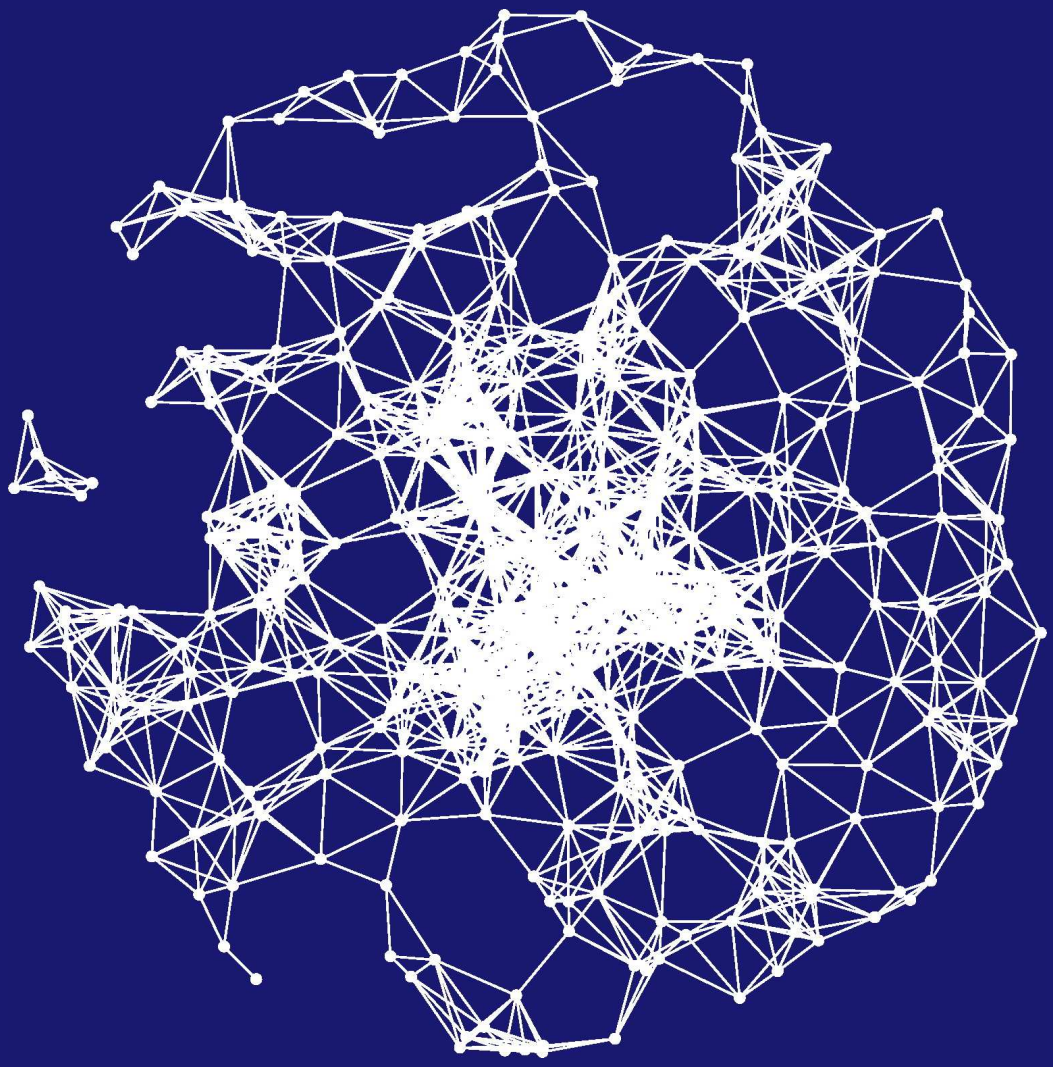
Research Evaluation Mathematics

2015–2020



Department of Applied Mathematics

University of Twente

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Head of department:

Prof. Dr. R.J. Boucherie (04/2013-03/2016)
Prof. Dr. S.A. van Gils (04/2016-09/2022)

This scientific report has been written by the Department of Applied Mathematics of the faculty of Electrical Engineering, Mathematics and Computer Science of the University of Twente.

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Contents

List of abbreviations

Chairs in Applied Mathematics

AA	Applied Analysis
DMMP	Discrete Mathematics and Mathematical Programming
HS	Hybrid Systems
MACS	Mathematics of Computational Science
MMS	Multiscale Modeling and Simulation
SOR	Stochastic Operations Research
ST	Statistics

Clusters of chairs

MOR	Mathematics of Operations Research, combining the chairs SOR, DMMP and ST
SACS	Systems, Analysis and Computational Science, combining the chairs AA, HS, MACS and MMS

Research Institutes

DSI	Digital Society Institute
MESA+	Institute for Nanotechnology
TechMed	Technical Medical Centre

Graduate Schools & Networks

Beta	Research School for Operations Management and Logistics
DISC	Dutch national graduate school on Systems and Control
LNMB	Dutch Network on the Mathematics of Operations Research
TGS	Twente Graduate School

Faculties

BMS	Faculty of Behavioural and Management Science
EEMCS	Faculty of Electrical Engineering, Mathematics and Computer Science
ET	Faculty of Engineering Technology
TNW	Faculty of Science and Technology

Other Relevant Abbreviations

AMI	4TU Applied Mathematics Institute
CHOIR	Centre for Healthcare Operations Improvement and Research
CTS	Centre for Transport Studies (Faculty ET)
EWI	Dutch for EEMCS: Elektrotechniek, Wiskunde en Informatica
IEBIS	Chair Industrial Engineering and Business Information Systems (Faculty BMS)
IGS	Institute for Innovation and Governance Studies
TOM(TEM)	Twents Onderwijs Model (Twente Educational Model)
T&SP	Training and Supervision Plan University of Twente
UT	University of Twente

Preface

We are happy to present the Self-Evaluation Research 2021 of the Department of Applied Mathematics (DAMUT) of the Faculty of Electrical Engineering, Mathematics and Computer Science of the University of Twente.

The department has experienced considerable growth in the last six years after more finances have become available on a structural basis. For example, this has enabled us to build a strong group in modern statistics. Machine learning will significantly influence how mathematics is performed now that data plays an increasingly important role in our lives. Statistics is indispensable.

We are proud of what we achieved, in particular in a period when COVID-19 made our work more difficult. We also foresee a bright future for our applied mathematics because we attracted highly competent junior staff members.

But certainly, there is room for improvements, as outlined in our SWOT analysis. We are confident that our people-first strategy to remove the weaknesses and counteract the threats will be successful.

This self-evaluation was prepared under the supervision of the head of the department. We felt it was important that midterm career staff members wrote essential parts, and earlier versions of the report were discussed with the board of professors.

Thanks are due to the supporting staff who swiftly provided all the information on finances, human resources, publications and more. Special thanks go to Floor Meijer for giving many suggestions for improvements.

Prof.dr. S.A. van Gils
Head Applied Mathematics

Prof.dr. J.N. Kok
Dean EEMCS

1 Introduction

1.1 DAMUT: Department of Applied Mathematics @UT

Mathematics at the University of Twente flourishes in an ecosystem with highly challenging and meaningful applications. We develop our role, on the one hand, by bringing mathematical insights to help advance adjacent fields. On the other hand, questions in application fields stimulate us, through abstraction, to develop new mathematics.

During the review period, research was organized in the two clusters of chairs, SACS (Systems, Analysis and Computational Science) and MOR (Mathematics of Operations Research).

SACS

The SACS cluster combines the chairs Applied Analysis (v Gils), Hybrid Systems (Zwart), Mathematics of Computational Science (vd Vegt) and Multiscale Modelling & Simulation (Geurts). Our research partners are mainly from physics and the health domain. Mathematics is strengthened in the fields of partial differential equations (PDEs), numerical methods and control. Research topics include:

Numerical methods: This research topic aims at the development and analysis of computational methods tailored to the mathematical structure of the governing mechanisms found in key areas of science and engineering. Time-parallel methods, high-order and structure-preserving discretizations, and robust finite element methods are the main directions of research. These methods are combined with uncertainty quantification, stochastic dynamics and inverse problems. Prominent examples of application are in (multiphase) fluid mechanics, nonlinear waves, neuroscience and electromagnetism.

Mathematical modeling: Powerful mathematical models are developed for the systematic description of various often multidisciplinary applications. The modeling approach combines established models from science, for example in terms of partial differential equations with data-driven models. Expertise in variational analysis is employed for medical imaging, kinetic equations and computational model reduction. Immersed boundary methods and interface reconstruction and tracking strategies are used in the analysis of diseased vessels as well as multiphase flow. Abstract delay equations and bifurcation methods are developed for neuroscience.

Mathematical Systems Theory: High-tech systems become increasingly complex, while the required specifications simultaneously tighten. The modeling of such systems poses challenging mathematical tasks beyond classical linear control theory for low order models. One prototypical problem is to improve the estimation of control parameters in the presence of intrinsic nonlinearities and an increasing number of sensors. Another entire problem class is the handling of constraints, decentralized structures and physical multi-component systems. Addressing these problems in the context of technologically relevant applications requires an interplay of system and control theoretic, functional analytic and differential geometric tools.

MOR

The MOR cluster combines the chairs of Discrete Mathematics and Mathematical Programming (Uetz), Stochastic Operations Research (Boucherie) and Statistics (Schmidt-Hieber). The societal contexts are mainly energy, traffic, and (healthcare) logistics, while the mathematical focus is on the mathematics of operations research, theory of learning as well as statistics.

Mathematical optimisation aims at the development of techniques for the efficient solution of optimization problems, ranging from combinatorial optimization and mixed integer programming to nonlinear optimization problems. Specific strengths lie in the design and analysis of algorithms, in particular probabilistic and smoothed analysis, algorithmic game theory and polyhedral combinatorics. Models and techniques find their way into practice in optimising smart

energy grids, health processes, logistics and traffic models.

Stochastic Operations Research targets methods for systems that are exposed to randomness, and includes both theory and application of queuing systems, polling models, Petri nets, random graphs, Markov chains, rare event simulation, Markov decision processes and approximate dynamic programming. In terms of applications, probabilistic and statistical methods are developed in modelling and optimising of health processes, communication systems, and large and complex networks.

A major strategic change during the period of this assessment was the formation of a new group in **Statistics**. As full professor and chair, Johannes Schmidt-Hieber has been appointed in 2018. To a large extent we have used the sectorplan budget to enable him to form a completely new group in statistics, that will be the core of a new cluster on data science. The research topics of the mathematical statistics group are on contributing to the mathematical foundation of machine learning from different angles. Research topics include deep learning, ensemble learning techniques, privacy and stochastic optimization, analyzing shape via optimal transport, multiple hypotheses testing and time series analysis. Several of the ongoing projects are built around specific applications and are developed in collaboration with other groups on the campus and abroad.

1.2 Funding

Table A6 contains the money streams *direct funding*, *research grants* and everything else collected in *other*. The direct funding is based on the resources that the faculty of EEMCS receives from the UT-allocation model. The faculty board of EEMCS allocates the resources from the UT-allocation model to the departments of EEMCS based on an internal allocation model. The research grants include grants from the Dutch Science Foundation (NWO) and the European Union (EU). In 2022, the faculty board and the department heads will reconsider the division of the resources within the faculty. We expect to receive a larger percentage of the EEMCS resources than we currently receive. The discussion centres around what is required for infrastructure per discipline and the development of growth of the disciplines.

head of department

The role of the head of the department is under development. Increasingly, the department head is held responsible by the faculty board for the department's financial health. This responsibility puts the department in the position to develop its own strategy.

1.3 Research environment and embedding

faculty and multidisciplinary research institutes

The department of Applied Mathematics is one of the three departments of the Faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS). Since 2018, the faculty board has been formed by the dean, two vice-deans (research and education) and the managing director. Until March 2021 the head of our department participated in the faculty board as vice-dean of education.

The strength of the UT lies in the collaboration between the various disciplines. In the research institutes the UT connects technology (high tech) to human behaviour and social relevance (human touch). Before 2017, the scientific institutes organized the research. It was the prerogative of the institutes to develop strategic lines for research and govern the research in the research chairs. However, in the reporting period (since 2017), the university board changed this model considerably, and governance was transferred to the faculties. Given the previous situation, all research chairs of Applied Mathematics (AM) are participating in one or more research institutes of the university.

DSI

The Digital Society Institute (DSI) performs scientific research in technology that is essential for

digitisation, on methods and techniques for integrating digital technology in our environments, and in how we can come to intelligent, well-informed decision making. An important aspect of their mission is to conduct research that has a positive impact on society.

TechMed

The Technical Medical Centre (TechMed Centre) is a leading Innovation Hub impacting healthcare by excellent Research, Innovation and Educational programmes. It is equipped with state-of-the-art infrastructure, ranging from research labs, preclinical testbeds and simulated hospital environments.

MESA+

MESA+ is one of the world's leading research institutes on nanostructures, nanomaterials, nanosystems and nanodevices. Embracing a cross-disciplinary approach and benefiting from the NanoLab - infrastructure that ranks among the very best worldwide - over 500 researchers deliver high quality, competitive and frequently ground-breaking research. The results are evident in their numerous publications as well as in various high-profile achievements.

national embedding

The department participates in the NWO clusters DIAMANT (DMMP), NDNS+ (AA, MACS, MMS), and STAR (SOR, STAT), and in national research and graduate schools: Beta (DMMP, SOR), LNMB (DMMP, SOR), DISC (HS), and the J.M. Burgers Center (MACS, MMS).

4TU.AMI

The department participates actively in the 4TU.AMI (Applied Mathematics Institute), a joint venture of the four Dutch TU's in the Netherlands. Presently, Prof. Hurink is the scientific director of this institute. We co-chair the Strategic Research Orientation (SRO) on Energy and Health.

