Research Evaluation 2021-2025

Department of Computer Science

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Computer Science, Aalborg University
Research Evaluation 2021-2025

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RESEARCH EVALUATION 2021-2025

Department of Computer Science

Aalborg University 2026

1 The Evaluation

1.1 The Evaluation Committee

Geraldine Fitzpatrick



Geraldine Fitzpatrick is Professor i.R. at TU Wien since 2023. Prior to this she was Full Professor and led the Human Computer Interaction (HCI) Group in the Informatics Faculty at TU Wien from 2009-2023, also serving as Head of the Institute for Design and Assessment of Technology until a faculty restructure in 2017. Before this, she was Director of the Interact Lab at the University of Sussex (2003-2009), User Experience consultant at Sapient London (2001-2003), and a Senior Researcher at the Center for Online Health and the Distributed Systems Technology Centre in Australia. Her diverse background includes an earlier career in nursing and midwifery (including hospital, community and private practice roles), a Bachelor of Informatics (Hons.) and PhD in CS&EE from the University of Queensland Australia, and more recently a MSc in Applied Positive/Coaching Psychology from University of East London UK. She has international experience working in academia, research, industry, healthcare and consulting.

Geraldine's research focuses on socio-technical and people-centred perspectives of computing, with a particular focus on supporting collaboration, healthcare, older people, and physical, mental and social wellbeing. This has meant working at the challenging intersection of disciplines to understand how to design new and emerging technologies to best fit in with the messy 'real world' of life and work, taking a values-led and participatory approach to engaging people in the de-

sign/deployment/evaluation process. In support of this she has extensive experience in collaborative multi-disciplinary research projects, with funding from diverse national, EU and industry sources, and resulting in numerous collaboratively authored publications.

She is an awarded researcher, teacher and leader. Recognitions include ACM Distinguished Scientist, IFIP Fellow, SIGCHI Lifetime Service Award, IFIP TC-13 Pioneer Award, TU Best Teacher Award, and ACM Distinguished Speaker. She has an extensive peer service record, having served as co-editor of the Computer Supported Cooperative Work (CSCW) journal and also playing key leadership roles in CSCW, HCI, Health Informatics, Ubicomp and related international conferences and professional organisations. She has also served on various international project and faculty advisory boards and faculty evaluation panels.

Geraldine now focusses her work efforts on developing future academic leaders and crafting more collegial sustainable research cultures. Towards this she delivers consulting, speaking, training and coaching internationally, and has hosted the Changing Academic Life podcast series since 2016.

Peter Flach



Peter Flach has served as professor in the Department (now School) of Computer Science at the University of Bristol since 1997 and was promoted to Professor of Artificial Intelligence in 2003. Peter Flach is an internationally leading scholar in the evaluation and improvement of machine learning models, with several publications on mining highly structured data, on knowledge-driven and explainable AI, and on the methodology of data science. Peter Flach books on Intelligent Reasoning by Example, and Machine Learning: the Art and Science of Algorithms that Make Sense of Data have been particularly impactful.

From 2010 until 2020, Peter Flach was Editor-in-Chief of the Machine Learning journal, one of the two top journals in the field that has been published for over 25 years by Kluwer and now Springer-Nature. He is a founding board member, previous President and current Vice-President of the European Association for Data Science. He is

a Fellow of the European Lab for Learning and Intelligent Systems, and of the European Association for Artificial Intelligence. He was the founding director of the UKRI Centre for Doctoral Training in Interactive Artificial Intelligence, and currently directs the UKRI AI Centre for Doctoral Training in Practice-Oriented Artificial Intelligence.

Dave Parker



David Parker is a Professor of Computer Science at the University of Oxford, Deputy Head of Department (Research) as well as a Tutorial Fellow at Trinity College. Prior to that, David Parker was a Professor in the School of Computer Science at the University of Birmingham.

The research of David Parker is in formal verification: rigorous techniques for checking that systems function correctly. In particular, he work on verification methods for establishing the correctness and robustness of AI-based systems, and work on techniques and tools for providing formally guaranteed solutions to problems across sequential decision making, multi-agent systems and neuro-symbolic systems.

David Parker leads the development of PRISM, the most widely-used software tool for verification of probabilistic systems. In 2024, David Parker together with Marta Kwiatkowska and Gethin Norman won the ETPAS Test-of-Time Tool Award for PRISM.

