Midterm Research Evaluation Mathematics

2015–2018

Department of Applied Mathematics

University of Twente

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Head of Department:

Prof. S.A. van Gils (05/2016-05/2019)
Prof. R.J. Boucherie (04/2013-04/2016)

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 for the midterm evaluation.

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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
ET	Faculty of Engineering Technology
EEMCS	Faculty of Electrical Engineering, Mathematics and Computer Science
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

1 Research Area and Objective

1.1 Research Area / Research lines

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 through abstraction the development of 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: 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 discretization, uncertainty quantification and finite element methods with associated stochastic algorithms are main directions of research. Prominent examples of application are in (multiphase) fluid mechanics, nonlinear waves, neuroscience and electromagnetism.

Mathematical modeling: Powerful mathematical methods are developed for systematic modeling of problems in multidisciplinary applications. Expertise in variational analysis is adopted for medical imaging and kinetic equations. 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.

Systems and control: High-tech systems are becoming increasingly complex, whereas the required specifications are becoming tighter. Simple classical linear controllers can often no longer provide this. Better models are therefor required, such as models described by PDEs or decentralized models with the interconnections modeled via a graph. Techniques for the estimation of the model parameters must be improved to handle intrinsic nonlinearities as well as the increasing number of sensors. Control theory needs to be able to handle constraints and decentralized structures, while still meeting challenging specifications.

MOR

The MOR cluster combines the chairs of Discrete Mathematics and Mathematical Programming (Uetz), and Stochastic Operations Research (Boucherie). From the end of the review period (Dec. 2018), the MOR cluster also includes the new chair in Statistics (Schmidt-Hieber). Research topics include:

Mathematical optimisation: Aims at the development of techniques for the efficient solution of optimisation problems, ranging from combinatorial optimization and mixed integer programming to nonlinear optimization problems. Specific strengths lie in the design and analysis of algorithms, including probabilistic and smoothed analysis, as well as algorithmic game theory to address situations with more than one decision maker. 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.

Statistics: Will be part of a larger, multidisciplinary data science center at the faculty level. The new chair in mathematical statistics is appointed as of december 2018. The research topics of the mathematical statistics group will specifically focus on mathematical theory for deep neural networks.

1.2 Vision, Mission and Objectives

Vision

Modern society is more than ever dominated by systems influenced by breakthroughs in mathematical sciences. Close interaction and collaboration between mathematics and its application domains in academia and society enable progress both in mathematics and its application areas.

Mission

The mission of the Department of Applied Mathematics is to advance mathematics through research and teaching, developing state-of-the-art research in computational science and operations research, and making progress in applications of societal and technological relevance.

Objectives

Our objective is training of high potentials in mathematical sciences as well as contributing to research in mathematics. In applications we focus on systems that are crucial to every-day life. We contribute to smart grids that make energy networks more efficient, mathematical models that assist medical doctors, schedules that make hospitals more efficient and numerical schemes to study multiscale fluid problems and wave progagation from nano to kilometer scales.

1.3 Strategy

General embedding

The UT has a long tradition of co-operation between different disciplines, including the social sciences. It is the strategy of the Department of Applied Mathematics to actively engage in collaborative projects within and across the faculty. These activities are stimulated by the research institutes: DSI for ICT-related research, MESA+ for nanotechnology, and TechMed for biomedical technology and technical medicine.

Fundamental and applied research

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

Data science

The Department strives for a closer collaboration with Computer Science. As an example, it was recognized during the review period that it is crucial to have data science more prominently visible in the faculty. The three disciplines of the faculty now join forces to build a datascience cluster. It has motivated the department to actively search for a professor of modern statistics resulting in the appointment of Johannes Schmidt-Hieber as of December 1, 2018. Within the department we have created a core of people that contribute to the faculty wide datascience initiative: Jasper Goseling (Network Information Theory), Marie-Colette van Lieshout (Spatial Statistics), Nelly Litvak (Complex Networks), Christoph Brune (Medical Imaging) and Johannes Schmidt-Hieber (Statistics). Data Science within the department will bridge activities between the MOR and SACS cluster and will also strengthen our ties with Computer Science. We have a vacancy in statistics, that allows Scmidt-Hieber to appoint an UD and to start building a statistics group.

Energy

Another strategic orientation of the department is a growing engagement in decentralized energy management (DEM). Indeed, within the University of Twente, the topic 'Sustainability' has gained central attention lately, and is chosen as one of the main research areas for the upcoming years. The department is represented in this activity by Johann Hurink, who leads the group on smart energy systems, and is also a member of the core team Energy Transition@UT.

Young talent

The Department invests in young mathematical talent. Since 2015 we have appointed five young staff members (Matthias Schlottbom, Kathrin Smetana, Dietmar Gallistl, Alexander Skopalik, Aleida Braaksma). It is not always easy to keep talented young staff members. Three of them left during the review period: Paolo Frasca, Peter Dickinson and Arnoud Den Boer.

Young staff members are intensively coached when writing proposals. This has lead to several highly ranked proposals including several personal interviews, yet unfortunately no personal grant was funded in the review period. Coaching of young staff is not restricted to personal grants. For example, senior staff was actively involved in the preparation of a successful research proposal for the DeepNL program.

Not only tenure trackers, but also junior UDs get a reduction of their teaching load to facilitate grant writing. We limit the number of tenure track positions, as we want to be able to guarantee a chair for successful tenure trackers. At present, Christoph Brune, Matthias Schlottbom, Jasper Goseling and Bodo Manthey are the staff members in tenure track positions.

An implementation of the strategy into concrete actions for the coming years, in line with the upcoming Sector Plan for mathematics, is worked out in the roadmap in Section 7.

1.4 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). The dean of EEMCS, together with the portfolio holders for education, research and management, and a student assessor form the board of the faculty. At the level of the university, there are three research institutes: DSI for ICT-related research, MESA+ for nanotechnology, and TechMed for biomedical technology and technical medicine. The role of the institutes has changed during the review period. At the faculty level, strong disciplines are supported, while the research institutes promote the development of larger programs across the faculties.

The Department is actively involved in three of the four Dutch Mathematics Clusters, namely DIAMANT, NDNS+ and STAR.

Within the department 6 groups (vakgroepen) are active. The group leaders report to the Dean. These 6 groups together form two clusters (SACS and OR), which are natural research units. We have just realized a 7th group in statistics (as of December 1, 2018), which is presently part of the MOR cluster. It is envisioned that this group will grow out to a third research line.

2 Resources and Facilities

Within the Department, supported by the board of the faculty, we have a pro-active staff-replacement policy. We have been able to hire five young staff members in the last three years at the level of UD or tenure track. One tenure track position (Manthey) was converted in a

permanent position at the UHD level, an intermediate step in the Tenure Track. At the start of 2015, the total research volume of scientific staff amounted to 12 fte (=50% of the total volume of scientific staff). Our target is a total volume of about 40 PhD students financed through external funding. Currently this number is 31. Table 1 shows the numbers for various categories of staff members in the period 2015–2017. Note that "PhD's (not employed)" are PhD students who are employed at another institution, for example at the Foundation for Fundamental Physics (FOM) or at a a hospital, but who work (partly) at the UT and have a UT promotor. The number of fte scientific staff dropped from 30 in 2015 to 27 in 2017. The expalnations is that we had difficulties filling in all vacancies. In 2018 we have been able to fill in almost all positions.

Research Staff and FTE

Total	2015		2016		2017	
	#	FTE	#	FTE	#	FTE
Scientific staff	30	10,41	28	9,56	27	9,38
Researchers (incl.postdoc)	6	2,42	10	3,00	12	5,51
PhD candidates (employed)	25	16,05	21	12,77	18	10,45
PhD candidates (not employed)	28		27		22	
Visiting fellows (> 3 months)						
Total res. Staff	**89**	**28,88**	**86**	**25,33**	**79**	**25,34**

MOR	2015		2016		2017	
	#	FTE	#	FTE	#	FTE
Scientific staff	16	5,64	15	4,97	14	4,75
Researchers (incl.postdoc)	2	0,15	3	0,37	4	1,95
PhD candidates (employed)	13	8,68	12	7,40	12	6,63
PhD candidates (not employed)	15		16		12	
Visiting fellows (> 3 months)					0	
Total res. Staff	**46**	**14,48**	**46**	**12,74**	**42**	**13,34**

SACS	2015		2016		2017	
	#	FTE	#	FTE	#	FTE
Scientific staff	14	4,77	13	4,59	13	4,62
Researchers (incl.postdoc)	4	2,27	7	2,62	8	3,56
PhD candidates (employed)	12	7,37	9	5,37	6	3,81
PhD candidates (not employed)	13		11		10	
Visiting fellows (> 3 months)						
Total res. Staff	**43**	**14,40**	**40**	**12,59**	**37**	**12,00**

= not registered

Table 1: Research staff and research-fte.