2 Mission and strategy during the past six years

2.1 Mission and strategic aims

Our mission is based on the conviction that the interaction between mathematics and its application domains in academia and society is key for both, progress in mathematics and its application areas. In this way, we contribute manifold to modern society, which is influenced by breakthroughs in mathematical sciences more than ever. We are convinced that data, models, algorithms and AI will continue to play a crucial role in society, and our strategy paves the way to contribute to these developments. This is consistent with the overall mission of the UT, as set out in the new strategic plan Shaping 2030.

Mission

> Our mission is to be an internationally leading institute for mathematical sciences and applied mathematics, covering the full spectrum from fundamental research to applications of societal relevance. We involve and train young scientists to become capable of taking a leadership position within the broad spectrum of topics of applied mathematics.

2.2 Strategy

general embedding

The UT has a tradition of co-operation between different disciplines, including the social sciences. The Department's strategy is to engage actively in collaborative projects within and across the faculty. The research institutes stimulate these activities: DSI for ICT-related research, MESA+ for nanotechnology, and TechMed for biomedical technology and technical medicine. As a department, we contribute to the institutes through research in the energy transition, medical imaging, logistics in hospitals, traffic, neuro-biology, robotics and optics.

Next to collaborative projects in various application domains, the department carries out research in the mathematics of computational science, operations research and data science. A

fundamental and applied research

healthy mix between fundamental research on the one side, and multidisciplinary, application--oriented research on the other side, is successful in applied mathematical sciences worldwide, and also at the UT.

It is the strategy of the faculty board to support the disciplines in doing fundamental research, facilitated by excellent labs and computer facilities, and at the same time stimulate interdisciplinary research, for instance on energy, health, data science and robotics. In 2019, a so-called Theme-Team-Call was launched, where four teams, each consisting of three young researchers from the three disciplines of the faculty, were formed in competition around the topics energy, health, data science and robotics. Each team appointed three PhD students, one in each discipline. The process of forming the teams and writing short proposals was very stimulating. Many young researchers from the faculty got to know each other in a match-making event, which otherwise would not have happened. It is an excellent opportunity for young researchers to broaden their perspective and step out of their comfort zones.

data science

The revolutionary developments in almost all areas of applied mathematics during the last decade, and the fact that the department lacked a chair in statistics since the last reorganization in 2014, let us search actively for a new chair in modern statistics. The result is the appointment of prof. Schmidt-Hieber as of December 1, 2018. Partly with the help of the sectorplan resources, he has by now created a strong group in statistics. This group does, among other topics, fundamental research in the theory of learning and AI. The group is very tightly linked within the department itself, via topics such as optimization, algorithms, and imaging. For example, prof. Brune builds a group on 'Mathematics of Imaging & AI, a more modern version of the Applied Analysis group, which will be a an application-oriented complement to the group of prof. Hieber. Other newly appointed researchers of the department e.g. in algorithms, optimization & learning have their focus also on areas that link to data science. The building of this cluster on mathematics of and for data science is a major achievement, and has resulted from constructive discussions in our regular meetings of the board of professors.

AI4Health

To strengthen the relationship between research and education, we shall start in September 2021 with a master track, AI4Health. We expect that this will give a boost to our master's programme. This new masters track combines our interests in data science and health and receives support from the whole department. In this way, we also hope to increase intake in our master programme. Although our education programme was declared 'top-opleiding' [1] several times [2] during the review period, the number of students has not increased sufficiently as compared with other technical universities.

2.3 Human Resources strategy

female staff

A goal of the EEMCS faculty is to hire more female employees; for 2025 we aim for the following percentage of female employees: 20% full professors, 20% associate and 35% assistant professors. At present, these numbers are 12% full professors, 13% associate and 30% assistant professors within the faculty. To achieve this goal, it will be necessary to fill 50% of all vacant positions with female staff. Currently, the faculty of EEMCS is looking into possibilities to prioritise female applications. In 2015, the percentage of female staff members in our department was 7%. To increase female staff we advertised for female applicants only in 2017. The response of applicants was of high quality and we hired two female assistant professors. In 2020, the percentage of female staff increased to 16.4%.

[1] The NSE (Nationale Studenten Enquete) is a yearly survey amongst students. Based on the results, the best programmes get the predicate top-programme.

[2] The Bachelor programme was top-rated in the years 2015 and 2016. The Master programme was top-rated in 2018 and 2019. In 2020 and 2021, the 'Keuzegids' did not award any top rated programmes due to COVID-19.

Table 2.1: The percentage of woman in fte, counted January first.

% woman in fte	2015	2016	2017	2018	2019	2020
UD	6,6%	7,6%	9,0%	24,8%	24,8%	24,8%
UHD	22,2%	18,5%	22,8%	0,0%	0,0%	0,0%
HGL	0,0%	0,0%	0,0%	11,1%	10,0%	10,0%
Total	7,2%	7,5%	8,5%	17,0%	15,7%	16,4%

At present the department has two female staff members who will feasibly become full professors within the next six years. Their progress is followed with special care.

Diversity is more than simply the representation of women in the department. We strive for an international environment both in teaching and in research. From the table below it becomes clear that our research staff is gradually becoming more international.

%NL vs other	2015	2016	2017	2018	2019	2020
UD	56,3%	64,3%	58,3%	61,5%	61,5%	52,9%
UHD	83,3%	66,7%	60,0%	66,7%	50,0%	40,0%
HGL	87,5%	87,5%	87,5%	88,9%	80,0%	80,0%
Total	70,0%	71,4%	68,0%	72,0%	63,0%	59,4%

In an annual meeting organized by our HR department, the chair-holders discuss the functioning of all our staff members. This way, we guarantee equal treatment of our staff. We identify promising junior faculty and determine appropriate growth paths.

More generally, we observe that our AM discipline is no exception to the experience of academics in the Netherlands in terms of work pressure and working hours. We systematically monitor all activities related to teaching duties. We use a table in the department that relates educational activities to hours. In this way, we maintain a good overview of the division of work. The table also enables us, for example, to grant a reduction of the teaching load to young employees in a controlled manner. After concluding that the Twente Education Model (TOM) requires more effort than reimbursed in our model, we adjusted the table in 2021. Consequently, income from education will decrease, but we hope to compensate for this by an increased percentage of the faculty's research funding.

young talent

The department invests in young mathematical talent. Young staff members are intensively coached when writing proposals. This coaching is organized at the institutional level, but also at the level of the faculty and the department. This process has led to several highly ranked proposals including several personal interviews. During the period of the review we obtained two VENI grants (Stegehuis, Wolterink) and one VIDI grant (Schmidt-Hieber), plus several grants in the NWO open competition.

Since 2019, we have adopted the policy that all young staff members are assigned a teaching load of 33% of their full time working hours, reduced from the standard 50%, during their first three years of employment. This reduction was already the case for staff members in a tenure track position, who get this reduction during the first five years of employment.

2.4 Strategy for issues regarding scientific integrity

2.4.1 The ethics protocol of the Faculty of EEMCS

The UT stimulates an environment within which responsible research practices can unfold. The Code of Ethics University of Twente (2015, updated in 2019) contains regulations and

additional codes of conduct. Employees are required to adhere to the rules, requirements and instructions applicable within the University of Twente, including the regulations on research integrity, privacy and security, ancillary activities and health and safety. Furthermore, staff are expected to uphold the scientific integrity principles as specified in the Dutch (Netherlands Code of Conduct for Research Integrity 2018) and European (The European Code of Conduct for Research Integrity 2017) codes of conduct for scientific integrity. The Executive Board established the Scientific Integrity Complaints Procedure in order to protect and guarantee scientific integrity.

As of 2020, the UT has an integrated integrity programme called House of Integrity In addition to academic integrity, this framework also covers social and corporate integrity. With its activities, House of Integrity aims to contribute to the Shaping2030 target of 100% compliance with the standards for integrity and safety. Examples include scientific integrity education for all PhD candidates, mandatory ethical assessments for all research, a data management policy, including guidance on safe storage and sharing of research data, registration of academic staff's ancillary activities, and investing in cultural game changers.

In the past year, the UT has also established a university-wide ethics policy and four research committees focusing on the ethical assessment of research in the following domains: Natural Sciences & Engineering Sciences, Computer & Information Sciences, Humanities & Social Sciences, and Geo-Information Sciences. A web-based tool prepares students and researchers to submit their research proposals to the relevant committees for approval. For complex issues and quality assurance, the UT has a university-wide committee.

The proof of the pudding is in the eating. During the review period the university's ethics protocol was put to the test in a case where scientific integrity was at stake. The department chair brought the case before the dean who passed it on to the rector. After a thorough legal investigation, the rector issued a ruling requesting the two deans involved to carry out the necessary steps to maintain scientific integrity.

2.4.2 Data strategy

open data

Open data and related research-data policies are gaining importance in academia. In 2017, at the national level, a National Plan Open Science was presented by all major Dutch research organizations. In 2015, an overall research-data management policy was established by the UT, updated in 2018. The UT policy statement Shaping2030 formulated that in support of the Open Science transition the UT aims for 100% Open Access publication by 2023. In 2020, 45% of our publications were open access, which is less than the 72% realised in 2018. The availability of resources to finance open access publications is decisive. Tools such as the UT Open Access website help researchers in this process. Shaping2030 also established FAIR [3] data as the new norm for UT researchers. The university-wide data-management policy serves as a starting point for tailored data policies of UT faculties, institutes and research groups.

EEMCS

In 2019, the faculty of EEMCS formulated a tailored research data management policy which is a refinement of the UT-wide policy. In turn, several individual groups already have formulated or are in the process of formulating further refinements in the form of practical guidelines and workflows for the handling of research data. The guiding principles in all of these are scientific integrity and FAIR data. Some mathematical works are fully self-contained and do not need a reference to external data. In addition, we often work with the data of others, such as data from hospitals or neuro-biology labs. At present, staff members are not systematically instructed to follow general guidelines and many researchers still follow an ad-hoc policy. Many

[3] The dean of the faculty EEMCS is one of the authors of the paper The FAIR Guiding Principles for scientific data management and stewardship, Scientific data 3 (1), 1-9, 2016. FAIR data is still a subject of research.

small pieces of code are not published at all. Data involving the General Data Protection Regulation (GDPR), however, are handled as required by the guidelines. It will be the future responsibility of the chair-holders to make sure that the data policy is handled with care within the chairs, and the responsibility of the head of department to monitor this process.

Twente Graduate School

The *Twente Graduate School* offers a compulsory course on Research Data Management for all PhD-students for which the data stewards function as trainers. Subjects in the course are management of data for verification and reuse, the value of research data as the scientific output of one's research, awareness of legal issues in handling research data, and writing a data management plan (DMP). The long term storage of data is not a shared responsibility of PhD students and their supervisor, which is a point of attention as that typically leads to situations where long term storage of data is not taken care of properly. Again, in the future chair-holders must take responsibility, monitored by the head of the department.

2.5 Recommendations of the previous research assessment

We have taken the recommendations of the previous Review 2009-2015 and the Midterm Review into account. We have been active in attracting new junior staff members in tenure track and assistant professor positions. To relieve the high teaching load, we attracted several highly motivated teaching staff, both permanent and temporary, next to junior staff members. In addition, the assignment of research time to AM staff was reviewed, leading to a more precise identification of tasks to relax the pressure on research time. There is an ongoing discussion with the faculty board to review the funds available for our department's research.

To continue our interdisciplinary cooperation we extended our activities on smart energy systems, led by Prof. Hurink, especially on decentralized energy management (DEM). Prof. Brune built a group on geometric deep learning with a focus on medical imaging. Prof. Boucherie continued his activities on healthcare logistics. The increased demand for the development of new methods for healthcare optimization under uncertainty was translated into the hiring of Dr. Braaksma as a new assistant professor.

To stimulate the success in grant proposal writing, the department and the faculty of EEMCS have taken measures to professionalize the development and support of new research projects. Prof. Litvak has taken a leading role in coordinating the development of personal grants (VENI, VIDI, and ERC) within EEMCS. In addition, EEMCS attracted professional support for the preparation of Applied and Engineering Sciences and EU proposals and consortia. To stimulate participation in large grant applications, we have requested help from the Strategic Business Development department at the UT. They have introduced their vision on the so-called Acquisition Machine approach to external funding. This is an approach for multidisciplinary proposals with an effective and efficient way of working, intended to increase the chances of successful proposals, mobilizing funding acquisition initiatives in a broader spectrum. The role of senior staff to teach juniors to co-develop proposals is essential. While it is too early to measure the effect it is already clear that this approach resonates within the department.

To establish a 'data science & big data plan' we have pushed a faculty-wide data science initiative. This initiative has resulted in close collaboration between the chairs SOR and AA with the Data management and Biometrics group of Prof. Veldhuis. Prof. Litvak organized a large number of data science seminars on this topic before COVID-19. The faculty is working on developing a separate sports-data science master, collaborating with the Vrije Universiteit Amsterdam, where we shall contribute. Dr. Goseling will be the managing director of a Data Science and AI lab within our faculty. This lab will (i) strengthen DS-AI teaching, (ii) create visibility for DS-AI activities at EEMCS, and (iii) be the central hub for the DS-AI teaching and research community. The faculty provides financial support for this initiative.

3 Research quality and societal relevance

3.1 Key Performance Indicators

The key performance indicators (KPIs) have been chosen to reflect the values of our discipline. We aim for outstanding research in an open and collaborative academic culture, oriented on and inspired by society. In this fashion we remain relevant to society and vice versa. We strive for our science to be open, while respecting the interests of societal partners such as companies. Table A7 specifies the resulting six KPIs.

3.1.1 Demonstrable Products - Research products for peers

Table A1 contains the figures of the scientific output in the form of refereed articles, books, PhD theses and conference papers. As the number of fte has increased since 2019, we expect a growth of scientific output in the next few years. In 2020, the number of PhD theses was low due to COVID-19. Here we mention the books that we published and a selection of some of our top publications with a short description of why we are proud of them.