1.2 Evaluation Guidelines

The following guidelines apply to the members of the evaluation committee for the research evaluation of the Department of Computer Science at Aalborg University, conducted in Spring 2026:

General responsibilities

Committee members are expected to:

- Perform the evaluation to the best of their professional ability, applying their expertise, judgement, and ethical standards.
- Collaborate with fellow committee members and the department representative throughout the evaluation process.
- Participate in a preparation meeting and the evaluation visit on April 27–29.
- Contribute to the written evaluation report, which should be finalised by the end of the visit or shortly thereafter.
- Contribute to the presentation of the evaluation results, as specified in the evaluation programme.

Evaluation material

The research evaluation material was distributed to the committee members on March 4th, 2026.

Division of responsibilities

- All committee members are expected to read the overall evaluation report.
- Each committee member has primary responsibility for one research group. The member with primary responsibility for a given research group should review the corresponding group chapter in detail and provide comments and recommendations.
- Other committee members are encouraged to contribute comments on selected aspects where relevant.
- The primary responsible member(s) are responsible for integrating comments into the final evaluation report for their assigned research group.

Department-level evaluation

All committee members are expected to provide comments and recommendations on the department-level chapter as well as for the vision and strategy (Part B).

Scope of evaluation

Comments and recommendations may address, but are not limited to:

- Research topics, quality, and impact
- External funding
- Strategic development and future directions
- Internal organisation and collaboration across groups
- Synergies within the department
- Collaboration with industry and external partners
- Internationalisation
- Contributions to society, including SDGs and innovation

Levels of assessment

Comments should be provided at the department, research group (including both old and new groups), and, where relevant, subgroup levels.

Presentation of findings

The main findings will be presented during dedicated feedback sessions, as specified in the evaluation programme:

- The primary responsible member(s) will present the findings at the research group level.
- The external evaluators will jointly present the overall findings at the department level.

1.3 Evaluation Process

The final draft of the research evaluation was sent to the evaluation committee on March 13, 2026. On April 9, 2026, the committee met with the Head of Department and the Deputy Head of Department for Research to discuss the planning

of the three-day evaluation seminar held in Aalborg from April 27–29, 2026. The evaluation seminar was structured to accommodate the recent reorganization of the department.

- The first day focused on the research activities conducted during the evaluation period (Part I of this report), with presentations from the department and the four former research groups. The day concluded with a dinner attended by the committee and the Deputy Heads of Department for Research and Education.
- The second day began with parallel presentations and discussions by the twelve newly established research groups (Part II of this report). The day concluded with a meeting and dinner involving the committee, the Dean (Thomas Bak), the Vice-Dean for Research (Mikael B. Skov), the Head of Department, and the Deputy Head of Department for Research.
- On the final day, the committee met with and interviewed selected PhD students, postdoctoral researchers, and assistant professors. This was followed by a meeting with the department management. The seminar concluded with a plenary feedback session, during which the committee presented its assessment and recommendations for the department. The session was attended by all department staff as well as the Vice-Dean for Research, Mikael B. Skov.

Following the seminar, the committee finalized its written assessment and recommendations. These are included at the end of the relevant chapters and sections in both Parts I and II for the different organizational units.

Part I

Activities and Results

2 The Department of Computer Science

2.1 Introduction

Department of Computer Science consists of 160 employees and 1300 students. The department was established as a department on its own in 1999. The number of staff and students has grown substantially since its inception and has recently stabilized.

The department is part of Aalborg University's Technical Faculty of IT and Design (TECH), which comprises four departments. The faculty was formed in 2016.

The department has a campus in both Aalborg and Copenhagen. In Aalborg, the department resides in a building by itself, yet co-located close to several other departments. The building houses all staff and nearly all students. In the Copenhagen Campus, all staff and students are situated in the main building with staff in the same office corridor and all students on the same floor. Due to the university's learning paradigm, all students work in groups and have their own group rooms.

2.1.1 Structure and Management

The department is formally managed by a Head of Department (Professor Peter Axel Nielsen since 2021) responsible for the overall operation, budget, and staff, a Deputy Head of Department for Studies (Associate professor Ulrik Nyman) responsible for education, and a Head of Administration (Helle Westmark) responsible for support and support staff. A Deputy Head of Department for research (Professor Thomas Dyhre Nielsen) was added in 2024 with responsibility for research strategy, funding, and coordination.