Table 2 lists the funding available for research during the period of review. The percentage of direct funding is steadily around 80% during this period, as it was in the period of the previous evaluation as well.

3 Research Quality

Rather than summing up all research areas, in the following we choose to present a few sample highlights in some detail.

Research funds

	2015		2016		2017		Average 2012-2017	
Funding	k€	%	k€	%	k€	%	k€	%
Direct Funding	6216	78%	6586	84%	6934	84%	6579	82%
Research grants nat.	849	11%	624	8%	663	8%	712	9%
Research grants inter.	185	2%	63	1%	104	1%	117	1%
Contract Research	753	9%	571	7%	536	7%	620	8%
Other	0	0%	0	0%	0	0%	0	0%
Total Funding	**8003**	**100%**	**7844**	**100%**	**8237**	**100%**	**8028**	**100%**
Expenditure	k€	%	k€	%	k€	%	k€	%
Personelle Costs	5240	86%	4841	86%	5035	88%	5039	86%
Other Costs	878	14%	805	14%	678	12%	787	14%
Total Expenditure	**6118**	**100%**	**5646**	**100%**	**5713**	**100%**	**5826**	**100%**

Table 2: Research funds.

3.1 Research highlights

Finite Element Methods for Wave Problems

A focal point in the research on finite element methods has been the development and analysis of finite element discretizations for complex wave problems, with applications ranging from seismic, electromagnetic to nonlinear water waves. We focused on several important topics: i) preserving the underlying mathematical structure in the finite element discretization and ii) developing more efficient numerical discretizations.

A first example is the development of a novel finite element discretization for the nonlinear inviscid incompressible potential flow water wave equation, which can be written as a potential flow that preserves the Hamiltonian structure, even on time dependent unstructured meshes. This resulted in a numerical discretization with zero numerical dissipation and excellent long-term accuracy [2]. The second example is the computation of light in photonic crystal nanostructures for which a mixed discontinuous Galerkin discretization of the Maxwell eigenvalue problem was developed that preserves the divergence constraint imposed on the electric field. This removed the zero eigenvalues and results in a significant savings in computational cost. For this numerical discretization a detailed mathematical analysis was provided in [22] showing that the computed eigenvalues converge to the exact eigenvalues upon mesh refinement, without the generation of spurious eigenvalues.

Wave computations in complex media also require very efficient numerical methods. We addressed this by deriving efficient time-explicit finite element discretizations using mass lumping. By a careful analysis of the mathematical conditions required to preserve numerical accuracy after mass lumping we noticed that the generally used conditions were too strong. This extra freedom enabled us to derive novel third and fourth order accurate quadrature rules for tetrahedra that result in a diagonal lumped mass matrix and also in a stiffness matrix with a significantly smaller number of degrees of freedom, while preserving the order of accuracy of the numerical discretization. These new quadrature rules give an order of magnitude reduction in computational cost and make for instance finite element methods now more attractive for seismic computations [10].

Port-Hamiltonian systems

There is a natural tension between (mathematical) systems theory, and (engineering) control theory. Roughly speaking, system theory aims to prove general theorems, whereas control theory aims to make a specific plant behave according to design specifications. So, there can be a gap between both theories. The class of port-Hamiltonian systems, introduced by Bernhard Maschke and Arjan van der Schaft, bridges this gap, since it studies systems from a clear physical point of view. For instance, notions as energy and power play a central role. This class has a nice and clear mathematical structure, whereas at the same time many physical systems are an element of it, see e.g. [29]. Although initially the focus was not on existence theory, the existence results for port-Hamiltonian systems described by a linear p.d.e. on a one dimensional spatial domain are very simple and intuitive. The simplicity of the conditions to be checked, combined with the fact that many physical systems are port-Hamiltonian, makes it a perfect class to teach control of p.d.e.'s to e.g. engineering students. Over the past years, his has been done frequently and with great success. Among others, it has led to the book with Birgit Jacob [19]. The existence results has been extended to higher spatial domain, and although the proof becomes technically harder the nature of the results stays the same, [21]. Since the energy is a key concept within this class, it is only naturally to use this for stabilizing controller design. That controllers who decrease the energy indeed stabilize the system was shown in e.g. [26]. These controllers can be non-linear, have saturation, etc., and so this class represents realistic controller models.

Naturally, the research on port-Hamiltonian systems will be continued. Future topics, on which we want to focus are approximations, numerical calculations, and existence results for port-Hamiltonian systems with constraints. The research on numerical simulation and error estimation will be done in close collaboration with e.g. Jaap van der Vegt and is closely related to the previous research highlight. First results on port-Hamiltonian systems with constraints described by differential algebraic equations have been published very recently in [1]. For this research topic, the collaboration with Volker Mehrmann will be continued.

Algorithmic Game Theory

Several members of the MOR cluster work in algorithmic game theory (Jasper de Jong, Walter Kern, Alexander Skopalik, Judith Timmer, Marc Uetz). This is a relatively young area that has formed since 1999 with three influential publications [25, 27, 20]. It is located on the intersection of Mathematics, Computer Science and Economics, and has applications wherever decisions involve more than one decision maker, prime examples being market designs (such as auctions) and congestion games (such as traffic).

This activity has led to a set of papers in which we contribute to a better understanding of the quality of equilibria in profit sharing and congestion games [4, 5], specifically considering settings where decisions are being taken sequentially [3, 6, 7]. Sequentiality is in many applications more appropriate, and leads to the analysis of subgame perfect instead of Nash equilibria. In some cases sequential decisions lead to a significant reduction of what is known as the price of anarchy [6, 7]. Quite surprisingly, however, for network routing games we even prove an unbounded price of anarchy [3]. Deeper understanding of the Mathematical primitives behind these previously unknown phenomena is ongoing research.

We also made progress in mechanism design problems where one seeks a system of (monetary) incentives so that equilibrium outcomes are at least approximately optimal. For the multi-unit-variant of the fundamental problem of bilateral trade, we gave a complete characterization and mechanisms that approximate the social welfare [11]. In the context of classical scheduling

problems, we have derived new mechanisms both optimal and with provable worst-case performance [17, 8], and we recently solved an open problem on the polynomial time solvability of a mechanism to minimise total costs [18]. Generally, market and mechanism design problems play an important role also in the economic design of future energy grids.

Information Theory

In this line of work we propose to use physical-layer network coding for wireless multiple access communication. Simultaneous transmissions in such a network lead to interference and the prevalent way of dealing with interference has been to consider only one of these signals, while treating the other signals as noise. This has the drawback that simultaneous transmissions lead to a destructive collision in which the receiver does not obtain any information and that, therefore, transmissions need to be scheduled over time. We propose to embrace interference instead of battling it: Physical-layer network coding is used, such that in the presence of simultaneous transmissions, the receiver obtains a linear combination of the individual messages. Over several rounds of transmission, the receiver can thus obtain more linear combinations and eventually recover all original messages.

We obtained the throughput that is achieved by this strategy in closed-form making use of a random coding argument in [12] and showed that this throughput is significantly superior to the best-known strategies, including multipacket reception. In follow-up work [14] we introduced signature codes to address the issue of detecting which users are active. In [13] we introduce an efficient feedback and control mechanism. We establish the stability region of the resulting system by extending the pseudo-Bayesian approach of Rivest. Moreover, we demonstrate that at realistic packet sizes the overhead imposed by network coding and the feedback mechanism is negligible.

3.2 10 Top-publications SACS

1. G.L. Kooij, M.A. Botchev, **B.J. Geurts**, (2017). A block Krylov subspace implementation of the time-parallel Paraexp method and its extension for nonlinear partial differential equations. Journal of computational and applied mathematics, 316, 229-246.

   To be efficient on massively parallel platforms, algorithms need to employ all possible means to parallelize computations. When solving partial differential equations (PDEs) with a time-dependent solution, an important way to parallelize the computations is, next to the parallelization across space, parallelization across time. This adds a new dimension of parallelism with which the simulations can be implemented. We present a new time-parallel integration method extending 'Paraexp' to nonlinear partial differential equations using Krylov methods and waveform relaxation.

2. L. Zeune, G. van Dalum, L.W.M.M. Terstappen, **S.A. van Gils, C. Brune**, (2017). Multiscale Segmentation via Bregman Distances and Nonlinear Spectral Analysis. SIAM Journal on Imaging Sciences, 10(1), 111–146.