Books

1. Theory of Spatial Statistics: A Concise Introduction. Van Lieshout, M. N. M., 2019, Boca Raton: Chapman and Hall/CRC. 168 p. (Texts in Statistical Science)
2. Numerical Bifurcation Analysis of Maps: From Theory to Software. Kouznetsov, I. A. & Meijer, H. G. E., Mar 2019, Cambridge, UK: Cambridge University Press. 420 p. (Cambridge Monographs on Applied and Computational Mathematics; vol. 34)
3. Introduction to Infinite-Dimensional Systems Theory: A State-Space Approach. Curtain, R. F. & Zwart, H., 2020, Springer New York. 752 p. (Texts in Applied Mathematics book series; vol. 71)

Top publications

1. T.L. Eissa, K. Dijkstra, C. Brune, R.G. Emerson, M.J. Van Putten, R.R. Goodman, S.A. van Gils. Cross-scale effects of neural interactions during human neocortical seizure activity. **Proc. of the National Academy of Sciences**, 114(40): 10761-10766 (2017).

   Collaboration between the lab of Wim van Drongelen in Chicago and the Applied Analysis group in Twente, supported by NWO through a visitor grant, has led to a fundamental insight in the role of feedforward inhibition in the brain. Brain activity at the millimeter scale registered by a so called Utah array was modeled by a neural field.

2. B. Al-Hdaibat, W. Govaerts, Y.A. Kuznetsov, H.G.E. Meijer. Initialization of homoclinic solutions near Bogdanov–Takens points: Lindstedt–Poincaré compared with regular perturbation method, **SIAM J. on Applied Dynamical Systems** 15(2): 952-980 (2016).

   Many results for nonlinear systems involve homoclinic orbits, including traveling waves and chaos. We provide new higher order asymptotics to initialize the numerical continuation of global homoclinic orbits starting from local information only. Our implementation into MatCont greatly facilitates the numerical analysis of such homoclinic bifurcations.

3. S. Geevers, J.J.W. van der Vegt. Sharp Penalty Term and Time Step Bounds for the Interior Penalty Discontinuous Galerkin Method for Linear Hyperbolic Problems. **SIAM J. on Scientific Computing**, 39(5): A1851–A1878 (2017).

   Both optimal time step bounds and penalty terms for the DG discretization of hyperbolic wave equations are provided, significantly increasing the stable time step for explicit

time integration methods and the numerical accuracy of the DG discretization. This considerably improves the computational efficiency of explicit DG discretizations for time-dependent wave problems. The time-step bounds and penalty terms hold for generic meshes. So far only results were available on simple structured meshes.

4. H. Egger, M. Schlottbom. A Perfectly Matched Layer Approach for P_N-approximations in Radiative Transfer. **SIAM J. on Numerical Analysis**, 57(5): 2166-2188 (2019).

   The proper formulation of boundary conditions for moment approximations of radiative transfer equations has been a long standing research question. Mathematically rigorous approaches, proposed in the past decade, unfortunately lead to a dense coupling of the moment equations, which, in turn, is the main obstruction for efficient computations. In this paper we fully overcome this bottleneck by introducing new boundary conditions that do not couple the moment equations at all.

5. B. Jacob, F.L. Schwenninger, H. Zwart, On continuity of solutions for parabolic control systems and input-to-state stability, **J. of Differential Equations**, 266(10): 6284-6306 (2019).

   This publication deals with the abstract study of control systems governed by linear parabolic PDE's and where the input functions are measured in extremal norms, which still guarantee continuity of solutions. For that we use a blend of operator-theoretic tools such as the holomorphic functional calculus and related square function estimates. The results have implications for open questions in mathematical systems theory.

6. J. Schmidt-Hieber. Nonparametric regression using deep neural networks with ReLU activation function, **Annals of Statistics** 48(4): 1875-1897 (2020).

   This publication provides bounds on the generalisation error, proving that even in high-dimensional settings deep neural networks with ReLU activation function can achieve fast convergence rates. It also shows that for the same type of underlying structures, wavelet methods suffer from the curse of dimensionality. It therefore provides a scenario for which deep learning can be theoretically shown to outperform another method that otherwise achieves optimal convergence rates over a wide range of problems. Interestingly, the theory suggests to scale the network depth with the logarithm of the sample size.

7. R. van der Hofstad, J. S. H. van Leeuwaarden, C. Stegehuis. Optimal subgraph structures in scale-free configuration models. **Ann. Applied Probab.** 31(2): 501-537 (2021).

   This paper studies small subgraphs in large, complex scale-free networks. While many networks are scale-free, networks often differ substantially in their subgraph counts, which may signal important information about the function of the network. This paper contains the first mathematical results for subgraph counts in a scale-free null model for networks. These results allow for the development of statistical tests for network subgraphs that avoid long numerical simulations.

8. A. Garavaglia, R. van der Hofstad, N. Litvak. Local Weak Convergence for PageRank. **Ann. Applied Probab.** 30(1): 40-79 (2020).

   PageRank is Google's algorithm to rank web pages by their importance using a random walk on the web graph, and also a tool for finding central nodes. It is however hard to quantify the effect of network structure on the ranking. This article achieves a breakthrough by showing that asymptotic in the network size, the distribution of PageRank is defined by the local weak limit of the underlying graph. For the first time we tie together ranking in networks and the notion of local weak convergence in random graphs.

9. T. Brunsch, K. Cornelissen, B. Manthey, H. Röglin, C. Rösner. Smoothed Analysis of the Successive Shortest Path Algorithm. **SIAM J. Computing** 44(6): 1798-1819 (2015).

   This foundational paper for theoretical understanding of one of the most popular and practical algorithm for computing minimum-cost flows, previously published in SODA 2013, offers a clean probabilistic analysis of the successive shortest path algorithm for computing minimum cost flows. The probabilistic analysis is tight, which is also shown in this paper, and it is close to the performance of the algorithm as observed in experiments.

10. J. Correa, J. de Jong, B. de Keijzer, M. Uetz. The inefficiency of Nash and subgame perfect equilibria for network routing. **Mathematics of Operations Research** 44(4): 1286-1303 (2019).

    Network routing models are most fundamental for the area algorithmic game theory, and at the same time essential for analyzing traffic problems. The paper answers a question about symmetric network routing that was open for more than a decade, and shows that –counter-intuitively– sequential decisions may yield outcomes that can be arbitrarily bad in relation to the system optimum.

11. V. Gupta, B. Moseley, M. Uetz, Q. Xie. Greed works – online algorithms for unrelated machine stochastic scheduling. **Mathematics of Operations Research** 45(2): 497-516 (2020).

    Unrelated machine scheduling has been a benchmark problem for the development of state-of-the-art algorithmic techniques in discrete optimization. This paper shows a surprising result, namely that a simple greedy algorithm gives best-known competitive ratios for the clairvoyant online scheduling problem, and it even generalises these results to online scheduling under uncertainty.

12. N. Kortbeek, A. Braaksma, C.A.J. Burger, P.J.M. Bakker, R.J. Boucherie. Flexible nurse staffing based on hourly bed census predictions, **International Journal of Production Economics** 161: 167-180 (2015).

    Workloads in nursing wards depend highly on patient arrivals and lengths of stay, both of which are inherently variable. This paper provides the foundation of several other applications in healthcare, including capacity planning for physiotherapy, planning of nuclear diagnostics and re-opening operating rooms in times of COVID-19. It is also a key starting point for a well-developed product-line of Rhythm including the Patient Flow Forecasting module that is operational in several Dutch hospitals.

3.1.2 Demonstrable use of products - Use of products by peers

Firstly, in Table A14 we have collected the number of citations per staff member. Secondly, we consider public software development as an important contribution, both to science and society.

- TUtest was developed by Dr. Walter and Prof. Trumper (UDallas) to test a given matrix A for total unimodularity. TU matrices play an important role in discrete optimization and are taught in every integer programming course. Their presence indicates that integer programmes can be solved by linear programming alone. The first theoretically efficient recognition algorithm follows from P. Seymour's celebrated decomposition theorem for regular matroids (1980). A first practically efficient implementation was created by Dr. Walter and Prof. K. Truemper (2013), which is maintained by the first author at the University of Twente.

- IPO was developed by Dr. Walter. The software is a C++ library for Investigating Polyhedra by Oracles. It requires that the associated linear programming problem can be solved, and as such a solver must be accessible as a block box. The main application is to connect IPO to a state-of-the-art integer linear programming solver. IPO can easily handle 100-dimensional polyhedra. The software was created by Dr. Walter and is being maintained and actively developed at the University of Twente.
- MatCont, MatCont is a Matlab toolbox for numerical bifurcation analysis. The software allows the user to compute branches of equilibria, limit cycles and connecting orbits of parametrized ODEs and maps. MatCont is freely available at `sourceforge.net` and has about 10000 downloads per year. At DAMUT, we actively maintain the code and support users through tutorials, extensive documentation and the Sourceforge forum. Within an external PhD project co-supervised by Dr. Meijer `http://hdl.handle.net/1854/LU-8615817`, we implemented new features in MatCont. Prof. Kuznetsov and Dr. Meijer published a book with Cambridge University Press in 2019 on the version for discrete-time dynamical systems. Subsequently, in the category Faculty, this book won the SIAM DSWeb 2019 Contest on Tutorials on Dynamical Systems software
- DEMKit, short for Decentralized Energy Management toolKit, is a software tool developed by the energy management group at the University of Twente for research on smart grid technologies. It provides a cyber-physical systems-oriented framework in which abstract device models and optimization algorithms are provided to support innovative smart and sustainable energy solutions. DEMKit is available with an open-source licence for researchers and research projects. It is already used by several researchers and research groups in the Netherlands and some researchers outside the Netherlands.
- AEROSOLVED is a computational fluid dynamics software package conceived as a standalone realisation based on the OpenFoam software package and written in C++. Aerosolved can be used to model and simulate the generation, transport, evolution, and deposition of multispecies aerosol mixtures. Flow in complex technological devices and the upper human airways can be represented, enabling the improved design of airborne medication and medical ventilation equipment. The software was created in a sequence of three collaborative industry-funded PhD projects and one PD project. Aerosolved is currently employed in collaboration with Unilever for understanding the exposure to aerosols emanating from consumer products.
- TBFSOLVER is a highly parallel fortran-based Navier-Stokes solver specialising in the modeling and simulation of dispersed turbulent multiphase flow. The software was created during an NWO-funded PhD project in which two PhDs and one PD worked toward the modeling and simulation of flow-regime maps for safe design of multiphase systems. The TBFSolver received the Wim Nieuwpoort prize in 2018 for high-performance simulation software. On the basis of TBFSolver new collaboration with other groups was initiated, amongst which Imperial College London and the Universität der Bundeswehr in Munich. The technology developed in TBFSOLVER has found its way into the HiParSolver developed for stochastic partial differential equations studied in the NWO-TOP1 project SPRESTO.
- ACCEPT – Automated CTC Classification Enumeration and PhenoTyping is an open source Matlab toolbox for automatic, robust, and user-friendly classification of circulating tumour cells (CTCs). Based on reproducible mathematical biomedical imaging, with scale-space analysis at its core, it allows direct counting of CTCs from fluorescent blood sample images. The tool provides a novel way for medical hospitals to calculate hazard ratios for cancer patients more reliably than before. The scientific development arose from a multidisciplinary EU Innovative Medicine Initiative project CANCER-ID. The ACCEPT framework has been extended to a Python deep learning module resulting in a Nature Machine Intelligence publication and won the Dutch Computable award in 2020 in the category digital transformation.

3.1.3 Demonstrable marks of recognition - Marks of recognition from peers

In Tabel A7 we have listed five items.

grants

- personal grants: two VENI grants, see sections B.1, B.2, and one VIDI grant, see highlight I in Section 3.2.1.
- The projects in Table A11 from NWO, FOM and EU.

leadership

- Prof. van Gils acted as chair of the cluster NDNS+ from 2018-2020.
- Prof. Hurink was Scientific Director of the Dutch Network on the Mathematics of Operations Research (LNMB) from 2010 to 2021.
- Prof. Hurink is the scientific director of 4TU-AMI since July 2020.
- Prof. Boucherie is the chair of the Dutch Platform for Mathematics (PWN) since March 2021.
- Prof. Geurts is coordinator of the special interests group of ERCOFTAC on aerosol engineering.
- Prof. Zwart is chair of the EU Marie Sklodowaska-Curie project Conflex.
- Prof. van der Vegt obtained the Fellowship Chinese Academy, High-end Foreign Expert Recruitment Program in 2015, 2016, 2017, 2018.
- Dr. C. Stegehuis is one of the Faces of Science.
- Prof. Uetz co-founded the joint research school NEDO on Networks, Economic Decisions and Optimization (collaboration of UT and NPU China).

editorships

- Table A8 gives the numbers of various categories of editorships.

keynotes

- Table A9 gives an overview of keynote lectures.

conferences

- Table A12 shows our involvement in the organization of conferences and workshops.

3.1.4 Demonstrable products - Research products for societal target groups

Tables A2 and A5 show our success in educating PhD students. In the period 2015-2020, 131 doctoral degrees have been awarded.

The one, but important, spin-off company that we can mention is Rhythm. Rhythm is an initiative of the research group CHOIR, Center for Healthcare Operations Improvement and Research of the University of Twente, and ORTEC, the consultancy services and software supplier specialized in optimization. Rhythm currently employs 15 FTEs, and during the period 2015-2020, 9 PhDs started and finished within CHOIR.

Table A15 lists the outreach events and products.

3.1.5 Demonstrable use of products - Use of products by societal groups/companies

Next to use in academia, the software products DEMKit, AEROSOLVED and ACCEPT are used by societal groups and companies. The software package ACCEPT is actively used by more than five academic hospitals, including the UMCs Hamburg-Eppendorf, Düsseldorf and Groningen, and developed within our EU public-private-partnership network with 36 partners from 13 countries, including world-leading institutes like the German Cancer Research, Institute Curie and the Charite Berlin.

3.1.6 Demonstrable marks of recognition - Marks of recognition by societal groups/-companies

Here, we mention the projects in Table A11 from RVO / Companies (including Hospital, University, Healthcare sector and Foundation), altogether for a total of € 2.816.675.