A Department Leadership Group oversee the management of the department with the formal role of advising the Head of Department (Figure 2.1). This group includes a professor from each of the four research groups. The group meets every two weeks to discuss the overall management of the department.

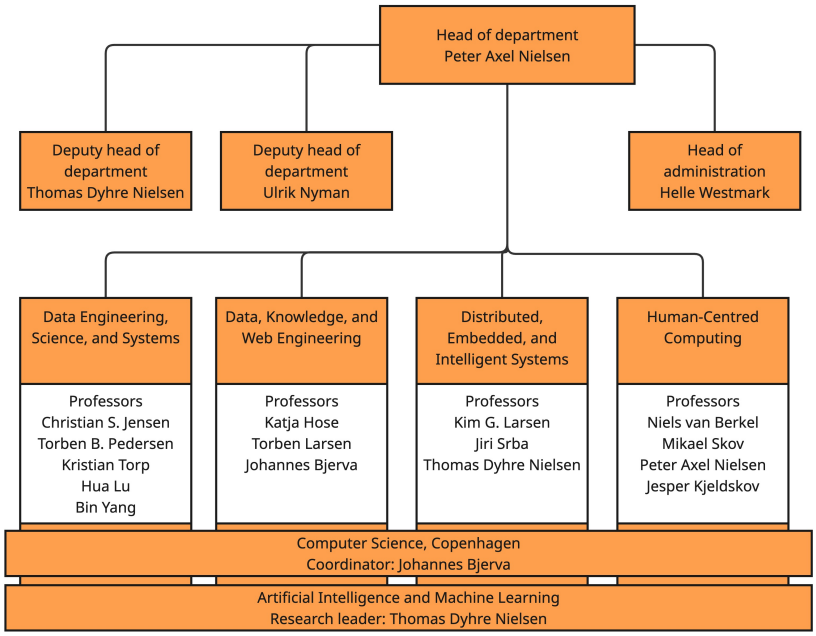


Figure 2.1: Organisational structure of Computer Science 2021-2025

In addition, there is a Department Council, and by law it consists of 50% scientific staff, 25% technical and administrative staff, and 25% students. The council meets every quarter and advises the Head of Department on issues as economy and the overall conditions for staff and students in the department.

During most of the research evaluation period (2021–2025), the department was organized into four research groups, and this organizational structure is hence mirrored in the evaluation section (Part A) of the current research evaluation report.

- **DESS:** Data Engineering, Science, and Systems conduct research that aims to advance value creation from data, including spatio-temporal, multidimensional, time series, sensor, and graph data, with applications in a broad range of areas, including intelligent mobility, digital and renewable energy, smart buildings, and greenhouse gas emissions reduction.

- **DEIS:** Distributed, Embedded, and Intelligent Systems covers mathematical foundation, verification tools, validation methodologies, probabilistic graphical models, and machine learning focusing on distributed, embedded, and intelligent systems.

- **DKW:** Data, Knowledge, and Web Engineering covers the areas quantum, natural language processing, knowledge, and web. The focus is on large amounts of heterogeneous data and addressing a broad range of use cases and applications, with particular focus on healthcare, bioscience, education, and security.

- **HCC:** Human-Centered Computing focuses on designing, developing, and applying interactive computing technologies. The group has a long tradition of empirical and solution-orientated research that focuses on processes, products, and theory.

The research groups form the main focus on the research evaluation and are presented in detail in subsequent sections (Part A). The department was reorganized with effect over the summer 2025. The new organizational structure into sections with new, smaller research groups focusing of the forward looking part of the research evaluation in Part B.

The (old) research groups covered the two campuses in Aalborg and Copenhagen. The Copenhagen branch started in 2020 and cuts across the four research groups. The Copenhagen branch was managed jointly by a team lead and the Head of Department.