   This work combines nonlinear variational segmentation models with scales space theory. Based on Bregman distances and spectral decompositions, nonlinear eigenvalue problems are solved numerically and show impact in biomedical imaging under challenging conditions with uncertainty.

3. T.L. Eissa, K. Dijkstra, **C. Brune**, R.G. Emerson, M.J. Van Putten, R.R. Goodman, **S.A.**

van Gils, (2017). Cross-scale effects of neural interactions during human neocortical seizure activity. Proceedings of the National Academy of Sciences, 114(40), 10761-10766.

Despite enormous efforts to understand the functioning of the brain under normal and pathological conditions, many questions are wide open. 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 inhibition in the brain. Brain activity at the millimeter scale registered by a so called Utah array *was modeled by a neural field, which proved to be a very successful tool since their introduction in the seventies by Hugh Wilson and Jack Cowan. The interaction between the neural field and the neural mass allowed to hypothesize the role of feedforward inhibition in cortex.*

This work combines nonlinear variational segmentation models with scales space theory. Based on Bregman distances and spectral decompositions, nonlinear eigenvalue problems are solved numerically and show impact in biomedical imaging under challenging conditions with uncertainty.

4. B Al-Hdaibat, W Govaerts, **YA Kuznetsov, HGE Meijer** (2016). Initialization of homoclinic solutions near Bogdanov–Takens points: Lindstedt–Poincaré compared with regular perturbation method, SIAM journal on applied dynamical systems 15 (2), 952-980.

   Many important results for nonlinear systems involve homoclinic orbits, including travelling 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. Moreover, we conjecture a relation between the results of two methods to obtain the asymptotics.

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

   The solution of large-scale time-dependent wave problems, in e.g. seismics or electrodynamics, requires extremely efficient explicit time integration methods and spatial discretizations. A key benefit of discontinuous Galerkin (DG) methods versus standard finite element methods is that a (block) diagonal mass matrix is obtained, which does not require the solution of a large linear system during each time step. In this article, both optimal time step bounds and penalty terms for the DG discretization of hyperbolic wave equations are provided, which significantly increase the stable time step for explicit time integration methods and the numerical accuracy of the DG discretization. This resulted in a large improvement in the computational efficiency of explicit DG discretizations for time-dependent wave problems. A very important result is that these time-step bounds and penalty terms hold for generic meshes, including unstructured nonconforming heterogeneous meshes of mixed elements and apply to a large class of wave problems, including the (an)isotropic elastic wave equation and the Maxwell equations. So far only results were available on simple structured meshes.

6. H. Egger, **M. Schlottbom** (2016). A class of Galerkin schemes for time-dependent radiative transfer. SIAM Journal on Numerical Analysis, 54(6), 3577-3599.

   The numerical solution of radiative transfer problems is challenging due to the high-dimensionality and the anisotropic structure of the underlying integro-partial differential equations. In this paper we develop a variational formulation for the time-dependent ra-

diative transfer equation that inherits basic structural properties of the underlying equations such as exponential decay to equilibrium. The key step is to rewrite the radiative transfer equation as a system of evolution equations, which has a similar structure to first order hyperbolic systems in acoustics or electrodynamics. We provide a rigorous a priori error analysis by taking the example of a spectral mixed finite element method combined with an implicit Euler time discretization. The generalization of our arguments to other time stepping schemes used in acoustics or electrodynamics, such as the leap frog scheme, is straight forward.

7. Z. Lu, A. Cesmelioglu, **J.J.W. van der Vegt** (2017). Discontinuous Galerkin Approximations for Computing Electromagnetic Bloch Modes in Photonic Crystals. Journal of scientific computing, 70(2), 922-964.

   Photonic crystals are lattice-like nanostructures with a periodic electric permittivity. For specific electric permittivities, they possess photonic band gaps in which the propagation of light with specific frequencies is prohibited inside the photonic crystal. This gives many possibilities to manipulate light at the nano-scale. Using Bloch/Floquet theory for periodic differential operators a Maxwell eigenvalue problem is obtained on a unit cell. We could significantly reduce the cost of solving the eigenvalue problem for the time-harmonic Maxwell equations by explicitly enforcing the divergence constraint using a mixed discontinuous Galerkin (DG) discretization. In this formulation nearly all zero eigenvalues are removed, which resulted in about 50% less eigenvalues to be computed, and also improved the efficiency of the iterative eigenvalue solver when computing the smallest non-zero, physically most interesting eigenvalues. In order to ensure that no spurious eigenvalues are computed we conducted a detailed a priori error analysis of the mixed DG discretization of the time-harmonic Maxwell eigenvalue problem. This analysis shows that the DG discretization converges to the exact eigenvalues with the correct multiplicity and without spurious eigenvalues.

8. A. Macchelli, Y. Le Gorrec, H. Ramírez, **H. Zwart**, (2017). On the synthesis of boundary control laws for distributed port-Hamiltonian systems, IEEE transactions on automatic control, 62 (4), 1700-1713.

   Port-Hamiltonian systems are systems whose dynamic is described via a Hamiltonian function and which have control and observations at the boundary of their spatial domain. For a subclass of port-Hamiltonian systems described by linear partial differential equations, stabilizing controllers is designed. This is done by shaping a new Hamiltonian function using a Casimir function.

9. 14. D. Wu, T. Yang, **A.A. Stoorvogel**, J. Stoustrup, (2017). Distributed optimal coordination for distributed energy resources in power systems. IEEE transactions on automation science and engineering, 14 (2), 414-424.

   Driven by smart grid technologies, distributed energy resources (DERs) have been rapidly developing in recent years for improving reliability and efficiency.Emerging DERs require effective and efficient coordination in order to reap their potential benefits. In this paper, we consider an optimal DER coordination problem over multiple time periods subject to constraints at both system and device levels. Fully distributed algorithms are proposed to dynamically and automatically coordinate distributed generators with multiple/single storage. With the proposed algorithms, the coordination agent at each DER only maintains a set of variables and updates them through information exchange with a few neighbors. We show that the proposed algorithms with properly chosen parameters solve the coordination problem as long as the underlying communication network is connected.

10. **F.L. Schwenninger, H. Zwart**, (2015). Zero-two law for cosine families. Journal of

evolution equations, 15 (3), 559-569.

For $C(t), t \geq 0$, being a strongly continuous cosine family on a Banach space, we show that if the difference in norm between $C(t)$ and the identity becomes for large t less than 2, then $C(t)$ converges to the identity. This implication has become known as the zero-two law. We further prove that if this norm inequality holds for all t, then $C(t) = I$ for all t. For discrete cosine families the bound 2 has to be replaced by $\frac{3}{2}$.

3.3 10 Top-publications MOR

1. I. Bomze, J. Cheng, **P.J.C. Dickinson**, A. Lisser (2017). A fresh CP look at mixed-binary QPs: new formulations and relaxations. Mathematical Programming, 166(1-2), 159-184.

   This paper provides a new and unified way of looking at a number of approximations related to quadratic optimisation, both existing approximations and new approximations introduced in this paper. A difficulty connected to solving these approximation problems is that in general they have a nonzero duality gap. We show for the first time that the approximation of smallest computational size will also have the smallest duality gap. We also prove that some commonly known conditions will even imply a zero duality gap.

2. M. Skutella, M. Sviridenko, **M. Uetz** (2016). Unrelated Machine Scheduling with Stochastic Processing Times. Mathematics of Operations Research, 41(3), 851-864.

   Scheduling tasks with uncertain durations has always remained a challenge both in theory and practice of operations research. In earlier work starting from 1999 we showed that methods from combinatorial optimisation can be extended to obtain approximation algorithms also in settings with stochastic inputs. However the unrelated machine model has so far resisted such attempts. This paper solves this open problem for the first time, using a novel time-indexed linear programming relaxation.

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

   The minimum-cost flow problem (MCF) is a fundamental combinatorial optimization problem. The successive shortest path algorithm (SSP) is a very simple algorithm to solve MCF. Although the worst-case performance of SSP is exponential, it is very fast in practice, even faster than many polynomial-time algorithms. In this paper, almost tight polynomial bounds are obtained in the framework of smoothed analysis, explaining its practical performance. Furthermore, the results show that the simplex method for linear programming runs in expected polynomial time on flow polytopes.

4. **R.P. Hoeksma, M. Uetz** (2016). Optimal Mechanism Design for a Sequencing Problem with Two-Dimensional Types. Operations Research, 64(6), 1438-1450.