3.2 Research highlights

This subsection contains four research highlights. The list of research highlights is not comprehensive, but instead presents exemplars of how we simultaneously combine research quality and societal relevance.

3.2.1 Contribution to a statistical theory of machine learning

Machine learning methods were neglected for a long time within the mathematical statistics community. The success of deep learning came as a surprise and demanded better mathematical foundations. While today there remains no complete theory available taking all aspects of deep learning into account, the field has advanced quickly in the past few years, with significant contributions from the UT statistics group.

Research highlight I: Statistical risk bounds for deep ReLU networks

To explain the success of deep networks, it is natural to identify scenarios where deep networks can outperform other methods. The main idea of the work is that if the learning tasks have a hierarchical structure, deep neural networks can incorporate this structure and achieve near-optimal statistical convergence rate, where optimality is defined in the minimax estimation sense.

The work incorporates many of the aspects of modern deep networks. In particular, it allows the number of parameters in the neural network to grow faster than the sample size and deals with the ReLU activation function. The mathematics behind the results combines approximation theory with bounds for empirical processes and concepts from nonparametric statistics.

Schmidt-Hieber, J: *Nonparametric regression using deep neural networks with ReLU activation function.* Annals of Statistics, 2020 (with discussion and rejoinder). See also Section 3.1.1.

While the research of the statistics group started with several projects on the statistical properties of deep ReLU networks, a much broader perspective has been adopted in the past two years. The focus is now on a statistical foundation for the new phenomena observed in modern machine learning. To approach depth in statistical methods from a different angle, a recent preprint studies posterior contraction for deep Gaussian process priors. Another example is the work on understanding overparametrization.

To extend this line of research, the next major step is to integrate the research interests of the new group members, including ensemble learning (Hanyuan Hang), privacy and stochastic optimization (Cristóbal Guzman) and time series (Annika Betken).

3.2.2 Computational Electromagnetics

Accurate computations of the optical behavior of light in nano-structures requires the accurate solution of the Maxwell equations. Traditional methods, such as finite difference schemes or plane wave basis expansions, have an extremely high computational cost, partly due to the required high resolution near material interfaces.

Research highlight II: Accurate computation of photonic bandstructures

We developed and analyzed a discontinuous Galerkin finite element discretization for nanophotonic applications, which resolves material interfaces with relatively few elements and has provable error bounds. Moreover, we showed that the discrete eigenvalues reliably approximate the spectrum of Maxwell's equation, which are an important object to measure the quality of the underlying nanoscale structure. We also developed accurate boundary conditions that minimize reflections from artificial boundaries that are used to limit the size of the computational domain.

[Z. Lu, A. Cesmelioglu, J.J.W. Van der Vegt, Y. Xu: *Discontinuous Galerkin approximations for computing electromagnetic Bloch modes in photonic crystals*. J. Sci. Comput. 70:922-964. 2017.]

Moreover, we used such finite element discretizations to investigate the performance enhancement of solar cells using photonic crystal as a back reflector (PhD Thesis Devashish), and to compute "Cartesian Light", an unconventional propagation of light in a 3D superlattice of coupled cavities and disorder effects on the 3D photonic band gap in inverse woodpile photonic crystals [S.A. Hack, J.J.W. van der Vegt, W.L. Vos: *Cartesian light: Unconventional propagation of light in a three-dimensional superlattice of coupled cavities within a three-dimensional photonic band gap*. Phys. Rev. B 90:115308. 2019.].

This research highlight is part of a larger, externally funded research line ranging from the computation of real-world nanostructures obtained from X-ray holotomography to electromagnetic wave propagation in quasicrystals. To strengthen this line of research, Carlos Perez-Arancibia, an expert in computational photonics, started as Assistant Professor in September 2021.

3.2.3 Contributing to Decentralized Energy Management (DEM) and Control

The ongoing energy transition has a tremendous impact on our energy systems. These systems belong to the most complex system created by humankind. We now face various challenges due to the uncertainty, intermittence and stochasticity of supply and demand resulting from the integration of renewable energy and various new types of distributed energy resources. These challenges urge a multi-disciplinary approach to enable cornerstone elements of the energy transition, namely decentralization, decarbonization and digitalization. This is crossing over domains of, among others, optimization, control and data science. A core interest of the group is the decentralized aspects of energy management and control.

Research highlight III: Online Duality-Driven Optimization with a focus on Energy Management

Sequential decision-making under data uncertainty is a core challenge in energy management problems. These problems are often convex optimization problems with uncertainty in the objective function. In this work, a new framework called "Online Duality-Driven Optimization" (ODDO) is proposed that distinguishes itself from existing paradigms for optimization under uncertainty in its efficiency, simplicity, and ability to solve problems without any quantitative assumptions on the uncertain data. The key idea is that the optimal Lagrange multipliers are predicted instead of the actual uncertain data. Subsequently, these predictions are used to construct an online primal solution by exploiting strong duality. The framework is robust against prediction errors in the optimal Lagrange multipliers, both theoretically and in practice.

The ODDO framework is a promising addition to the set of paradigms for optimization under uncertainty and provides the community with a new approach to tackle these types of problems.

Martijn H. H. Schoot Uiterkamp, Marco E. T. Gerards, Johann L. Hurink: ODDO: Online Duality-Driven Optimization. https://arxiv.org/abs/2008.09838

The above work focuses on a conceptual approach considering robustness and uncertainty,

also taking into account aspects of efficiency, which are crucial for the successful applicability of DEM approaches in practice. For a large scale introduction of DEM, flexible, intelligent and efficient local optimization algorithms for specific device classes need to be introduced (for example electric vehicles, storage devices). As these algorithms will run on embedded hardware and need to react very fast, the ODDO framework perfectly supports developments in this field.

The DEM group is working on generalizations of their decentralized energy management concept called Triana and the Decentralized Energy Management toolKit (DEMKit) by incorporating the mentioned robustness aspects, increasing their efficiency and extending their scope. The goal is to use these tools in hardware-in-the-loop simulations and field tests.

3.2.4 Medical Imaging

Personalized medicine also known as "theranostics" is one of the main objectives in our healthcare system. The goal is to move away from a "one therapy fits all" approach to individualized treatment and medication based on the needs of the individual patient. In biomedical imaging, with its fundamental methods in mathematical imaging and analysis, deep learning rapidly outperformed human performance in recent years in practice, for example in histopathology or radiology, but the "black-box" perception left a big gap regarding robustness (stability), interpretability (modeling) and generalisability (representation).

The AA group developed two key principles in medical imaging and inverse problems, from classical variational methods towards deep learning, namely (i) combining model- and data-driven methods for inverse problems, and (ii) from nonlinear spectral decompositions to deep learning autoencoders.

With the thesis of Y. Boink we pioneered the systematic combination of variational methods with data-driven deep learning techniques to achieve adaptive regularization for stable and advanced image reconstruction in photonics. With photoacoustic tomography for painless breast cancer screening (Health Holland, EU project) we made a significant impact.

Research highlight IV: Deep Learning of Circulating Tumour Cells

In our works on deep learning of circulating tumour cells (PhD L. Zeune, EU CANCER-ID) we developed a systematic path from variational scale-space methods to interpretable nonlinear deep learning autoencoding schemes. As the key research highlight our automatic, stable and interpretable autoencoding model identified unexplored extracellular vesicles in the latent space for tumour cell features which led to a Nature paper and the 2020 Dutch Computable award.

Zeune, L.L., Boink, Y.E., van Dalum, G. et al. Deep Learning of Circulating Tumour Cells. Nature Machine Intelligence 2, 124–133 (2020). https://doi.org/10.1038/s42256-020-0153-x

To extend these two lines of research we attracted TT and Veni laureate Jelmer Wolterink via a large 4TU Precision Medicine program and Mengwu Guo via the NWO sectorplan. In combination with additional advances on dynamics and deep learning we envision a new generation of geometric deep learning in applied mathematics and medical imaging.

3.3 International collaborations

All our researchers have their own, well-established international networks. In this paragraph we highlight longstanding international collaborations.

USTC

Since 2012, Prof. van der Vegt is visiting professor at the University of Science and Technology of China (USTC) in Hefei, Anhui Province, China for 2.5 months per year. This position is funded by fellowships from the Chinese Academy of Sciences (High-End Foreign Experts

Recruitment Programme) and USTC. This collaboration has resulted in a double PhD programme between USTC and the University of Twente. So far, five PhD students have been jointly supervised by Prof. van der Vegt and Prof. Yan Xu, of which three already successfully graduated in Twente and/or USTC. In 2021, Prof. van der Vegt was one of the recipients of the Huang Shan Price (黄山奖) awarded by Anhui Province for his collaboration with USTC.

NPU

Prof. Uetz, together with Prof. Broersma from the Computer Science department, co-established a research institute on Networks, Economic Decisions and Optimization (NEDO) in 2019. It is a joint undertaking of the University of Twente and the Northwestern Polytechnical University (NPU) in Xi'an, Shaanxi Province, China. The institute strengthens the collaboration between the two universities, which has been existing for approximately 30 years. Since 1991, more than 20 graduates from NPU have defended their PhD in Mathematics at the UT. The institute facilitates funding for joint projects and mutual exchange of staff and students. It includes a double-degree PhD program. The first three double-degrees were awarded in 2019 and 2021 and were jointly supervised by Prof. Uetz and Prof. Hao Sun. Funding for joint PhDs projects comes mainly from the China Scholarship Council (CSC).

Imperial College

Since 2005, Prof. Geurts has been Visiting Professor at the Imperial College of the University of London after previous engagements at Queen Mary College (1999-2005). This research involvement is made possible by direct support of the college and through EPSRC-funded fellowships, associated with various projects and consortia, amongst which the Turbulence Consortium (2005, 2007-2009), the High-Performance Simulation Consortium (2010-2012) and the Graduate School for Mathematics of Planet Earth (MPE, since 2013), recently also honoured by an ERC Synergy grant STUOD (2019-2024). The mathematics research focuses on modelling stochastic dynamics through variational principles and associated structure-preserving discretization. Prof. Geurts was involved in two recent MPE PhD theses and jointly supervised two more PhD projects with Prof. Darryl Holm of ICL.

4 Academic culture and personnel policies[4]

4.1 PhD Policy and training

It is part of our mission to educate well-trained PhD students. Since 1 January 2014 all PhD students are registered in the Twente Graduate School (TGS). As a result uniform procedures and rules apply for all PhD students:

- Central registration of all PhD students in the Hora Finita system;
- PhD charter;
- GO/NO-GO decision during first year including formal appointment of the promotor;
- digital Training and Supervision Plan (T&SP) in the Hora Finita system;
- forecast and drop-out registration.

The Training and Supervision Plan (T&SP) is obligatory for all categories of PhD candidates. A copy of the agreed T&SP is kept in the central Hora Finita archive. The T&SP contains a summary of the research plan, the supervision plan, and the educational programme of 30EC to be followed by the PhD candidate. It is defined by the candidate and the supervisor, and approved by the dean. The educational program can contain courses offered by the university, national research schools and international programs, such as summer schools. The T&SP further details the teaching obligations of the PhD candidate. The plan is set up by the supervisor and the PhD candidate within three months after the start of the PhD candidate, and is periodically reviewed and updated. A formal 'qualifier' after nine months aims to determine a conclusive assessment whether or not to proceed with the remainder of the PhD project.

[4] For our Human Resources strategy, we refer to section 2.3

In recent years, several (inter)national investigations have addressed the topic of PhD well-being. These surveys all point to PhD students suffering from stress and mental disorders such as anxiety and depression. Since 2019, all graduating PhD's at the UT receive an electronic exit questionnaire. About 50% of the graduates (around 200 per year) respond, and they give their experience an average mark of around 8 (out of 10). PhD's who quit earlier receive an invitation for a confidential discussion about the reasons to stop.

4.2 Seminars and reading groups

Various activities are organized in the department aimed at community building aligning the research direction of individual staff members with the department's strategy, and keeping up-to-date with recent developments in the field(s). They are highly appreciated, especially by new staff members who experienced less personal interaction with colleagues during the pandemic.

- A bi-weekly department colloquium provides a platform for guests and, more recently, a means for new staff members to introduce their research area. The colloquium is followed by drinks (or online meetings).
- Weekly seminars of the clusters where presenters are a mixture of external guests, PhD students and staff members.
- Reading groups on various topics. The reading groups are inclusive for all members of the department. Recent topics covered by these reading groups are the EM algorithm, computational complexity, dynamics and deep learning, domain decomposition and Discontinuous Galerkin methods.

5 Strategy for the next six years

5.1 SWOT Analysis

Table 5.2 lists the strength, weaknesses, opportunities and threats.

The administrative load increased substantially after the introduction of the Twente Educational Model in 2013. As a lot of our teaching activities are related to service teaching, we shall not be able to change the setting substantially, but, during the academic year 2021-2022, we shall revise our own Applied Mathematics curriculum, making it more efficient and at the same time, raising the level of abstraction in the curriculum.

We have little influence on the university's management. In our opinion, there are too many changes in short time whose implementation take time and energy, distracting from our core business. Within our department, we try to be lean and efficient, to create an environment that leaves maximal room for teaching and research.

The fact that faculty members receive good offers from other universities is a threat on the one hand, but it also shows that we can attract excellent staff members.

At present, we have an excellent discussion within the faculty on how the first stream of money for research should be divided. The outcome will improve the current situation, which in our opinion, is not very transparent.

5.2 Strategy

The availability of additional funding via the so-called 'sectorplan' allowed us to realize a major strategic goal, namely to build a strong group in statistics. Indeed, with sectorplan budget and additional funding from the university, we were able to hire seven new faculty members,

Table 5.2: SWOT Analysis.