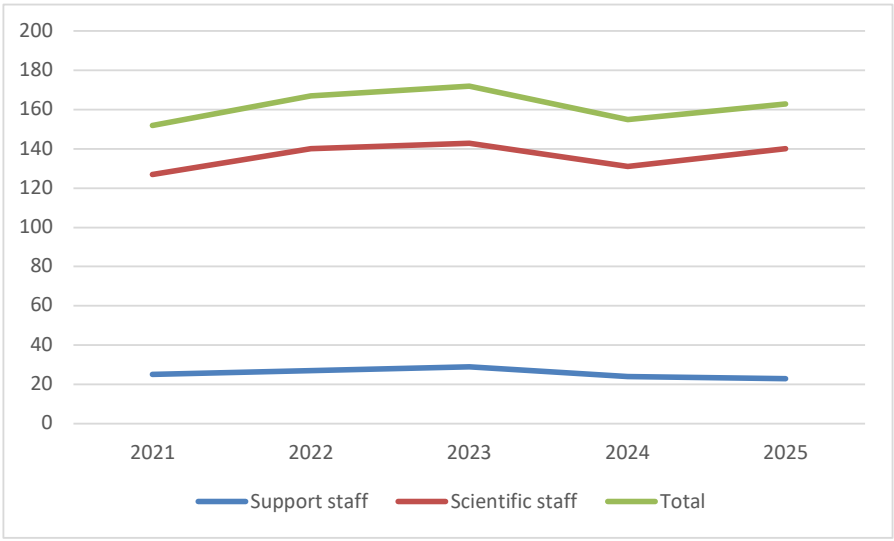


Figure 2.2: Number of scientific and support staff

Finally, there is a team on AI and machine learning, AIML, that runs across all research groups as a matrix that, e.g., organises joint events with Thomas Dyhre Nielsen as the team lead.

2.1.2 Staff

For the whole of 2021-2025, the department's student population and increased external research funding has allowed for active recruitment. The number of the scientific staff lies between 130–140 and the support staff experienced a small decline (Figure 2.2). At the same time the staff turnover has been significant. The turnover includes both junior staff in temporary positions as well as some senior staff in positions as associate or full professors.

In 2024 the department recruited five new full professors (Figure 2.3). Before then the department had not recruited new full professors for more than five years. The number of associate professors is gradually increasing as research and research groups mature. At the same time, the number of assistant professors fluctuates around 20.

Externally funded research projects finance PhD students, postdocs, and joint positions.

Support staff recently had a small decline in numbers as communications staff

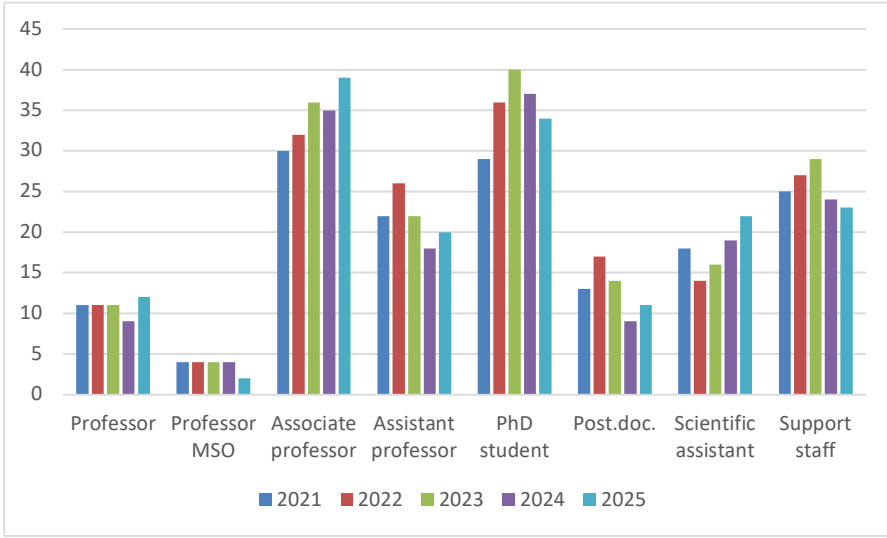


Figure 2.3: Number of staff by category. Data from August 2025 prior to reorganisation

moved to the central university administration. The department's support staff covers study administration (8), department economy (2), project economy (3), management support (3), fund raiser (1) and HR (1).

Figure 2.4 breaks down the current scientific staff in the research groups by position category.

The department strategy as outlined in the previous research evaluation (2016-2020) consists of four dimensions.