   Mechanism design is the mathematical science to align incentives of self-interested users. The paper addresses the situation of a waiting line where the service provider only has probabilistic information about the individual cost of time and the required service durations of customers. This paper provides the first polynomial-time solution to solve this Bayesian mechanism design problem optimally, thereby solving an open problem that was posed in earlier work.

5. **T. van der Klauw**, M.E.T. Gerards, **J.L. Hurink** (2017). Resource allocation problems

in decentralized energy management. OR Spektrum, 39(3), 739-773.

Within the framework of decentralized energy management, scheduling flexible loads based on steering signals becomes more important. By using the strong relation of these problems to classical resource allocation problems, efficient algorithms are developed which lead to solutions which approximate optimal solutions to the original, NP-hard problems and can be used in decentralized energy management systems. The basis for the achieved results is the careful analysis of two NP-hard discrete variants of the problems, and their natural relaxations.

6. **M. de Graaf, B. Manthey** (2017). Probabilistic analysis of power assignments. Random Structures and Algorithms, 51(3), 483-505.

   Concentration of measure results for Euclidean optimization problems are known for decades, but only for the case where the distance-power gradient p is smaller than the dimension d of the underlying space. Existing techniques fail to work for larger p. In this paper, concentration of measure results for the case $p \geq d$ are obtained for the first time. These findings are applied to the power assignment problem for wireless networks, where the case $p \geq d$ is of particular interest.

7. **N. Kortbeek, A. Braaksma**, F.H.F. Smeenk, P.J.M. Bakker, **R.J. Boucherie** (2015). Integral resource capacity planning for inpatient care services based on bed census predictions by hour. Journal of the Operational Research Society, 66(7), 1061-1076.

   This paper presents a generic analytical approach to predict bed census on nursing wards by hour, as a function of the Master Surgical Schedule and arrival patterns of emergency patients. The developed method is used in the AUMC-AMC as a decision-support tool in a complete redesign of the inpatient care operations, and provides the foundation of the ICT solution that is now being finalized in our spin-off Rhythm. This solution will be commercially available for hospitals in 2019. This paper illustrates the CHOIR approach bridging the gap between scientific research to a solution in practice.

8. N. Chen, **N. Litvak**, M. Olvera-Cravioto (2017). Generalized PageRank on directed configuration networks. Random Structures and Algorithms 51 (2), 237-274.

   The paper proves the so-called 'power law hypothesis' for PageRank in large random networks. PageRank is the algorithm developed by Google to rank web pages. This is the first time that the distribution of PageRank is formally derived in a specific random graph model. The proofs involve new techniques such as coupling with a branching process, local approximation of PageRank and convergence of empirical distributions to the endogenous solution of a fixed-point equation.

9. **J. Goseling**, M. Gastpar and J.H. Weber (2015). Random access with physical-layer network coding, IEEE Transactions on Information Theory, 61(7), 3670–3681.

   This paper proposes a physical-layer network coding strategy for the random-access channel, based on compute-and-forward. When packets collide, it is possible to reliably recover a linear combination of the packets at the receiver. Over many rounds of transmission, the receiver can thus obtain many linear combinations and eventually recover all original packets. This is in contrast to current approaches to random access, like slotted ALOHA, where packet collisions lead to complete erasures. The strategy is shown to be significantly superior to the best known strategies, including multi-packet reception.

10. O. Cronie and **M.N.M. van Lieshout** (2018). A non-model based approach to bandwidth selection for kernel estimators of spatial intensity functions. Biometrika 105(2), 2018, 455-462.

Kernel smoothers are widely used to estimate the intensity function of a spatial point process, that is, the likelihood of finding a point as a function of location. The amount of smoothing is governed by a 'bandwidth' parameter that is notoriously hard to set appropriately because its theoretically optimal value depends on the unknown moments of the point process. In practice, rules of thumb are being used. They require numerical evaluation of integrals or make unrealistic assumptions on the underlying point process. This paper proposes a new, fully non-parametric bandwidth selection method that does not require knowledge of moments. The approach is also computationally straightforward and does not require numerical approximation of integrals.

3.4 Activities & Distinctions

Members of the department are active and serve in their respective communities, in the form of editorships of journals, memberships in programme commitees, memberships in panels for research funding, etc. In the table below we list overall numbers of editorships, conference organization, long term visitors and long term visits. Involvement in editorial tasks is rather high, compared to the fte staff members. For example is Uetz is Area Editor for Operations Research Letters, Litvak is Managing Editor for Internet Mathematics and Boucherie was Editor in Chief of "Nieuw Archief voor de Wiskunde" (until 2016). Other positions in editorial boards include the Journal of Scientific Computing, Journal of Mathematical Analysis and Applications, Journal of Mathematical Neuroscience, Mathematics of Control, Signals, and Systems, Discrete Optimization, Journal of Scheduling, and OR Spectrum, to name just a few. Several staff members also have international positions at partner Universities, for example with Washington State University (Stoorvogel), the University of Chicago (van Gils), or the University of Science and Technology (van der Vegt). Invitations of staff members as long-term visitors or as invited lecturers at summer schools include the University of California at Berkeley, the Technical University Berlin, the RWTH Aachen, and others.

Activities

Type	2015	2016	2017
Publication peer-review and editorial work -			
Editorial work	26	29	30
Membership -			
Membership of committee	9	12	13
Participating in or organising an event -			
Organising a conference, workshop, ...	12	12	12
Visiting an external institution -			
Visiting an external academic institution	0	1	2
Hosting a visitor -			
Hosting an academic visitor	1	3	7

Table 3: Editorships, conference organization, long term visits and visitors.

3.5 Cooperation with China

In the review period, several members of the department have established and intensified strategic alliances with Chinese Universities. Specifically, these activities include the University of

Science and Technology (USTC) in Hefei, which is operated by the Chinese Academy of Sciences, where van der Vegt is a research fellow and visiting professor on a yearly basis since 2012. With the Northwestern Polytechnical University (NPU) in Xi'an, Uetz (together with Broersma from the Computer Science department) has recently established a joint research institute for fundamental research into "Networks, Economic Decisions and Optimization" (NEDO). This institute serves as a catalyst for staff and student exchange, including a double-badged PhD program under which first two Chinese PhD students will soon defend their PhD theses in Twente.

3.6 Research Output

In Table 4 below we list the research output during the period of the midterm-evaluation. The number of PhD thesis is in the order of 10 per year, which aligns with our target to have approximately 40 PhD's in the department. Refereed articles have been almost at the same level, which is satisfactory.

Research outputs

Organisational unit	SEP output type	2015	2016	2017
MOR	Book	1	0	2
	Refereed article	39	42	34
	Non-refereed article	7	3	0
	Book chapter	3	1	6
	PhD thesis	5	5	8
	Conference paper	16	19	14
	Professional publication	13	7	5
	Publications aimed at the general public	1	0	1
	Other research output	1	2	6
SACS	Book	1	1	0
	Refereed article	48	39	47
	Non-refereed article	0	1	0
	Book chapter	0	0	0
	PhD thesis	5	4	5
	Conference paper	20	24	11
	Professional publication	0	0	0
	Publications aimed at the general public	0	0	0
	Other research output	3	9	13

Table 4: Research output.

4 Relevance to Society

Decentralized Energy Management

The Department in cooperation with Computer Science has taken the lead in establishing a research group on smart energy systems, especially on decentralized energy management

(DEM). Next to 32 publications in journals and refereed international conference proceedings this has led to the development of an energy management concept TRIANA and an underlying steering mechanism called 'profile steering'. These two results are the base for a simulation and control tool called DemKIT which allows the integral control of multiple energy commodities (e.g. electricity, heat, gas) and hardware in the loop simulations. Based on request from academia and practice the tool has been made available as open source tool end of 2018. At this moment the research group has 6 PhD students, one PostDoc and an open PhD position. Furthermore, the group is involved via staff members in an Interreg and an EU twinning project. On 4TU level the group is involved in a broader cooperation (involving also electrical engineering and computer science) of smart grid related researchers and Netbeheer Nederland. To strengthen this cooperation the research group from UT has initiated in 2017 the setup of the workshop 'Energy Open'. This first of these workshops was organized by local group and held in Enschede. It has been setup as an international workshop being held every year rotating between the 4 TUs. Within the University of Twente, the topic 'Sustainability' is gaining central attention and is chosen as one of the main research areas for the upcoming years. The department is involved in this development via Hurink, who was asked by the university board to be a member of the core team Energy Transition@UT.