Strengths	**Weaknesses**
• The ability to connect mathematical research topics to societally relevant themes including proper funding • Significant increase of female researchers over the past 5 years • The department has expanded its scientific staff over 25% in the past 6 years. • The ability to attract good PhD students	• The teaching and administrative load, particularly for senior staff is substantial and competes with research activities • Ethics and data management need to be better implemented and grow into the DNA of the organization • Complex and overloaded management structure (departments, clusters, faculties, institutes) • Quite some PhD's take $>$ 4 years
Opportunities	**Threats**
• The department's research profile is highly relevant for societally relevant themes such as energy, health, and high-tech systems, opening future opportunities for funding and collaboration • The department is in an excellent position to contribute to the mathematical relevant themes such as uncertainty quantification and mathematics of deep learning (AI) • The cross-disciplinary spirit at the UT offers constantly new fields of application that require novel mathematics	• Low success rates in funding research through personal grants from NWO or the EU leads to personal frustrations, hindering staff to perform at full potential • Faculty members are constantly offered positions at other universities and it remains a challenge to avoid a quick outflow of staff. • The division of the faculty's revenues for research is not transparent

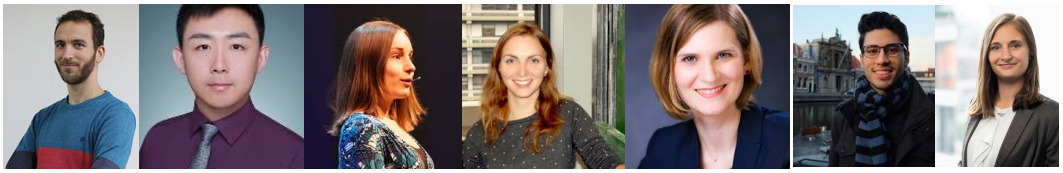

Figure 1: The first five people are the staff members appointed through the sectorplan budget from left to right. The last two are the staff members assigned by the additional funding from the UT.

three of them being part of the statistics group (Betken, Proksch and Guzman), see Fig. 1. The proliferation of the statistics group, and its integration with other research activities of the department is a major strategic goal that anticipates on data science related developments that we currently witness in many domains. The additional funding allowed us to enforce some of the department's other strengths as well, with a particular focus on the link to statistics and data science. Next to this, and in order to allow young staff to develop a strong research profile, we realize that it is crucial to shape a working environment where the teaching load is

reduced teaching

reduced to a reasonable proportion. As a result, in the first three years of employment it is no more than 33% of full time working hours, and thereafter no more than 50%.

three organizational clusters

Presently, the statistics group is part of the mathematics of operations research (MOR) cluster. It is foreseen that the statistics group will be the heart of a newly formed cluster for the mathematics of data science, as one of three mathematics clusters, next to mathematics of operations research and mathematics of computational science (currently SACS); see Fig. 2.

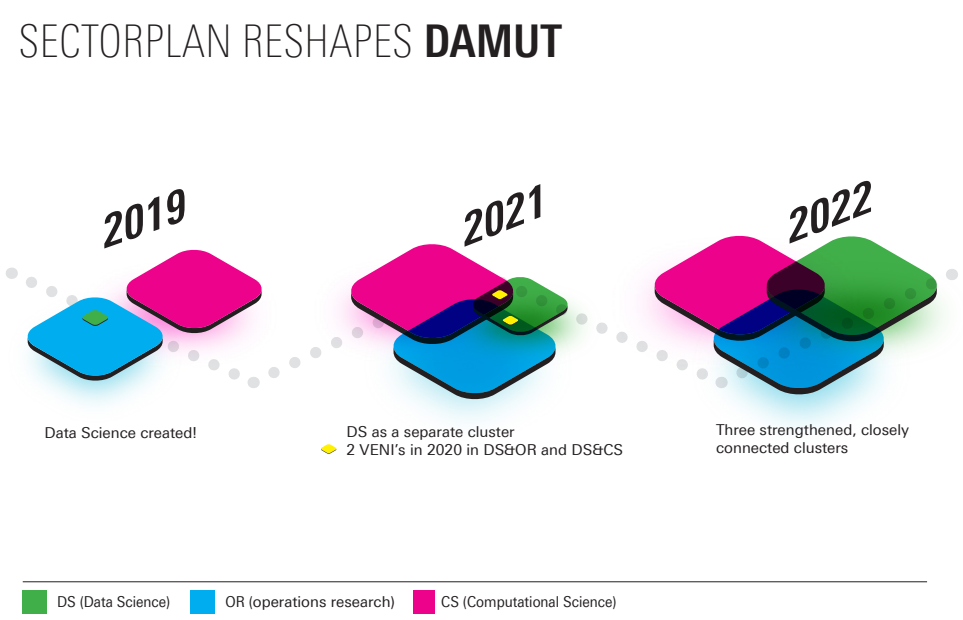

Figure 2: Effect of the sectorplan on the department.

The formation of the three clusters is not meant as a separation, and in terms of staff, there is large overlap amongst the clusters. For example, optimization is associated with operations research and data science alike. Also, statistics lies at the core of data science, but links to uncertainty quantification in computational science as well.The three clusters are primarily meant to help organize activities like seminars, proposal writing and master courses. Moreover, it helps to realize clear communication of the research portfolio to current and prospective students, as well as the outside world.

ICAI labs

Our data science activities have by now led to participation in two so-called ICAI labs: Our energy group is part of an ICAI lab within the Long Term Programme (LTP) ROBUST (Trustworthy AI-based Systems for Sustainable Growth), involving Alliander and researchers from UT, TUD and RU. The imaging group is also part of an ICAI lab,'Healthy AI', within the same NWO LTP Robust program, with Siemens Healthineers (NL and DE) and involving researchers from UT, RUMC and UMCG.

visibility

To increase the visibility of the mathematics department outside the Netherlands, several measures will be taken, ranging from partnerships with other universities to the organization of workshops and conferences on the campus as well as inviting more visitors. We hope to get additional support from the faculty, especially to invite long-term visitors. In this way, we also aim to increase external funding for our research and become an even more attractive institute.

We understand applied mathematics as developing mathematics for applications and not just

mathematical science

using (existing) mathematics. This understanding has been and will remain a leading principle in the hiring process. We are an international institute and embrace diversity. Therefore, we shall continue to stimulate female participation at all levels of hierarchy and aim to strengthen the international character of the department. Mutual understanding and awareness of biases are essential for a welcoming and inclusive work environment.

post-corona effects

The corona pandemic has changed our way of working. We expect partially working from home becomes the standard. Consequently, there will be fewer informal discussions in the common room or during lunch breaks. As a consequence, members of the department might be less informed about ongoing discussions, the current research at the institute and new staff members. Actions are required to maintain a close relationship of the institute with its members, including a monthly newsletter, an active colloquium and joint social activities. Once a year, there should be a general assembly of all faculty with the department head to overview the state of affairs for all critical issues and plans regarding the institute.

Regarding the institute's administration, we want the tasks to remain distributed. We also wish all members with particular roles such as the teaching director, the chairs, and the department head to do active research next to their administrative and teaching duties. Constantly, new administrative systems are introduced. Maintaining a time-efficient administration will be a significant challenge for the coming years requiring additional management support.

6 Summary

A major development in the past six years was the formation of a statistics group. It forms the heart of our activities in data science and we are in the process of restructuring the department into three clusters: mathematics of operations research, data science and computational science, respectively. Supported by the sectorplan funding, we have been able to attract seven young and very talented researchers. This was augmented by several replacements, such that we now have an energetic mix of young and senior staff members. The atmosphere in the department is characterized by many informal contacts and scientific discussions conducted in all openness. There is an attitude of cooperation rather than competition. The positive atmosphere extends to the faculty, where strong disciplines are supported, and at the same time, interaction on strategic themes is stimulated. We get the freedom of the management of the faculty to develop our strategy.

During the period of this review, the percentage of female staff members more than doubled to 16.4% and the percentage of foreign staff members increased to 40% contributing to the international and inclusive character of the department.

Related to the focus on data science, we have recently initiated the new master track, AI4Health. The new track aligns with our increased activities in imaging and also connects well to the TechMed Centre. We expect to increase the intake in our master programmesubstantially. The teaching load was still (too) high. We undertake appropriate action to reduce the teaching load, which is critical as we have so many young staff members who need to flourish both in research and teaching.

We shall adhere to our strategy to obtain funding both from NWO and EU and from industry. The recent success that we had with personal grants has fueled our ambition. We foresee that collaborative grant applications, in which our international office can play a crucial role, will become more critical.

All in all, we can conclude that we see a bright future for the department. We continue to work on creating the conditions for employees to perform optimally in research and education.

A Tables

Table A1: Scientific output

	2015	2016	2017	2018	2019	2020	Total
Academic publications							
a. Refereed articles	83	77	78	90	67	77	472
of which open Access (%)	17%	35%	53%	72%	63%	45%	47%
c. Books							
- Refereed book chapters	6	2	6	2	1	4	21
- Monographs	0	0	0	0	3	1	4
e. PhD Theses	10	9	13	4	10	3	49
f. Conference papers (refereed)	36	40	26	33	31	27	193
Total Academic publications	135	128	123	129	112	112	739
Editorships	20	22	29	31	32	36	

Table A2: Research staff

	2015		2016		2017		2018		2019		2020	
	#	FTE	#	FTE	#	FTE	#	FTE	#	FTE	#	FTE
Full professor	8	7,6	10	8,4	10	8,4	12	9,5	12	10,1	13	10,5
Professor by special app.	2	0,4	2	0,4	2	0,4	2	0,4	2	0,3	1	0,2
Associate professor	6	3,9	5	3,9	5	3,6	4	2,6	6	3,7	9	6,3
Assistant professor	16	14,1	15	11,5	14	11,4	15	12,9	19	14,3	20	15,1
Total scientific staff	**32**	**26,0**	**32**	**24,2**	**31**	**23,9**	**33**	**25,5**	**39**	**28,4**	**43**	**32,1**
Postdocs	6	2,7	10	3,3	12	6,1	8	3,0	6	4,3	12	7,5
PhD candidates (incl. FOM)	31	25,8	26	20,6	22	17,8	20	15,6	19	15,4	28	20,4
PDEng candidates	0	0	0	0	0	0	3	1,3	3	3	2	1,7
Total PD + PhD + PDEng	**37**	**28,5**	**36**	**23,9**	**34**	**23,9**	**31**	**19,9**	**28**	**22,7**	**42**	**29,6**

Table A3: Diversity of research staff: Gender and nationality

	2015				2016				2017				2018				2019				2020			
	F		M		F		M		F		M		F		M		F		M		F		M	
	NL	int	NL	int	NL	int	NL	int	NL	int	NL	int	NL	int	NL	int	NL	int	NL	int	NL	int	NL	int
Full Professor	0	0	7	1	1	0	8	1	1	0	8	1	2	0	8	2	2	0	8	2	2	1	8	2
Professor by special app.	0	0	2	0	0	0	2	0	0	0	2	0	0	0	2	0	0	0	2	0	0	0	1	0
Associate Professor	1	0	4	1	1	0	3	1	1	0	3	1	0	0	3	1	0	0	3	3	0	0	4	5
Assistant professor	1	0	8	7	1	0	8	6	2	1	6	5	2	1	6	6	3	2	7	7	2	3	8	7
Total scientific staff	**2**	**0**	**21**	**9**	**3**	**0**	**21**	**8**	**4**	**1**	**19**	**7**	**4**	**1**	**19**	**9**	**5**	**2**	**20**	**12**	**4**	**4**	**21**	**14**
Postdocs	1	0	1	4	1	0	4	5	1	0	5	6	1	1	2	4	1	2	1	2	1	3	3	5
PhD candidates	4	6	11	10	4	3	11	8	4	3	10	5	4	3	9	4	2	3	9	5	2	4	10	12
PDEng candidates	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	2	1	0	0	2	0	0	0
Total PD + PhD + PDEng	**5**	**6**	**12**	**14**	**5**	**3**	**15**	**13**	**5**	**3**	**15**	**11**	**7**	**5**	**11**	**8**	**5**	**6**	**10**	**7**	**5**	**7**	**13**	**17**

Table A4: Diversity of research staff: Age distribution of staff in 2020

	21-30	31-40	41-50	51-60	>60
Full professor (incl. special app.)	0	2	1	6	5
Associate professor	0	2	4	1	2
Assistant professor	2	10	4	2	2
Total Scientific staff	**2**	**14**	**9**	**9**	**9**

Table A5: Progress of PhD candidates

	Enrolment		Cumulative success rates: PhD candidates graduating within											
Starting year	**Total**	**4 years + 3 months**		**5 years**		**6 years**		**until Dec. 2020**		**Ongoing**		**Discontinued**	
		#	**%**	**#**	**%**	**#**	**%**	**#**	**%**	**#**	**%**	**#**	**%**
2012	8	4	50%	6	75%	6	75%	6	75%	0	0%	2	25%
2013	12	4	33%	10	83%	10	83%	10	83%	0	0%	2	17%
2014	18	4	22%	8	44%	9	50%	10	56%	3	17%	5	28%
2015	10	0	0%	4	40%	6	60%	-	-	1	10%	3	30%
2016	6	1	17%	1	17%	-	-	-	-	4	67%	1	17%
2017	8	2	25%	-	-	-	-	-	-	5	63%	1	13%
2018	11	-	-	-	-	-	-	-	-	-	-	-	-
2019	8	-	-	-	-	-	-	-	-	-	-	-	-
2020	16	-	-	-	-	-	-	-	-	-	-	-	-
Total	97	15	24%	29	54%	31	65%	26	68%	13	21%	14	23%

Table A6: Funding and expenditure. In this table Contract research refers to research funded by business. Other refers to money coming from: 3TU, 4TU, Sectorplan, faculty, temporary PhD's from already finished 2nd and 3rd money stream projects, i.e. alreay financed from projects.

