic road vehicle motion modelling and control, PhD Thesis. Stockholm: KTH, TRITA-AVE: 2006:85, 2006.
[PhD2] M. Jonasson, Exploiting individual wheel actuators to enhance vehicle dynamics and safety in electric vehicles, PhD Thesis. Stockholm: KTH, TRITA-AVE: 2009:33, 2009.
[PhD3] J. Edrén, Motion modelling and control strategies of over-actuated vehicles, PhD Thesis. Stockholm: KTH, TRITA-AVE 2014:75, 2014.
[PhD4] D. Wanner, Controlling over-actuated road vehicles during failure conditions, PhD Thesis. Stockholm: KTH, TRITA-AVE 2015:23, 2015.
[PhD5] M. Davari, Exploiting over-actuation to reduce tyre energy losses in vehicle manoeuvres, PhD Thesis. Stockholm: KTH, TRITA-AVE 2017:35, 2017.

Sources to corroborate the impact

The technology transfer between KTH researchers and the company Zoox Inc. can be seen in the following sources:

- https://blog.blackbird.vc/zoox-memory-lane-919fdecda9e8
- https://spectrum.ieee.org/cars-that-think/transportation/self-driving/secretive-robotaxi-startup-zoox-prepares-for-realworld-testing
- https://www.nyteknik.se/innovation/sjalvkorande-taxi-tar-teknik-fran-kth-6393434
- https://www.kth.se/aktuellt/nyheter/nar-de-bygger-bil-i-usa-1.567781

Patent on "Brake force distribution" (US10322724) by Johannes Edrén can be linked to Johannes own research as a PhD student at KTH [6, PhD3]. Patent on "Vehicle self-diagnosis" (US10395444) by Johannes Edrén can be linked to the research done by Daniel Wanner [7, PhD4] since Johannes was a PhD student at the same time as Daniel Wanner. Patent on "Independent control of vehicle wheels" (US10821981) by Johannes Edrén can be linked to Johannes own work as a PhD student at KTH [PhD3] but also previous work by J. Andreasson [1, PhD1], M. Jonasson [3, PhD2] and M. Nybacka [8].