Operations Research for Healthcare

Since 2003 Hans (IEBIS) and Boucherie (SOR) have been collaborating on the development of Operations Research methods for logistics planning in healthcare. To facilitate sharing of information on Operations Research solutions in healthcare, in 2008 Hans and Boucherie co-founded the Center for Healthcare Operations Improvement and Research (CHOIR). A large share of research results from CHOIR have been adopted by healthcare organizations via prototype planning tools and organizational interventions. To further develop and implement these results, in 2014 Hans and Boucherie, jointly with CHOIR alumnus dr. Nikky Kortbeek, and OR-TEC B.V. co-founded the spin-off Rhythm B.V. that currently has 15 employees. 12 CHOIR PhD students graduated in Operations Research since 2011. Within CHOIR, SOR currently trains 6 PhD and 3 PDEng students. Funding for all current PhD and PDEng students is awarded by healthcare organizations. All PhD and PDEng students are half-time in a healthcare organization and half-time at UT, thereby directly participating in the dissemination of Operations Research methods in healthcare. CHOIR collaborates with approximately 40 Dutch healthcare organizations. The results of CHOIR have been recognized both in healthcare and Operations Research via various awards. CHOIR organizes a bi-monthly seminar on healthcare logistics as well as several larger symposia each year attended by roughly 100 participants from academia and healthcare organizations.

Healthcare logistics is about the right care for each person at the right moment at the right costs, considering constraints of the patient, the care provisioner, the care organization, and society. There is continuing and growing interest in application of optimization of logistics processes in hospitals, as well as in balancing the care chain among and outside hospitals, including e.g. home care, nursing homes, and general practitioners. To reduce societal costs for healthcare, treatment in the care chain will be shifted to the care provisioner that is most suited for the particular treatment. This includes shifting low and medium level care from academic hospitals to peripheral hospitals or even to general practitioners. Models to be developed include game theoretical models to balance care and costs in the care chain, and prediction models that translate demographic changes to future required care. With diagnostics and treatment becoming more and more patient centered, multi-appointment strategies such as one-stop shop and rapid diagnostics are gaining importance. Methods to be developed include strategies for Markov Decision Processes considering future arrivals while assigning

slots for currently treated patients. With data becoming abundant, Personalized Healthcare includes advise and decisions on patients' disease and treatment based on individual patient characteristics such as bio-markers and DNA. Classification of patients in relation to their peers with similar characteristics may allow for adequate advice to the care provisioner on treatment and follow-up schemes for e.g. cancer patients. Methods to be developed include the combination of classification techniques such as machine learning to match each patient as closely as possible to his peers with optimization to determine the best treatment and with Partially Observable Markov Decision Processes to determine optimal follow-up strategies considering the uncertainty and non-observability in development of a disease (e.g. cancer) inside the body in between check-ups.

Epilepsy surgery

Epilepsy surgery is an option for patients that do respond to medication for controlling their seizures. The decision for surgery is difficult, but making surgery more successful for only a few cases already has an enormous societal impact, not just on patients but also on their families. We collaborate with various (inter)national groups that record subdural electrocorticography during the work-up for surgery. Mathematical modelling of the recorded neural activity has indicated how failure of inhibition may lead to the spread of seizures at small scales [23] and how this influences activity at larger distances [9].

Supported by a ZonMW-Translational grant, in collaboration with neurologists from University Medical Center Utrecht, we have set out a path translate results from computational models to clinical protocols. An essential ingredient for these models are networks, which still require a change of mindset for clinicians to interpret their data [15]. Constructing these networks in a novel way has shown that the seizure focus forms a densely connected subnetwork [28], and that seizure spreading evolves along edges of the network [24]. A comparison with traditional approaches shows that the new networks more closely represent known physiological connectivity [16]. These insights have led to various improvements in clinical routine and analysis. Recent advances involve modelling of stimulation induced network activity. This opens the perspective of a computational model for epilepsy surgery with individualized brain models. Such a predictive framework for the outcome of surgery could guide neurosurgeons in a better delineation of the tissue to be removed.

5 SWOT analysis

- Strengths
  - The ability to connect Mathematical research topics to societal relevant themes such as Energy, Health, Neuroscience, Seismicity, Traffic, and more, including a high volume of funding through the second and third money streams, and a strong network of collaborative research institutes, industries and healthcare organizations.
  - Continuous rejuvenation of staff including five new research staff and three new teaching staff, including a significant increase of female researchers; the hiring for three additional, new positions is ongoing. The selection of the candidates aligns with the Department's profile as well as the national research agenda "Sector Plan" in Mathematics.
  - The new group in Statistics forms the basis for the Department's engagement in

the faculties multidisciplinary Data Science center; the new group has a strong link with the SACS cluster.

- Weaknesses
  - Continuous efforts to support personal grant writing has resulted in several top evaluated research proposals including interview invitations, e.g. for VENI and ERC grants, yet no new personal grants have been obtained during the review period; our efforts to support particularly young staff in grant writing are ongoing.
  - The teaching load particularly for senior staff is still substantial and strongly competes with research activities; in particular with grant writing and establishing new research collaborations.
- Opportunities
  - The department's research profile is highly relevant for societal relevant themes such as Energy and Health, and several other high-tech systems, opening future opportunities for funding and collaboration.
  - The department has an excellent position for upcoming themes of societal relevance such as the accountability and reliability of Mathematical methods; e.g. through uncertainty quantification, algorithms and optimization under uncertainty, and the Mathematics of deep learning
- Threats
  - 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.
  - Mathematics is poorly positioned in the national research agenda of the 'Top Sectors' and in 'NWA'. Specifically, there are few thematic programs that fit the fundamental nature of research in Mathematics.

Viability

By appointing junior researchers in tenure track (with reduced teaching) and indefinite term positions, the rejuvenation of staff is being realized.

Junior staff is actively coached in developing their own research position, including training and coaching in the acquisition of (personal) grants.

The research agenda of the department is well aligned with strategic goals of the University of Twente, as well as the national research agenda (sector plans).

6 Recommendations of the previous research assessment

The 2015 Research Assessment Committee formulated a number of recommendations. Below is a brief overview on actions taken to implement these

- *The department is recommended to continue its path of rejuvenation of staff in both programs and make sure that the hiring of young researchers is consistent with the*

strategy.

We have been active to attract new junior members of staff in tenure track and in assistant professor staff positions. The numerical mathematics research in SACS was strengthened by Matthias Schlottbom (TT) and Kathrin Smetana (UD), working in the field of finite element methods. Moreover, in response to one member of staff accepting a position elsewhere, Dietmar Gallistl (UD) was appointed in Twente.

To further strengthen theoretical foundations of optimization problems connected to smart grids, Alexander Skopalik (UD) was appointed, who is working in algorithmic game theory. In order to strengthen the healthcare logistics activity, Aleida Braaksma (UD) was appointed. Moreover, we are in the process of filling a new UD position in "Optimization and Learning".

Finally, by appointing Johannes Schmidt-Hieber, we have re-installed the vacant chair of Statistics with an excellent young researcher. As it is timely to expand our activity in statitics and data science, another vacancy on the UD level in statistics has been opened.

- *The pressure on the senior researchers with respect to the high teaching load should be relaxed.*

  The Department could attract, next to the already mentioned junior staff members, a number of highly motivated teaching staff, both permanent and temporary. In addition, the assignment of research-time to AM staff was reviewed, leading to a more precise identification of tasks, in order to relax the pressure on research time. This process is not completed yet.

- *The strong interdisciplinary cooperation in areas of major societal relevance should be continued. The activities in Smart Grids may be a good start to become involved in the Top-Sector 'Energy'. This would ensure a strong participation of mathematics on a high national level, which is usually very hard to reach.*

  The Department in cooperation with Computer Science has taken the lead in establishing a research group on smart energy systems, especially on decentralized energy management (DEM). Next to 32 publications in journals and refereed international conference proceedings this has led to the development of an energy management concept TRIANA and an underlying steering mechanism called 'profile steering'. These two results are the base for a simulation and control tool called DemKIT which allows the integral control of multiple energy commodities (e.g. electricity, heat, gas) and hardware in the loop simulations. Based on request from academia and practice, the tool has been made available as open source tool end of 2018.

  At this moment the research group has 6 PhD students, one PostDoc and an open PhD position. Furthermore, the group is involved via staff members in an Interreg and an EU twinning project. On 4TU level the group is involved in a broader cooperation (involving also electrical engineering and computer science) of smart grid related researchers and Netbeheer Nederland. To strengthen this cooperation the research group from UT has initiated in 2017 the setup of the workshop 'Energy Open'. This first of these workshops was organized by local group and held in Enschede. It has been setup as an international workshop being held every year rotating between the 4-TUs.