	2015	2016	2017	2018	2019	2020
Funding:						
Direct funding (1)	35,4 FTE / 55 %	33,2 FTE / 56%	35,4 FTE / 61%	37,8 FTE / 66%	41,2 FTE / 65%	46,0 FTE / 60%
Research grants (2)	17, 8 FTE / 28%	13,5 FTE / 23%	13,1 FTE / 22%	8,4 FTE / 15%	12,9 FTE / 20%	21,1 FTE / 27%
Contract research (3)	7,4 FTE / 12%	6,5 FTE / 11%	6,0 FTE / 10%	6,4 FTE / 11%	5 FTE / 8%	3 FTE / 4%
Other	3,6 FTE / 6%	5,6 FTE / 10%	3,8 FTE / 7%	4,9 FTE / 8%	4,7 FTE / 7%	6,9 FTE / 9%
Total funding	64,1 FTE / 1000%	58,8 FTE / 100%	58,4 FTE / 100%	57,5 FTE / 100%	63,9 FTE / 100%	77,0 FTE / 100%
Expenditure:						
Personnel costs	M€ 5,240 / 78,0%	M€ 4,841 / 76,4%	M€ 5,035 / 78,5%	M€ 5,297 / 78,9%	M€ 6,074 / 81,8%	M€ 7,067 / 84,6%
Other costs	M€ 1,474 / 22,0%	M€ 1,495 / 23,9%	M€ 1,378 / 21,5%	M€ 1,414 / 21,1%	M€ 1,348 / 18,2%	M€ 1,282 / 15,4%
Total expenditure	M€ 6,714 / 100%	M€ 6,336 / 100%	M€ 6,413 / 100%	M€ 6,711 / 100%	M€ 7,422 / 100%	M€ 8,349 / 100%

Table A7: The Key Performance Indicators made specific for our institute.

	Research quality	Relevance to society
Demonstrable products	**1. Research products for peers** a. Publications: articles in a selected set of main journals and conferences; dissertations; books. b. Software	**4. Research products for societal target groups** a. Well-educated Masters and PhDs b. Spin-off companies c. Outreach
Demonstrable use of products	**2. Use of research products by peers** a. Citations b. Software, use of data	**5. Use of research products by societal groups/companies** a. Technical products (software, methods and patents)
Demonstrable marks of recognition	**3. Marks of recognition from peers** a. Major awards and grants (ERC, VENI, VIDI, VICI, large research grants) b. Senior positions in research-related organizations and leadership of international research projects c. Editorships of scientific journals d. Keynotes e. Organization of conferences	**6. Marks of recognition by societal groups/companies** a. Research funding from industry

Table A8: Overview of editorships.

	2015	2016	2017	2018	2019	2020
Associate Editor	17	19	26	28	30	33
Editor	1	1	2	2	1	1
Editor in Chief	1	1				
Managing Editor	1	1	1	1	1	2
Total	20	22	29	31	32	36

Table A9: Keynote lectures & tutorials

Title	Name	Date	Event
Life saving mathematics: operations research solutions to improve the quality of healthcare	Richard Boucherie	08/15	Opening keynote lecture 7th SEAMS-UGM International Conference on Mathematics and its Applications, Universitas Gadjah Mada, Yogyakarta, Indonesia
On the invariant measure of random walks in the quarter plane: a characterisation via geometric distributions and bounds on performance measures	Richard Boucherie	09/15	CanQueue 2015, Dalhousie University, Halifax, Canada
Stochastic scheduling & approximation algorithms	Marc Uetz	09/15	RWTH Summerschool on Decisions Under Uncertainty 2015
Ranking in scale-free random graphs	Nelly Litvak	05/16	37th Finnish Summer School on Probability and Statistics 2016
PageRank in random graphs	Nelly Litvak	05/16	The International Symposium on Web Algorithms 2016
Approximation algorithms for scheduling under uncertainty	Marc Uetz	09/16	1st International Workshop on Dynamic Scheduling Problems, IWDSP 2016
Theoretical and numerical analysis of connecting orbits in maps	Hil Meijer	07/16	13th Seminar on Differential Equations, Dynamical Systems and Applications 2016
Inclusive Mathematics	Nelly Litvak	10/18	Celebrating Mathematics 2018
Google PageRank and network centrality	Nelly Litvak	07/19	20th INFORMS Applied Probability Society Conference 2019
Shortest paths, mechanism design, and revenue equivalence	Marc Uetz	06/19	Int. Conf. on Network Games, Tropical Geometry, and Quantum Communication

Table A10: Funding of projects from the first money stream.

Project Name	Start	End	Funding	Funding amount
Mechanisms for Decentralised Service Systems	15/02/2012	15/02/2016	3TU.AMI	€ 175.000
Local discontinuous Galerkin methods for phase transition problems	01/12/2011	01/12/2015	China Scholarship Council	€ 82.400
Queueing and Traffic	01/09/2010	01/09/2015	CTIT	€ 178.000
Control and communication for automated driving	01/09/2014	01/09/2018	CTIT	€ 182.000
Networked and Hybrid Systems	01/01/2014	31/12/2015	UT	€ 100.000
Multi-armed bandit problems with underlying discrete-choice models	01/07/2014	01/07/2019	UT	€ 178.000
Waiting time and Personnel Capacity Optimization	01/09/2013	01/09/2017	UT	€ 89.000
Artificial Intellegence empowered endo ultrasonographic assessemnt of bowel wall infiltration in early colorectal cancer	01/12/2020	30/11/2021	PIHC Innovation fund	€ 34.200
Accelarating bone metastasis fracture risk assessment using physics informed graph neural networks	01/12/2020	30/11/2021	Twente University Radboudumc Opportunities	€ 40.000
Data science en OK planning: De perfecte fit	01/07/2020	01/01/2021	PIHC Innovation fund	€ 60.000
PDeng ZORGLOGISTIEK	01/02/2015	31/12/2021	UT	€ 50.000
3TU OZ APPLIED MATHEMATICS INSTITUTE	01/05/2015	31/12/2021	3TU.AMI	€ 240.000
4TU - BLENDED LEARNING	01/08/2019	31/12/2021	4TU	€ 240.000
THEME CALL: ENERGY	01/11/2020	31/10/2024	UT	€ 211.821
THEME CALL: HEALTH	01/10/2020	30/09/2024	UT	€ 211.821
PIHC OPERATIEKAMER OPTIMALISATIE	01/11/2020	31/10/2021	PIHC Innovation fund	€ 60.000
4TU- PRECISION MEDICINE	01/01/2018	31/12/2022	4TU	€ 480.000
Sectorplanpositie 2	01/07/2019	31/12/2024	OCW	€ 709.800
Brinksma innovation grant	01/03/2019	01/07/2019	UT	€ 21.000
Sectorplanpositie 1	01/07/2019	31/12/2024	OCW	€ 709.800
Sectorplanpositie 3	01/07/2019	31/12/2024	OCW	€ 709.800
Sectorplanpositie 4	01/07/2019	31/12/2024	OCW	€ 709.800
Sectorplanpositie 5	01/07/2019	31/12/2024	OCW	€ 709.800
Total funding				**€ 6.182.242**

Table A11: Funding of projects from NWO, FOM, ZonMw, EU, Region, Companies and Hospitals.

Projectname	Funding Agency	Start	End	Funding amount
HYBRID ENERGY GRID MANAGEMENT	EU	1-1-2015	1-1-2016	€ 65.500
DYNAFLOAT: URBAN TRAFFIC FLOW MANAGEMENT USING FLOATING-CAR, PLANNING, AND INFRASTRUCTURE DATA	NWO	1-1-2015	31-12-2021	€ 267.170
MULTI-APPOINTMENT PLANNING IN REHABILITATION	Hospital - Sint Maartens Kliniek	1-2-2015	1-2-2019	€ 285.000
UNDERSTANDING THE ABSORPTION OF INTERFERING LIGHT FOR IMPROVED SOLAR CELL EFFICIENCY	FOM	1-9-2015	1-10-2022	€ 60.734
FRAMEWORK FOR RANDOM METRIC SPACES	NWO	1-10-2015	1-9-2021	€ 221.171
SUPREME	EU	1-11-2015	1-11-2018	€ 115.625
15CSER49 PORT-HAMILTONIAN DISCONTINUOUS GALERK IN METHODS FOR SEISMIC WAVE COMPUTATIONS	FOM	1-7-2016	31-3-2021	€ 60.687
OPEN SOURCE BOUNDARIES	Company - Philip Morris	1-11-2016	1-10-2017	€ 144.000
DISTRIBUTED INTELLIGENCE FOR SMART POWER ROUTING AND MATCHING 2 - EXTENSION TO A CASE STUDY OF AMSTERDAM ARENA	NWO	1-12-2016	1-4-2019	€ 68.329
TKI URBAN ENERGY - GRID FLEX HEETEN	RVO	1-1-2017	30-9-2020	€ 348.165
HEALTHCARE IN A CLEAN ENVIRONMENT	Company - Asito	1-4-2017	21-12-2021	€ 348.165
HEALTHCARE IN A CLEAN ENVIRONMENT	Company - Asito	1-6-2017	21-12-2021	€ 307.500
FROM BLOOD WITHDRAWEL TO FIRST RESULT	Hospital - VU Medisch Centrum	1-10-2017	1-11-2021	€ 200.000
CONTROL OF FLEXIBLE STRUCTURES AND FLUID STRUCTURE INTERACTIONS	EU	1-10-2017	1-10-2021	€ 467.548
NONLINEAR DYNAMICS 16 18	NWO	1-2-2018	31-12-2019	€ 44.580
NONLINEAR DYNAMICS 18-20	NWO	1-2-2018	28-2-2021	€ 85.000
SMART ENERGY REGION EMMEN HAREN	Interreg	1-3-2018	28-2-2022	€ 28.175
MODELING NEW TREATMENT STRATEGIES FOR INTRACRANIAL ANEURYSMS	ZonMw	1-3-2018	1-3-2019	€ 29.420
NONLOCAL METHODS FOR ARBITRARY DATA SOURCE	EU	1-3-2018	28-2-2022	€ 112.500
NONLINEAR DYNAMICS PHD TRAVEL	NWO	1-7-2018	31-12-2019	€ 10.440
ACCURATE AND EFFICIENT COMPUTATION OF THE OPTICAL PROPERTIES OF NANOSTRUCTURES FOR IMPROVED PHOTOVOLTAICS	NWO	1-7-2018	1-7-2022	€ 247.205
SELF ORGANISING MARKETPLACE TO REALISE A SELFORGANISED SUSTAINABLE POWER SYSTEM	NWO	1-8-2018	30-4-2023	€ 227.553
AKUTE VERANDERUNGEN DURCH MANGELNDE ENGERGIEZUFUR AN GLUTAMATERGEN SYNAPSEN	University - Heinrich-Heine Universität Düsseldorf	1-10-2018	30-11-2021	€ 159.930
PDENG BEVOLKINGSONDERZOEK OOST	Healthcare sector - Bevolkingsonderzoek Oost	1-11-2018	31-10-2020	€ 65.000
PDENG RIJNSTATE	Foundation - Stichting Rijnstate	1-11-2018	31-10-2020	€ 65.100
MODELING INDUSTRIAL FLEXIBILITY TO THE ENERGY SYSTEM	Company - TNO	1-12-2018	30-11-2020	€ 65.000
COMPREHENSIVE MONITORING AND PREDICTION OF SEISMICITY WITHIN THE GRONINGEN GAS FIELD USING LARGE SCALE FIELD OBSERVATIONS	NWO	1-3-2019	14-9-2023	€ 247.038
DEEP MODELLING	NWO	1-3-2019	14-9-2023	€ 247.038
NONPARAMETRIC BAYES FOR HIGH-DIMENSIONAL MODELS: CONTRACTION, CREDIBLE SETS, COMPUTATIONS	NWO	1-4-2019	30-4-2021	€ 127.415
INTEGRATIE EN AANSTURING VAN DUURZAME SLIMME PARKEERPLAKKEN	RVO	1-7-2019	30-6-2022	€ 126.413
STRUCTURE-PRESERVING REGULARIZATION AND STOCHASTIC FORCING FOR NONLINEAR HYPERBOLIC PDES	NWO	1-9-2019	31-8-2024	€ 732.831
ULTRA FAST CRAWLING FOR REAL TIME WEBSCALE MARKET INTELLIGENCE PLATFORM	RVO	1-10-2019	30-9-2021	€ 256.578
VIDI:STATISTICAL FOUNDATION FOR MULTILAYER NEURAL NETWORKS	NWO	1-11-2019	31-10-2024	€ 799.832
VLIEGWIELTECHNOLOGIE VOOR ENERGIEOPSLAG IN MICROGRIDS	EFRO	1-11-2019	31-10-2022	€ 230.225
DATA DRIVEN RISK MANAGEMENT FOR FIRE SERVICES	NWO	1-2-2020	31-1-2024	€ 341.796
LOW RANK TENSOR PRODUCT APPROXIMATIONS FOR THE RADIATIVE TRANSFER EQUATION	NWO	1-6-2020	31-5-2024	€ 272.102
FAIR OPEN REALTIME DISTRIBUTED POWER QUALITY CONTROL FOR LOW VOLTAGE GRIDS	RVO	1-6-2020	31-5-2024	€ 204.672
OPTIMALISATIE VAN PATIENTENSTROMEN EN AFSPRAKENSCHEMAS OP DE ANDERHALVE METER POLIKLINIEK	ZonMw	29-6-2020	2-1-2021	€ 24.320
INTEGRATED DISTRIBUTED SCADA SECURITY THROUGH LOCAL APPROXIMATIONS OF POWER FLOW EQUATIONS	NWO	1-7-2020	30-6-2024	€ 263.102
NANOFILLER-ENHANCED WAX FOR HEAT STORAGE	NWO	1-9-2020	31-8-2023	€ 224.424
HET INDIË TERREIN: SLIMME BUURTBATTERIJ IN DE OUDE WEVERIJ	RVO	1-10-2020	30-9-2022	€ 241.152
SELF ASSEMBLED ICOSAHEDRAL PHOTONIC QUASICRYSTALS WITH A BAND GAP FOR VISIBLE LIGHT	NWO	1-11-2020	31-10-2025	€ 256.102
RIGOROUS ANALYSIS OF LOCAL SEARCH	NWO	1-12-2020	31-12-2024	€ 273.602
Total project funding				€ 8.968.139
Subtotal per Fundingtype				**Funding amount**
NWO / FOM / ZonMW				€ 5.131.891
EU / INTERREG / EFRO				€ 1.019.573
RVO / Companies (including Hospital, University, Healthcare sector and Foundation)				€ 2.816.675

Table A12: Contribution to the organisation of conferences and workshops.