- Research
- Education
- Engagement with society
- Workplace

The strategic dimension will be addressed in the following sections.

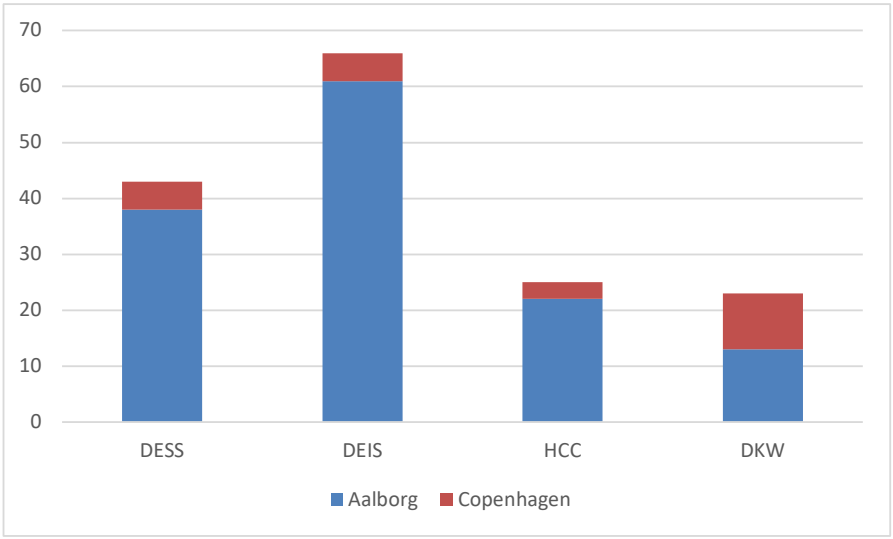


Figure 2.4: Research groups—Aalborg and Copenhagen. Data from August 2025 prior to reorganisation

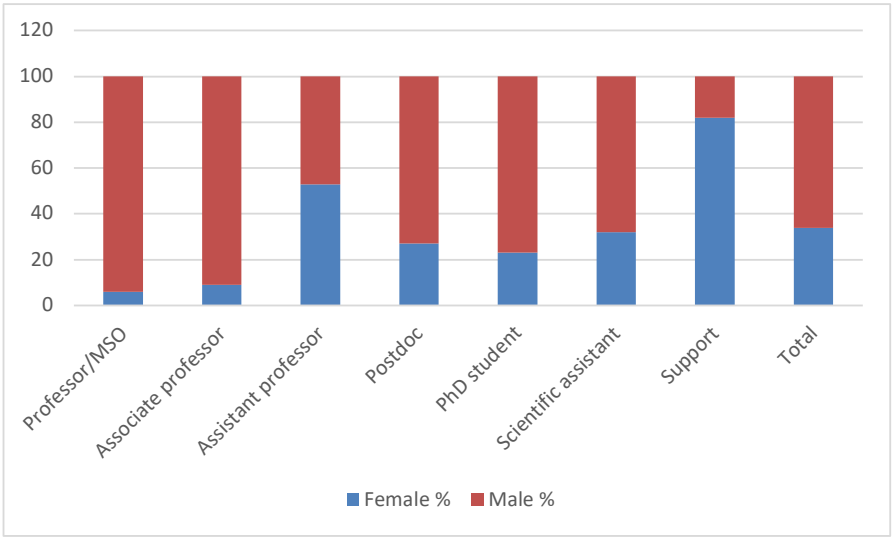


Figure 2.5: Gender balance in different staff categories

2.2 Research

It was part of the department's research strategy to seek a balance between on the one hand foundational computer science and on the other hand emerging technologies and application areas. A balance has been pursued in staying with existing research domains while at the same time also expanding on AI and seeking to apply core competences within the university's missions and platform, e.g., energy, health, and water.

Recruitment and talent attraction has been a concern that has been addressed in several initiatives. This encompasses developing a model of merits for positions, engaging with the new position type of tenure-track assistant professor, and developing a process for search committees with a particular focus on gender diversity.

Special attention was directed at attracting external research funding, see section 2.2.1, as well as advancing research through a focus on excellence in publication, see section 2.2.2.

2.2.1 Funding

Research funding comes from two sources: from within the university based on the Finance Act from the ministry and from external research funding agencies and foundations.