  In 2018, a team of researchers from this cooperation (UT, TUD and TU/e) in cooperation with researchers from RUG and CWI has submitted a Zwaartekracht proposal 'Digital Energy', where Hurink is one of the Co-PIs. Within the University of Twente, the topic 'Sustainability' is gaining central attention and is chosen as one of the main research

areas for the upcoming years. The department is involved in this development at central level via Hurink, which was asked by the university board to be a member of the core team Energy Transition@UT.

Finally, the appointment of Alexander Skopalik (UD) supports the development of mathematical foundations for the design of market mechanisms in future smart energy grids.

- *The experience in the health sector is so excellent that one might consider founding further spinoff companies in that direction.*

  This activity indeed enjoys further growth, with an existing spin-off company for consultancy activities (Rhythm). As mentioned also above, the increased demand for the development of new methods for healthcare optimization under uncertainty was recently translated into the hiring of Aleida Braaksma as a new assistant professor, strengthening the focus on this activity.

- *The university leaders should consider establishing a Project Development Office (PDO) similar to TU Eindhoven, or as a joint activity in 3TU.AMI*

  The department of applied mathematics AM and the faculty EEMCS have taken measures to professionalize the development and support of new research projects - Prof. N. 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 TTW and EU proposals and consortia. Further steps toward a PDO are being developed at UT level.

7 Roadmap

Recent developments in "data science" will have a major impact on future research agendas of both the SACS and the MOR cluster. In the following roadmaps, we sketch these plans in some detail, with the idea that they serve as sketches for future profiles of additional staff to strengthen the respective research directions.

7.1 Roadmap SACS

The availability of very large date sets offers new possibilities and challenges for research within SACS. Data driven science allows the discovery of hidden parameters or functions in dynamical systems from observed data by solving (ill-posed) inverse problems. Also, topics such as uncertainty quantification and model order reduction are rapidly gaining importance. We aim therefore to combine data driven science with our strong research in dynamical systems, scientific computing and mathematical systems theory. This will offer new opportunities to obtain more accurate data driven models, in for instance neuroscience, seismics and turbulence, but also present important mathematical challenges, such as understanding the mathematical properties of these new models and techniques and to derive and analyze accurate and efficient numerical discretizations for these novel approaches.

In the coming years the SACS research team will focus on the following topics in the area of dynamical systems, numerical analysis and scientific computing, and systems and control and in particular, their relation with data science.

(1) *Structure preserving numerical discretizations*. Many important physical problems have a

Hamiltonian structure and contain important symmetries and invariants. Preserving these structures in the numerical discretization and developing efficient numerical algorithms for this class of problems is a great challenge, but if successful, it generally results in superior (long time) numerical accuracy and stability. A focal point will be the analysis and development of numerical discretizations for various classes of wave problems, e.g. seismic and electromagnetic waves. A novel approach is to link the theory of port-Hamiltonian systems to discontinuous Galerkin finite element discretizations.

(2) *Inverse problems, data assimilation and optimal transport on graphs*. Developing and analyzing variational methods and nonlinear, nonlocal regularization techniques for inverse problems under integro-differential equations, reflecting basic neural networks, will be an important research area in the coming years. This research connects to data assimilation, which has been greatly influenced by dynamical systems theory.

When viewed as a collection of points in some possibly high-dimensional space, the shape and clusters of a dataset often reflects important patterns within data and optimal transport on graphs is an important tool in imaging and inverse problems.

(3) *Discovery of equations, model sparsity and uncertainty, deep machine learning for PDEs*. It is a major challenge to turn raw data into models that are not just predictive (data assimilation), but also provide insight into the nature of the underlying dynamical system that generated the data. Model order reduction via reduced basis methods will be of great interest in this context. Also, quantifying uncertainty, both in model-based data assimilation as well as in partial differential equations, is important for many of our research areas (inverse problems, model order reduction).

Deep recurrent artificial neural networks share a lot of structural and numerical similarities with nonlinear dynamical systems and are able to represent complex nonlinear, multiscale maps in a compressible linearizable fashion. Whereas, nearly all past approximation algorithms for PDEs suffered from the well-known curse of dimensionality, deep learning networks are able to tackle this dimensionality reduction efficiently via automatically learned emerging multiscale patterns (wavelet scattering, low-rank methods).

(4) *Control of partial differential equations*. There is a growing need for controller design techniques for systems described by partial differential equations. For instance, for suppression of vibrations in large wings of a windmill or in the wafer stage. In order to develop these techniques, mathematical and physical insight in the models is needed. Port-Hamiltonian models capture the underlying physics, and have at the same time good mathematical properties. The coming years the work on controller design for this class of system will be further extended to non-linear and to descriptor systems, i.e., implicit partial differential equations. Of course for the implementation and testing of the designed controller the results and tools from topic 1 (Structure preserving numerical discretization) will be used.

7.2 Roadmap MOR

Operations Research (OR) has been a field built on applications and data, with at its core the mathematical models for optimal decision making. The profile of the MOR cluster in Twente has had its main focus on two specializations, namely stochastic models (SOR), and algorithms & optimization (DMMP). In the value chain Data→Model→Decisions, the focus has been on mathematical models and optimal decision making. These are and remain core areas in the Mathematics of Operations Research. The recent availability of abundant data

about customers, businesses, and processes, underlines an increased necessity to focus stronger on the *input* side of decision support models, that is, data. That said, we identify the following key developments for the Operations Research cluster in Twente.

Trend: Data-driven methods in optimal decision making. While statistics was always an important activity within Operations Research, in the past years the chair in statistics remained vacant. Our continuing search to fill in this vacancy has resulted in the appointment of A.J. Schmidt-Hieber as full professor in statistics. Statistics is the "mathematics of data science", and in line with the faculty's strategy to establish a data science center, the new chair in statistics will form an integral part of this center. The MSc track on "Data Science" –a new specialization in the MSc program in applied mathematics– is another feature of this development. This allows us to better embrace the *complete* value chain Data→Model→Decisions, and leads to the following research direction.

(1) *Data driven decision making.* One of the challenges is to propagate statistical knowledge on input data through the mathematical models and decisions, e.g. leading to statistical estimates for solutions and decisions, or optimal decisions directly based on data. Here we witness a shift from a classical model-based approach to a data-driven approach. Another challenge is to fine-tune the interaction between data science on the one hand, and the choice and parametrization of mathematical models on the other hand. For example, machine learning could help in reducing search spaces to enable lower computation times for general purpose solvers, or support optimization of personalized healthcare.

From trend to challenge: Accountability and reliability of optimal decision making. Mathematics in general is about exact and provable statements. This general idea of "accountability and reliability" of mathematical models and methods is a strength of the discipline, and an added value to other branches of science and society at large: Think of an optimal instead of just some timetable, an optimized medical treatment, or the best possible matching of energy supply and demand. It is this general motive of "accountability and reliability" which is reflected by the following (future) research directions.

(2) *Mathematics of machine learning.* Statistics undergoes a sharp transition because of the recent success of machine learning for complex large scale data. Algorithmic solutions are being proposed at a high rate, but are often poorly understood and may lead to results that cannot be replicated. Statistical theory is challenged to provide a mathematical foundation for the successes of machine learning. We focus on statistical theory for deep neural networks. Neural networks define function classes that are difficult to analyze because of non-linearity in the parameters. Existing results cannot cope with many of the distinctive characteristics of deep networks such as multiple hidden layers or the rectifier linear unit (ReLU) activation function. Our ambition is to change that, and as a next step in this direction, we focus on manifold learning and statistical analysis of convolutional neural networks.

(3) *Models, algorithms and networks with uncertain inputs.* Considering the value chain Data→Model→Decisions, Operations Research has a wide range of mathematical models to *explicitly* model uncertain input variables, for example via stochastic inputs, stochastic events, worst-case or competitive analysis. One of the challenges for the future is to improve the interface between data and stochastic models, without losing the ability to still analyze such models also mathematically. This leads to robustness concepts for the desired solutions, of which there are several variations. Not all of these are yet fully understood, let alone, practically applicable.

(4) *Algorithms and models for decentralization.* Data and decision making is often locally dispersed and not centrally coordinated. This leads to game theoretic models, with the

necessity to understand equilibria as a prediction of observable outcomes. Mechanism design is the mathematical methodology to align incentives "proactively" in the design of systems, in such a way that desirable outcomes are stable in the equilibrium sense. A future topic is the interface of data, equilibrium models and decision making. Specifically, robustness of the solution concepts under uncertain inputs is a trend that is to be explored.