Year	Event	Person	Role	Period
2020	45th Woudschoten conference 2020	Matthias Schlottbom	Organiser	30/09/20-2/10/20
2020	11th Day on Computational Game Theory 2020	Alexander Skopalik	Organiser	13-14/02/20
2020	45th conference on The mathematics of operations research	Johann L. Hurink	Organiser	13/01/20-15/01/20
2019	12th International Conference of the ERCIM WG on Computational and Methodological Statistics, CMStatistics 2019	Maria Nicolette Margaretha van Lieshout	Organiser special session	14-16/12/19
2019	48th Annual Meeting of the Dutch Probability and Statistics Community 2019	Maria Nicolette Margaretha van Lieshout	Organiser	11-13/11/19
2019	4TU AMI annual event on Mathematical Deep Learning	Anselm Johannes Schmidt-Hieber	Organiser	5/11/19
2019	European Conference on Numerical Mathematics and Advanced Applications, ENUMATH 2019	Matthias Schlottbom	Organiser minisymposium	30/09/19-4/10/19
2019	Computability in Europe (CiE)	Bodo Manthey	Organiser special stream	15-19/07/19
2019	17th Cologne-Twente Workshop on Graphs and Combinatorial Optimization, CTW 2019	Bodo Manthey and Johann Hurink	Chair	1-3/07/19
2019	16th Conference on the Mathematics of Finite Elements and Applications, MAFELAP 2019	Matthias Schlottbom	Organiser minisymposium	18-21/06/19
2019	Statistics Conference	Anselm Johannes Schmidt-Hieber	Organiser	17-21/06/19
2019	55ste Nederlands Mathematisch Congres 2019	Maria Nicolette Margaretha van Lieshout	Organiser minisymposium	12-24/04/19
2019	44th Conference on The mathematics of operations research 2019	Johann L. Hurink	Organiser	14-16/01/19
2018	47th Annual Meeting of the Dutch Probability and Statistics Community 2018	Maria Nicolette Margaretha van Lieshout	Organiser	12-14/11/18
2018	IFIP TC 7 Conference on System Modelling and Optimization 2018	Christoph Brune and Matthias Schlottbom	Organiser minisymposium	23/07/18
2018	Lorentz workshop: Ion dynamics in the brain during metabolic stress	Stephan A. van Gils	Organiser	16-20/07/18
2017	26th Annual Computational Neuroscience Meeting 2017	Stephan A. van Gils	Organiser minisymposium	20/07/17
2017	42nd Woudschoten Conference on Scientific Computing 2017	Jacobus J.W. van der Vegt	Chair	1/01/17
2016	41st Woudschoten Conference 2016	Jacobus J.W. van der Vegt	Chair	1/01/16
2015	Lorentz workshop: Brain equations: Challenges and next generation models	Stephan A. van Gils	Organiser	13-17/04/2019

Table A13: The number of different nationalities amongst the permanent staff.

Number of nationalities	2015	2016	2017	2018	2019	2020
UD	7	6	5	4	3	5
UHD	2	2	2	2	2	2
HGL	2	2	2	2	2	2
UD+UHD+HGL	7	6	5	4	3	5

*Table A14: H-indices and number of citations per research staff member. People with a * left the University of Twente in the evaluation period. The table is up to date on October 9, 2021.*

Name	H-index [5]	#citations
Backhoff Veraguas, dr. J.*	12	362
Bertrand, dr. F.	5	119
den Boer, dr. A.V. *	9	780
Botchev, dr. M.A.*	19	1061
Boucherie, prof.dr. R.J.	32	3702
Braaksma, dr. A.	6	220
Brune, dr. C.	20	995
Dickinson, dr. P.J.C.*	13	503
van Dijk, dr. N.M.	33	4007
Dölz, dr. J.*	8	207
Gallistl, dr. D.*	16	627
Geurts, prof.dr.ir. B.J.	43	7308
van Gils, prof.dr. S.A.	30	3689
Goseling, dr.ir. J	13	960
de Graaf, dr. M	8	234
Hoeksma, dr. R	6	210
Hurink, prof.dr. J.L.	42	6504
Kern†, dr. W.	33	3429
Kuznetsov, prof.dr. Yu.A.	44	19392
Lieshout, prof.dr. M.C	22	2821
Litvak, dr. N.	26	2196
Mandal, dr. P.K.	11	513
Manthey, dr. B.	19	966
Meijer, dr. H.G.E.	20	1313
Meinsma, dr.ir. G.	21	1835
van Ommeren, dr. J.C.W.	17	768
Polderman, dr. J.W.	17	2592
Post, dr.ir. G.F.	17	1514
Proksch, dr. K.	6	104
Scheinhardt, dr.ir. W.R.W.	19	1004
Schlottbom, dr. M.	13	371
Schmidt-Hieber, prof.dr.J	12	971
Schwenninger, dr. F.L.	10	300

[5] The H-index is given for completeness and is not considered to be a measure for quality.

Skopalik, dr. A.	16	775
Smetana, dr. K.*	9	220
Stegehuis, dr. C.	10	419
Stoorvogel prof.dr.A.A.	39	14790
Timmer, dr. J.B.	16	880
Uetz, prof.dr. M.J.	23	2256
van der Vegt, prof.dr.ir. J.J.W.	22	2104
Vlasiou, prof.dr. M.	12	414
Walter, dr. M.	6	391
Wolterink, dr. J.M.	22	3225
Zwart, prof.dr H.J.	31	7793

Table A15: Outreach events.

year	participant	event
2015	Prof. Uetz	Volkskrant article about MSc traineeship of Loes Knoben (@ ZIB, Berlin), about a world record attempt for the S-Bahn Challenge, based on discrete optimization. Appearances also in Süddeutsche Zeitung, Berliner Morgenpost, and Coen & Sander Show.
2015	Prof. Uetz	NRC article, "Why Mathematics? Because you want to play the game strategically" about Jasper de Jong's PhD research on the analysis of equilibria in traffic networks, etc.
2019	Dr Stegehuis	'Snelheid van netwerken', I/O magazine, April 2019, page 26
2019	Dr Stegehuis	'In de verdediging', Nieuw archief voor wiskunde, March 2019, page 54. Appearence on Sound of Science podcast.
2019	Dr Stegehuis	Presenter of the 'Faces of Science Science quiz' at Corderius College, Amersfoort.
2019	Dr Stegehuis	Presentation at **Quadrivium** on 'Networks and jazz', Eindhoven.
2019	Dr Stegehuis	Presentation at **Techionista**, an event to empower women in technology, Adyen, Amsterdam.
2019	Dr Stegehuis	One of the seven organizers of the 'Faces of Science Science quiz', a **science quiz** in which 2000 high school students at 25 schools participated.
2020	Dr Stegehuis	Children's lecture at the **Nemo science museum**, for children aged 8-12.
2020	Dr Stegehuis	Appearance on Nemo/Kennislink Podcast 'Wat moet ik met mijn geld?'. Interview on the value of fundamental research.

B Case Studies

B.1 Understanding subgraph patterns in high-dimensional networks

Author: Clara Stegehuis, VENI laureat 2020.

Networks are everywhere, from social networks to the Internet to our brain. Network data is becoming increasingly rich in structure, where network members (vertices) have many features, like clicks, likes and locations. These features position the vertices in a geometric space, where each coordinate represents one feature. In many applications, the number of features is immense, creating a *high-dimensional geometry*.

Connections often appear between similar vertices, such as those representing people with identical hobbies. In mathematical terms, vertices that are close within the geometric space are likely to be connected. Thus, the geometric space strongly influences network connection patterns or *subgraphs*. Other subgraphs do not result from the geometry, but are characteristic for the particular network, see Figure 3.

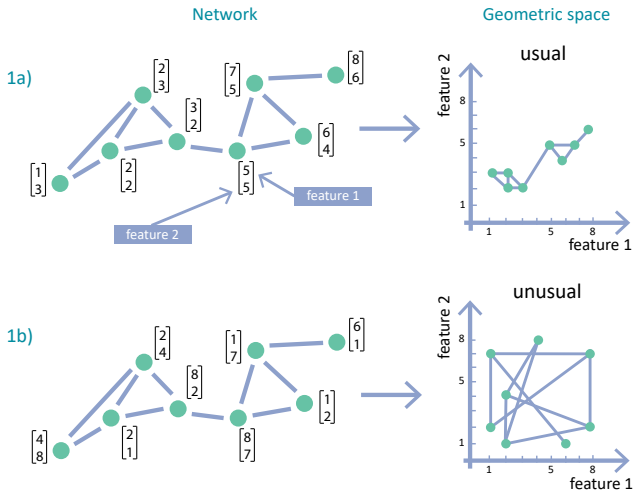

Figure 3: Networks 1a) and 1b) only differ in their features/geometry. In 1a), triangles are usual for the geometry because vertices in these triangles are close. In 1b), triangles are unusual (characteristic) because vertices in these triangles are distant. Thus, geometry influences which subgraphs are characteristic. MS: Specify color venigreen

These characteristic subgraphs often signal important network structures such as spam in email networks or crises in financial networks. Thus, it is crucial to identify the characteristic subgraphs for networks with geometric structures. However, due to their complexity current methods to identify characteristic subgraphs do not handle geometric structures, leading to incorrect identification of characteristic subgraphs. This creates the need to understand the relation between *high-dimensional geometry* and *characteristic subgraphs*, which I aim to do in two projects:

Understand subgraphs in high-dimensional network models My first aim is to identify characteristic subgraphs by analyzing network models that have high-dimensional geometry in combination with the frequently observed variability in the number of neighbors. Studying networks with both properties is novel and requires the design of new optimization models and advanced test statistics.

To address this, I will study subgraphs in a power-law network model in which every vertex has a d-dimensional position. When two vertices are close, they are likely to connect. The essential element of this proposal is that d grows as a function of the network size, making the network high-dimensional.

In particular, I will address the questions: When is a subgraph characteristic? When does de dimension d become too large for the geometry to be meaningful? And can we distinguish geometric and non-geometric networks with novel test statistics? I will answer these methods by combining techniques from random graph analysis with optimization methods that detect the most likely geometric location and degrees of subgraphs.

What do subgraphs reveal about geometry? The second aim is to investigate the influence of subgraphs on geometry, finding the 'hidden network information' that subgraphs capture. I will focus on a new application of subgraphs in embeddings: simpler network descriptions that excel at addressing problems like item recommendation and missing link prediction. However, the theoretical properties of these embedding remain uninvestigated.

I will investigate their properties in reverse approach of the previous subproject. Instead of investigating subgraphs created by geometric network models, I will investigate embeddings of geometric network models, created by subgraphs. This will allow to determine theoretically on which problems subgraph-based embeddings can give meaningful results, and explain what subgraphs reveal about networks.

In particular, I will focus on the questions: How should the embedding dimension be chosen? What properties of the original network does the low-dimensional embedding capture? Both questions are highly important for understanding under which conditions such embeddings can be used. The mathematical approach to answer these questions involves random walks and maximum likelihood estimators.

B.2 Geometric deep learning for personalized medicine

Author: Jelmer Wolterink, VENI laureat 2020

I have recently been awarded an NWO VENI grant for research that might help people with an abdominal aortic aneurysm (AAA). Around 2% of people in The Netherlands have such an AAA, a dilation of the abdominal aorta. If left untreated, an aneurysm may grow until the aorta wall can no longer sustain the forces exerted by the blood flow, and rupture occurs. A ruptured AAA needs to be operated on immediately, but most patients die before they reach the hospital or operating room, leading to 150,000 global deaths each year.

In patients with an AAA, the clinician decides between two options. The first option is *watchful waiting*, in which the growth of the aneurysm is monitored on a yearly basis. The second option is *elective repair*, in which the unruptured aneurysm is operated upon. The risk of watchful waiting is that aneurysms may rupture unexpectedly during surveillance intervals. On the other hand, 2% of patients undergoing elective repair die during surgery, and one in five patients develop a postoperative complication. Currently, the aneurysm's diameter is leading in the clinician's decision, but for many patients, surgery is either too late or unnecessary.

I believe that the key to improved decision-making lies in the information contained in the computed tomography (CT), magnetic resonance imaging (MRI), and ultrasound images that are periodically obtained for AAA patients. These images contain a lot of additional information about the shape, composition, and progression of an aneurysm that is barely used in practice, mostly because extraction is extremely time-consuming. In my VENI project, I develop new machine learning methods to fully exploit these images for a more patient-specific treatment

plan.

The focal point of my project is the data-driven analysis of anatomical models extracted from these images. This has the potential to lead to novel biomarkers that quantify the aneurysm shape or estimate blood flow in the aorta. For this, I rely on my expertise in deep learning, a branch of machine learning that uses artificial neural networks. However, standard deep learning techniques like convolutional neural networks assume that data is organized on a regular grid, which is not the case for (discretized) 2D manifolds. Hence, I will focus on innovations in so-called *geometric deep learning* methods, which are explicitly designed to work on graphs or manifolds.

One component of my project is the development of a generative model for anatomical shapes. A key application of this model is the unsupervised extraction of anatomical parameters beyond simple measurements like length, diameter, and surface area. The generative model will embed each shape in a low-dimensional latent space. The position of each shape in this latent space determines a shape descriptor, which can be correlated with AAA progression.