Continuity in core applications: health, energy, and more. The application areas healthcare logistics and smart energy systems will continue to be central for Operations Research in Twente. In order to support these activities optimally, two new assistant professors have recently been appointed, namely A. Braaksma and A. Skopalik. A. Braaksma develops approximate dynamic programming models with applications in healthcare logistics, and A. Skopalik develops methods in algorithmic game theory that will help to support market mechanisms for decentralized decision support in smart energy systems.

Next to these two application areas, the MOR cluster is maintaining active collaborations with various industry partners such as ORTEC, DAT.mobility, ARS, Mobidot, and the NS, to name a few. These collaborations largely focus on logistics and models for traffic and mobility, and we witness a steep increase in the demand for the development of new and more adaptive mathematical models that allow, e.g, to be calibrated with real-time data. These activities will remain to be relevant also in the future, and provide the societal framework for work in the core mathematical subdisciplines.

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A Appendices

A.1 Research staff at the institute

Research staff and research FTE

	Funding 1/2/3	2015 FTE	2016 FTE	2017 FTE
SACS				
Full professors				
Geurts, prof.dr.ir. B.J.	1	0,40	0,40	0,40
Gils, prof.dr. S.A. van	1	0,40	0,40	0,40
Stoorvogel, prof.dr. A.A.	1	0,40	0,40	0,40
Vegt, prof.dr.ir. J.J.W. van der	1	0,40	0,40	0,40
Zwart, prof.dr. H.J.	1	0,40	0,40	0,40
Associate professors				
Bokhove, dr.ir. O.	1	0,04	0,00	0,00
Polderman, dr. J.W.	1	0,16	0,16	0,16
Assistant professors				
Bochev, dr. M.A.	1	0,40	0,40	0,21
Brune, dr. C.	1	0,16	0,16	0,16
Brune, dr. C.	2	0,24	0,24	0,24
Frasca, dr. P.	1	0,40	0,30	0,00
Mandal, dr. P.K.	1	0,40	0,40	0,40
Meijer, dr. H.G.E.	1	0,40	0,40	0,40
Meinsma, dr.ir. G.	1	0,40	0,40	0,40
Schlottbom, dr. M.	1	0,00	0,13	0,40
Smetana, dr. K.	1	0,00	0,00	0,25
Zagaris, dr. A.	1	0,17	0,00	0,00
Extraordinary chairs				
Kouznetsov, prof.dr. I.A.		0,21	0,21	0,21
Kuerten, prof.dr. J.G.M.		0,21	0,21	0,21
Veldman, prof.dr. A.E.P.		0,21	0,21	0,21
Researchers (incl.postdoc)				
Adytia, dr. D.	2	0,47	0,20	0,00
Dijkstra, dr. K.	1	0,00	0,08	0,60
Frederix MSc, E.M.A.	3	0,00	0,15	0,26
Kalia MSc, M.	1	0,00	0,00	0,15
Kamthe MSc, S.S.	3	0,67	0,00	0,00
Kurnia MSc, dr. R.	2	0,00	0,43	0,47
Lourens, dr.ir. M.A.J.	1	0,00	0,00	0,15
Luiken, ir. N.A.	1	0,00	0,15	0,00
Rossi, dr. W.	1	0,90	0,90	0,90
Staniç, dr. M.	3	0,22	0,00	0,00
Wang MSc, W.	3	0,00	0,72	0,63
Wijaya, dr. A.P.	2	0,00	0,00	0,40
Total Scientific staff SACS		7,66	7,85	8,82

	Funding 1/2/3	2015 FTE	2016 FTE	2017 FTE
MOR				
Full professors				
Boucherie, prof.dr. R.J.	1	0,40	0,40	0,40
Hurink, prof.dr. J.L.	1	0,40	0,40	0,40
Uetz, prof.dr. M.J.	1	0,40	0,40	0,40
Associate professors				
Kern, dr. W.	1	0,40	0,40	0,40
Litvak, prof.dr. N.V.	1	0,40	0,40	0,40
Manthey, dr. B.	1	0,17	0,40	0,40
Still, dr. G.J.	1	0,40	0,40	0,25
Assistant professors				
Boer, dr. A.V. den	2	0,40	0,07	0,00
Braaksma, dr.ir. A.	1	0,00	0,00	0,07
Dickinson, dr. P.J.C.	1	0,16	0,16	0,16
Dickinson, dr. P.J.C.	2	0,24	0,24	0,24
Driessen, dr. T.S.H.	1	0,40	0,06	0,00
Goseling, dr.ir. J.	1	0,40	0,40	0,40
Manthey, dr. B.	1	0,23	0,00	0,00
Ommeren, dr. J.C.W. van	1	0,40	0,40	0,40
Post, dr.ir. G.F.	1	0,04	0,04	0,04
Scheinhardt, dr.ir. W.R.W.	1	0,40	0,40	0,40
Timmer, dr. J.B.	1	0,40	0,40	0,40
Extraordinary chairs				
Dijk, prof.dr. N.M. van		0,63	0,63	0,63
Lieshout, prof.dr. M.N.M. van		0,21	0,21	0,21
Researchers (incl.postdoc)				
Bikker MSc, I.A.	3	0,07	0,00	0,00
Drees, dr. M.W.	1	0,00	0,15	0,75
Klauw, dr. T. van der	2	0,00	0,00	0,82
Kortbeek, dr. N.	1	0,09	0,00	0,00
Reijnders MSc, V.M.J.J.	1	0,00	0,19	0,19
Vrugt, dr.ir. N.M. van de	1	0,00	0,03	0,19
Total Scientific staff MOR		**6,64**	**6,18**	**7,54**
Total Scientific Staff		**14,30**	**14,03**	**16,36**
Support staff				
Kamphuis - Kuijpers, T.	1	0,53	0,53	0,53
Langkamp, M.	1	0,84	0,70	0,00
Mulder, J.M.	1	0,74	0,74	0,74
Slotboom - Plekenpol, M.	1	0,84	0,84	0,84
Wychgel - van Dalm, L.S.J.	1	0,42	0,49	0,63
Total Support staff		**3,37**	**3,30**	**2,74**
Total Staff		**17,67**	**17,32**	**19,10**

A.2 Current research staff at the institute

Name and link to Google Scholar Page
Boucherie, prof.dr. R.J.
Braaksma, dr. A.
Brune, dr. C.
Gallistl, dr. D.
Geurts, prof.dr.ir. B.J.
Gils, prof.dr. S.A. van
Goseling, dr.ir. J
Hurink, prof.dr. J.L.
Kern, dr. W.
Lieshout, prof.dr. M.C[1]
Litvak, dr. N.
Mandal, dr. P.K.
Manthey, dr. B.
*M*eijer, dr. H.G.E.
Meinsma, dr.ir. G.
Ommeren, dr. J.C.W. van
Polderman, dr. J.W.
Post, dr.ir. G.F.
Scheinhardt, dr.ir. W.R.W.
Schlotbom, M.
Skopalik, dr. A.
Smetana, dr. K.
Stoorvogel prof.dr.A.A.
Timmer, dr. J.B.
Uetz, prof.dr. M.J.
Vegt, prof.dr.ir. J.J.W. van der
Schmidt-Hieber. prof.dr.J