A second component is the rapid estimation of hemodynamic parameters such as pressure and wall shear stress on 2D manifolds representing aorta walls. These parameters are usually estimated with finite element methods in computational fluid dynamics, which can be time-consuming. I will develop a geometric deep learning method to predict pressure and wall shear stress directly on the surface mesh that represents the aorta wall. Initial research conducted in collaboration with the QUVA Deep Vision Lab shows that this is, in fact, feasible. Extrapolation of this approach to real patient anatomies will require aspects such as conditioning on personalized boundary conditions, uncertainty quantification. Tackling this problem with relatively little training data requires invariance or equivariance to transformations and the incorporation of physics in physics-informed neural networks. For in-vitro validation of the developed models, I will rely on the expertise available in the Physics of Fluids group in our university.

As the final part of my project, I will develop a geometric deep learning method that predicts shape deformation over time to better estimate AAA progression. For this, a large data set containing medical images of over 750 patients collected in a national Parelsnoer biobank will be used. Throughout the project, I will work closely with vascular surgeons in AmsterdamUMC and Rijnstate hospital (Arnhem).

My personal goal is to conduct research that is not only state-of-the-art but also has a societal impact. Improved prediction of AAA growth could lead to personalized surveillance plans, instead of the current one-size-fits-all protocol. Moreover, the novel data-driven geometric deep learning approaches developed in this project might be relevant for other applications such as geometric analysis of the carotid arteries, myocardial motion analysis, or prediction of intracranial aneurysm rupture.

B.3 Predictive Avatar Control and Feedback (PACoF)

Author: Felix Schwenninger.

Predictive Avatar Control and Feedback (PACoF) is one of the four projects within the Theme Team Call.

PIs: Douwe Dresscher (RaM), Gwenn Englebienne (CS), Felix Schwenninger (AM)
PhD students: Christophe van der Walt (RaM), Luc Schoot Uiterkamp (CS), Alexander Wierzba (AM)

This project deals with robotic systems which enable the operator to act as if physically present

in a distant location. These devices, called avatar robots, have multiple applications, such as in disaster response, care or remote surgeries. The goal is to apply a person's skills and knowledge in hard-to-reach or/and dangerous environments and enable long-distance social connectedness.

Avatar systems consist of three parts: the avatar is located in a remote environment, a control pod from which the avatar can be controlled, and a structure consisting of VR and control algorithms to control the pod and the avatar following three goals. First, the operator must be isolated from the outside world. Secondly, the operator must experience the realistic stimuli on the measurements of the remote environment, such as temperature and counter-pressure. Lastly, the intuitive controls must result in almost the same movements of the avatar as of the operator simultaneously.

One of the main challenges is inevitable delays in the loops, such as a delay in the information transformation between the avatar and the operator. This delay problem is tackled by predicting how the avatar's environment will respond and using this in the feedback to the operator. PACoF is an interdisciplinary collaboration with robotics and computer science. The mathematical part will focus on developing novel control techniques to ensure that the avatar and operator are provided with undelayed information based on continuously updated models by the delayed communication. Methods may combine energy-based modelling and model-free control techniques. A discussion of the challenges can be found in the following article on the project, https://www.utwente.nl/en/news/2020/12/883516/improved-remote-control-of-robots.

B.4 Lower bounds for the bias-variance trade-off

Author: Johannes Schmidt-Hieber

The bias-variance trade-off is a widely observed phenomenon in nonparametric and high-dimensional statistics. Methods with too few parameters are not flexible enough and this results in a large deterministic error (bias). On the contrary, using too many parameters leads to overfitting and an exploding variance. Plotting the statistical risk (= squared bias + variance) in dependence on the number of parameters, such a bias-variance trade-off then typically looks like a U-shaped curve.

Modern machine learning operates in the overparametrized regime and next to the U-shaped curve predicted by the classical bias-variance trade-off, the risk decreases a second time for highly overparametrized models. This so called double descent phenomenon has given raise to many claims about the validity of the bias-variance trade-off.

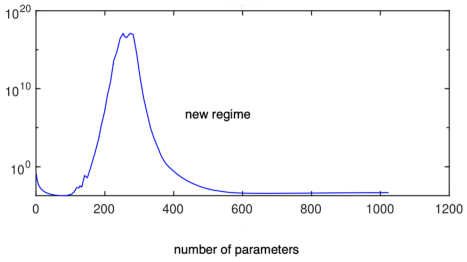

Figure 4: Double descent curve for the random Fourier model.

We were able to propose a general strategy to prove universal lower bounds for the bias-variance trade-off. For that we derive a number of change of expectation inequalities that connect bias and variance. Those are inequalities that lower bound the variance of a random variable by common information theoretic measures and the gap that occurs if the expectation is evaluated under different distributions. Applied to standard non-parametric and high-dimensional models, it is shown that weaker and stronger versions of the bias-variance hold that are universal and apply to all estimation procedures. While we can show that the U-shaped curve is unavoidable in function estimation and that any rate-optimal statistical procedure necessarily has to balance squared bias and vari-

ance, we also prove that the bias-variance trade-off is even more extreme in high-dimensional problems and can lead to sharp phase transition phenomena. The results imply in particular, that the bias-variance trade-off also holds in the overparametrized regime and renders invalid some of the claims in the recent literature.

Derumigny, A. and Schmidt-Hieber, J: *On lower bounds for the bias-variance trade-off.* ArXiv:2006.00278

B.5 Algorithms, Uncertainty & Distributed Data

Author: Marc Uetz

One of the major challenges in the design and theoretical analysis of algorithms for discrete optimization problems is uncertainty about input data. This is captured by methods in optimization that go by well-known names such as online, robust, or stochastic optimization. Moreover, methods differ in the underlying paradigms, with an arsenal of worst- or average-case analyses.

Orthogonal to that development, one observes that optimization may no longer happen in isolation, but as part of larger (ICT) infrastructures, which calls for an understanding of the performance of algorithmic techniques in decentralized systems. Classical examples are traffic or energy networks.

The department contributes to several new developments in these areas with a number of staff members, with a particular focus on providing a better understanding of the theoretical performance of algorithmic techniques, and as a result, improved algorithmic designs and mechanisms. We give a brief account of some successes in this research direction.

Smoothed Analysis is a probabilistic analysis of the performance of algorithms under the assumption of (small) random pertubations of the input. Bodo Manthey, together with several PhD and MSc students is at the forefront of this research direction, with funding by two NWO grants, an advanced Mastermath course on "Algorithms Beyond the Worst Case", and a recently published book chapter:

Manthey, B.: Smoothed Analysis of Local Search: In: Beyond the Worst-Case Analysis of Algorithms. T. Roughgarden (ed.), Cambridge UP, 2020.

Algorithms under Uncertainty is the analysis of (discrete) algorithms under uncertain inputs. Ruben Hoeksma, newly appointed assistant professor via the Sectorplans, has contributed to a re-ignition of research on optimal stopping theory, which owes its interest because of its relation with the analysis of posted price mechanisms. This has also led to a recent survey:

Correa, J., Foncea, P., Hoeksma, R., Oosterwijk, T. and Vredeveld, T: Recent developments in prophet inequalities, ACM SIGecom Exchanges 17, 2018, 61-70.

Since two decades, Marc Uetz is a driving force for research on scheduling under uncertainty, and in 2016 was invited to the Simons Institute (UC Berkeley), for a semester programme on "Algorithms and Uncertainty". Two recent breakthrough results in this area are:

Skutella M, Sviridenko M, Uetz M: Unrelated machine scheduling with stochastic processing times. Mathematics of Operations Research 41 (3), 851-864, 2016.

Gupta V, Moseley B, Uetz M, Xie Q: Greed works — online algorithms for unrelated machine stochastic scheduling. Mathematics of Operations Research 45 (2), 497-516, 2020.

Learning Augmented Algorithms are a recent trend in the design and theoretical analysis of algorithms. One seeks to understand the potential benefits of a combination of the worst-case

paradigm of algorithm design on the one hand, and (machine) learning on the other hand. The goal is to obtain provably better performance in case the learner is good, but not give in too much in case the learner is bad. This combines the "best of both worlds". A success in this direction has recently been obtained by newly appointed assistant professor A. Antoniadis:

Antoniadis, A., Gouleakis, T, Kleer, P, Kolev, P: Secretary and Online Matching Problems with Machine Learned Advice, 34th Conference on Neural Information Processing Systems (NeurIPS 2020).

Algorithmic Game Theory is addressing problems where the alignment of the incentives of individuals is necessary. The classic example is traffic, where individually choosing shortest paths may lead to traffic jams and overall bad performance. This calls for the analysis of equilibria, a.k.a. the price of anarchy, and the design of systems which lead to provably better equilibria, known as mechanism design. Antonios Antoniadis, Ruben Hoeksma, Alexander Skopalik, and Marc Uetz have had fundamental contributions in this area, highlighted by sample results:

Hoeksma R, Uetz M: Optimal mechanism design for a sequencing problem with two-dimensional types, Operations Research 64 (6), 1438-1450, 2016.

Correa J, Foncea P, Hoeksma R, Oosterwijk T, Vredeveld T: Posted price mechanisms for a random stream of customers, ACM Conference on Economics and Computation (EC 2017), Journal paper in Mathematics of Operations Research, 2021.

Gerstgrasser M, Goldberg P, de Keijzer B, Lazos P., Skopalik A: Multi-unit bilateral trade, 33rd AAAI Conference on Artificial Intelligence (AAAI 2019).

Antoniadis A, Cristi A, Oosterwijk T, Sgouritsa A: A general framework for energy-efficient cloud computing mechanisms, International Joint Conference on Autonomous Agents and Multiagent Systems (AAMAS 2020).

Disser Y, Fearnley J, Gairing M, Göbel O, Klimm M, Schmand D, Skopalik A, Tönnies A: Hiring secretaries over time: The benefit of concurrent employment, Mathematics of Operations Research 45 (1), 323-352, 2020.

Tributed to the increased importance and general interest in this area, Guido Schäfer from CWI and Marc Uetz have recently set up a new LNMB PhD course on "Algorithmic Mechanism Design" addressing some of the fundamentals in mechanism design theory (AMD).

B.6 Healthcare Logistics

author: Richard Boucherie

Healthcare expenditures are rapidly growing and in western countries are expected to increase to roughly 20% of GDP in 2035 under the current resource allocation policies. This increase is partly due to improved medical techniques and devices, but to a large extent due to our ageing population. Sustaining the current quality of care seems to require increasing capacity, which is in stark contrast with the unavailability of workforce such as due to ageing or illness as observed in times of COVID-19. Our take on sustaining care is based on developing logistical solutions to maximize the use of resources in a unique collaboration of operations research groups from the faculties EEMCS and BMS, with healthcare organisations across the Netherlands via the Center for Healthcare Operations Improvement and Research (CHOIR). This guarantees a scientific approach to healthcare optimisation in which we thrive to bridge the gap between scientific research and practice. This collaboration also extends to the CHOIR spin-off Rhythm B.V. This eco-system organises a PDEng programme in which so-far 3 PDEng students completed their projects with their results implemented in the ICT environment of the healthcare

organisation that supported their projects. PhD students work in close collaboration with the healthcare organisation that provides funding for their research and achieve balance between applied and fundamental research. PhD students spend approximately 50% of time in their funding healthcare organisation via co-appointments. Since the start of CHOIR 14 PhD students (of which 9 since 2015) completed their projects, and 9 PhD students are currently active of which 8 are funded by healthcare organisations. In addition, via a researcher-in-residence scheme, junior staff (assistant professor and postdoc) is affiliated with a hospital for 0.2 fte via co-appointments. Senior staff acts as advisor in interventions in healthcare organisations. Research finds commercial implementation in interventions and tooling via Rhythm B.V.

An overview of several lines of research within CHOIR aiming to deliver healthcare to the right patient at the right time by the right healthcare practitioner is provided in the handbook

M.E. Zonderland, R.J. Boucherie, E.W. Hans, N. Kortbeek, editors, Handbook of Healthcare Logistics – Bridging the Gap between Theory and Practice, International Series in Operations Research and Management Science, Vol 302, Springer, 2021.

Multi-appointment planning involves developing the theory for fast algorithms in integer linear programming, and Markov decision theory. The resulting algorithms allow for fast re-allocation of appointments in intricate appointment schemes required due to e.g. delayed or cancelled appointments. Aim is develop a decision support system in which patients can book their appointments, are notified of changes in their appointment schemes, such that the system re-optimises the appointments for all patients to maximise availability of healthcare. Results are implemented in hospital laboratories, one-stop-shop outpatient clinics, rehabilitation centers, and cancer diagnostics and treatment centers.

P.J.H. Hulshof, M.R.K. Mes, R.J. Boucherie, E.W. Hans. Patient admission planning using Approximate Dynamic Programming, **Flexible Services and Manufacturing Journal** 28, 30–61, 2016.

A.G. Leeftink, R.J. Boucherie, E.W. Hans, M.A.M. Verdaasdonk, I.M.H. Vliegen, P.J. Van Diest. Predicting turnaround time reductions of the diagnostic track in the histopathology laboratory using mathematical modelling. **Journal of Clinical Pathology** 69, 793–800, 2016.

Patient flow forecasting involves queueing theory and statistical forecasting. The resulting algorithms allow for prediction of the number of patients in a hospitals' clinic, diagnostics center, or treatment center several weeks or months ahead of time based on historical data available in the hospital's data centers. Aim is to develop and implement a hospital wide decision support environment to align resources and demand for care. Results are implemented in several hospitals to align capacity of the operating theater and the clinic, and match capacity of diagnostics (e.g., radiology) and treatment (e.g., physiotherapy) with the outpatient clinic appointment schedule.

N. Kortbeek, A. Braaksma, C.A.J. Burger, P.J.M. Bakker, R.J. Boucherie. Flexible nurse staffing based on hourly bed census predictions, **International Journal of Production Economics** 161,167 – 180, 2015.

S. Baas, S. Dijkstra, A. Braaksma; P. van Rooij, F.J. Snijders, L. Tiemessen, R.J. Boucherie. Real-time forecasting of COVID-19 bed occupancy in wards and Intensive Care Units. **Health Care Management Science** 24, 402-419, 2021.