[1] No Google Scholar Page available

A.3 Externally funded projects

Research funding period 2015 - 2017

Department	Projectnaam (kort)	Project Manager	Opdrachtgever	Status	Begindatum	Project Finish Date	Einddatum	Subsidie
MOR	EIT HEGRID INTEGRATION	Hurink , J.L.	extern: EIT DIGITAL HEADQUARTERS OFFICE	Gest2015	1-1-2014	1-4-2015	1-1-2015	€ 50.000,00
	HEGRID 2015	Hurink , J.L.	extern: EIT DIGITAL HEADQUARTERS OFFICE	Gest2016	1-1-2015	1-4-2016	1-1-2016	€ 65.500,00
	GRIF	Hurink , J.L.	extern: ENEXIS NETBEHEER BV	Lopend	1-1-2017	1-4-2021	1-1-2021	€ 213.885,00
	ORCCL	Boucherie , R.J.	extern: ERASMUS MEDISCH CENTRUM	Lopend	1-10-2017	1-2-2022	1-11-2021	€ 200.000,00
	NADINE	Litvak , N.V.	extern: EUROPEAN COMMISSION	Gest2015	1-5-2012	31-12-2015	1-5-2015	€ 312.318,00
	SUPREME	Hurink , J.L.	extern: INSTYTUT MASZYN PRZEPLYWOWYCH	Lopend	1-11-2015	1-2-2019	1-11-2018	€ 115.625,00
	MASIHC-JBZ	Boucherie , R.J.	extern: JEROEN BOSCH ZIEKENHUIS	Gest2017	1-4-2013	1-9-2017	1-4-2017	€ 285.000,00
	SMAC	Goseling , J.	extern: KPN	Gest2017	1-6-2013	31-1-2018	1-9-2017	€ 275.000,00
	RRR	Boucherie , R.J.	extern: RIJKSDIENST VOOR ONDERNEMEND NEDERLAND	Gest2016	1-7-2010	30-9-2016	31-12-2015	€ 308.534,00
	HEC	Hurink , J.L.	extern: RWE DEUTSCHLAND AG	Gest2016	1-6-2014	31-12-2016	1-1-2016	€ 50.000,00
	MAPREHAB	Boucherie , R.J.	extern: SINT MAARTENSKLINIEK NIJMEGEN	Lopend	1-2-2015	1-5-2019	1-2-2019	€ 285.000,00
	WPCO	Boucherie , R.J.	extern: STICHTING SANQUIN BLOEDVOORZIENING	Gest2017	1-10-2013	31-1-2018	1-10-2017	€ 150.000,00
	TNONLDA	Boucherie , R.J.	extern: TNO	Gest2018	1-10-2014	1-1-2019	1-10-2018	€ 240.420,01
	HICE (TTT100) OTTEN	Boucherie , R.J.	extern: ASITO BV	Lopend	1-4-2017	31-3-2021	31-12-2020	€ 307.500,01
	HICE (TTT100) 2 BOS	Boucherie , R.J.	extern: ASITO BV	Lopend	1-6-2017	31-3-2021	31-12-2020	€ 307.500,00
	EIT HEGRID FRAME	Hurink , J.L.	extern: EIT DIGITAL HEADQUARTERS OFFICE	Gest2015	1-1-2014	31-5-2015	1-1-2015	€ 35.000,00
	SMABEP	Manthey , B.	NWO	Gest2015	1-9-2011	1-3-2016	1-12-2015	€ 213.693,00
	INTEX	Boucherie , R.J.	NWO	Gest2015	1-1-2012	1-5-2015	31-12-2014	€ 207.882,00
	TENETS	Scheinhardt , W.R.W.	NWO	Lopend	1-9-2012	30-9-2019	30-6-2019	€ 208.032,00
	DISPATCH-2	Hurink , J.L.	NWO	Lopend	1-12-2016	1-7-2019	1-4-2019	€ 68.329,00
	TT-DMMP-DICKINSON	Uetz , M.J.	NWO Cluster Chemische en exacte Wetenschappen	Gest2018	1-4-2014	1-7-2020	1-4-2020	€ 125.000,00
	VENI/MAB-DCM	Boer den, A.V.	NWO Cluster Chemische en exacte Wetenschappen	Gest2016	1-11-2014	1-2-2018	1-11-2017	€ 250.000,00
	FRAMES	Manthey , B.	NWO Cluster Chemische en exacte Wetenschappen	Lopend	1-10-2015	1-12-2020	1-9-2020	€ 221.170,00
	DYNAFLOAT	Boucherie , R.J.	NWO-SGW	Lopend	1-1-2015	1-8-2019	1-5-2019	€ 267.170,00
	SMART MICRO GRIDS DMMP (ML)	Hurink , J.L.	STW	Gest2017	1-1-2013	1-11-2017	1-8-2017	€ 20.657,00
	SMART MICRO GRIDS DMMP (PL)	Hurink , J.L.	STW	Gest2017	1-1-2013	1-11-2017	1-8-2017	€ 181.223,00
SACS	PROMESED	Groesen van, E.W.C.	extern: RIJKSDIENST VOOR ONDERNEMEND NEDERLAND	Gest2015	1-1-2012	31-12-2015	1-4-2015	€ 112.521,00
	ELASTIC WAVE	Vegt van der, J.J.W.	extern: SHELL GLOBAL SOLUTIONS INTERNATIONAL BV	Gest2018	1-9-2014	1-12-2018	1-9-2018	€ 310.000,01
	TRAX	Mandal , P.K.	extern: EUROPEAN COMMISSION	Gest2017	1-10-2013	31-1-2018	1-10-2017	€ 251.754,00
	CONFLEX	Zwart , H.J.	extern: Marie Curie - TEL AVIV UNIVERSITY	Lopend	1-10-2017	1-1-2022	1-10-2021	€ 467.548,00
	HIPRINS NACM	Vegt van der, J.J.W.	extern: MINISTERIE VAN ECONOMISCHE ZAKEN	Gest2015	1-1-2008	31-12-2015	1-7-2015	€ 206.450,00
	AEROSOL - PHD3 MMS	Geurts , B.J.	extern: PMI SERVICE CENTER EUROPE SP ZOO PMP / PHILIP MORRIS	Gest2016	1-9-2012	31-12-2016	1-9-2016	€ 305.000,00
	AEROSOL PD MMS	Geurts , B.J.	extern: PMI SERVICE CENTER EUROPE SP ZOO PMP / PHILIP MORRIS	Gest2016	1-9-2012	31-12-2016	1-9-2016	€ 190.000,00
	OSB-PMI	Geurts , B.J.	extern: PMI SERVICE CENTER EUROPE SP ZOO PMP / PHILIP MORRIS	Gest2017	1-11-2016	31-1-2018	1-10-2017	€ 144.000,00
	NOMADS	Brune , C.	extern: WESTFALISCHE WILHEMS UNIVERSITAT MUENSTER	Lopend	1-3-2018	31-5-2022	28-2-2022	€ 112.500,00
	SIFC HS	Zwart , H.J.	NWO	Gest2015	1-10-2010	1-1-2016	1-10-2015	€ 205.013,00
	TT BRUNE	Gils van, S.A.	NWO Cluster Chemische en exacte Wetenschappen	Lopend	1-1-2014	1-4-2019	1-1-2019	€ 240.000,00
	DROPLETS (ML)	Geurts , B.J.	NWO-I	Gest2015	1-10-2010	1-10-2015	1-7-2015	€ 17.739,09
	NUM. TURBULENCE	Geurts , B.J.	NWO-I	Gest2017	1-4-2013	1-2-2018	1-11-2017	€ 11.625,54
	EFFICIENT SOLAR CELLS	Vegt van der, J.J.W.	NWO-I	Gest2018	1-6-2013	1-4-2018	31-12-2017	€ 33.342,13
	SEISMIC WAVES	Vegt van der, J.J.W.	NWO-I	Lopend	1-9-2014	1-12-2019	1-9-2019	€ 27.172,44
	ABSORPTION LIGHT	Vegt van der, J.J.W.	NWO-I	Lopend	1-9-2015	1-1-2023	1-10-2022	€ 65.000,00
	FOM-SHELL 15CSER049	Vegt van der, J.J.W.	NWO-I	Lopend	1-7-2016	1-12-2020	1-9-2020	€ 61.852,81
	PAINSIGHT AAMP (ML)	Gils van, S.A.	STW	Gest2015	1-4-2010	15-1-2016	15-10-2015	€ 5.000,00
	PAINSIGHT AAMP (PL)	Gils van, S.A.	STW	Gest2015	1-4-2010	15-1-2016	15-10-2015	€ 182.727,00
	POLYGRAFIC (ML)	Vegt van der, J.J.W.	STW	Gest2015	1-10-2010	15-12-2015	15-9-2015	€ 54.500,00
	POLYGRAFIC (PL)	Vegt van der, J.J.W.	STW	Gest2015	1-10-2010	15-12-2015	15-9-2015	€ 182.727,00
	BOILING-STW (ML)	Geurts , B.J.	STW	Gest2017	1-9-2012	1-2-2018	1-11-2017	€ 14.000,00
	BOILING-STW (PL)	Geurts , B.J.	STW	Gest2017	1-9-2012	1-2-2018	1-11-2017	€ 181.492,00
	DETERMINISTIC WAVE MODELL (M	Groesen van, E.W.C.	STW	Gest2018	1-2-2012	1-5-2018	1-2-2018	€ 97.300,00
	DETERMINISTIC WAVE MODELL (PL	Groesen van, E.W.C.	STW	Gest2018	1-2-2012	1-5-2018	1-2-2018	€ 464.089,00
	FASTFEM (ML)	Vegt van der, J.J.W.	STW	Lopend	1-12-2013	1-4-2020	1-1-2020	€ 50.000,00
	FASTFEM (PL)	Vegt van der, J.J.W.	STW	Lopend	1-12-2013	1-4-2020	1-1-2020	€ 306.084,00

Total MOR €4.964.438
Total SACS €4.299.437