The two sources are connected. The university through the TECH Faculty provides the internal research funding. This follows a budget model in which delivered teaching is a significant factor (45%). The budget model for internal research funding also takes other factors into account: Research Indicator (25%), external research funding (20%), and PhD degrees (10%).

Figure 2.6 shows that the internal research funding has been gradually increasing to just above 60M DKK.[1] The spending of external funds goes to a maximum of 33M DKK. The spending of external funding was relatively stable during 2021-2025. The university's goal and the TECH Faculty's goal is that external spending should be at par with internal research funding; hence the TECH Faculty's expectation have been considerably higher than what the department has managed.

Prior to 2021 the department's external research funding was meager and building to 20 M DKK granted in 2020. For the period 2021-2025 the year 2023 was an all time low in terms of granted funding. That led to a realization that effort had to increase dramatically leading to a number of initiatives including a concerted

[1] 1M DKK is approx. 134K €, or 1M € is approx 7.5M DKK.

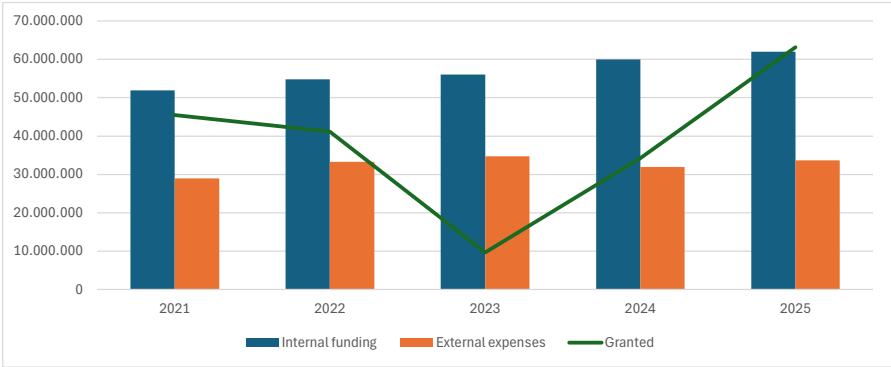


Figure 2.6: Research funding; blue: basic research funding, orange: spending of external funding, green: granted external funding

effort led by the CS Research Committee of devising and implementing a funding strategy. In addition, the department appointed a Vice Head of Department for Research, emphasizing the funding agenda. Several meetings had external funding on the agenda, and it gradually led to more and more scientific staff becoming involved in submitting applications to the external funding agencies.

There has been important improvements particularly on the effort employed in writing applications, good applications, and most importantly, in involving a much wider part of the scientific staff (see Figure 2.7). In terms of granted external funding, the results have increased significantly between 2023 and 2025 as can be seen in Figure 2.6.

2.2.2 Publications

The department's research has been conducted in the old research groups until Summer 2025. The reporting below as well as the evaluation of the research groups (Part A) is based on this (old) organizational structure even though the restructuring of the department into sections took place before the end of the evaluation period.

A few highlights are:

- The number of publications has increased from 226 (2021) to 368 (2025). See Figure 2.8.
- Articles in proceedings are the most common publications form and also provide substantially more citations than journal articles.

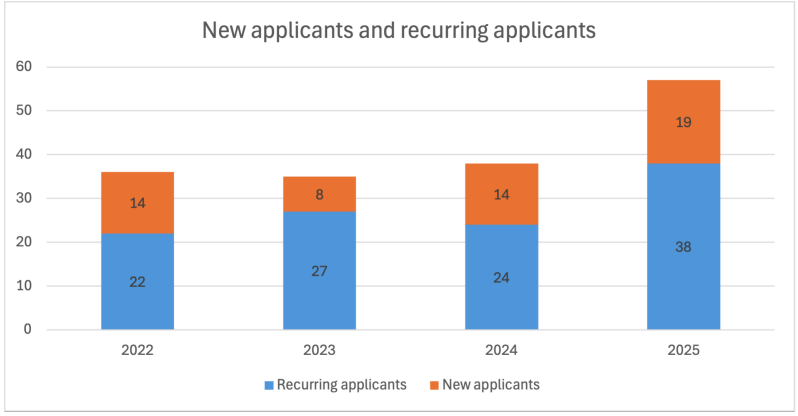


Figure 2.7: The number of new and returning applicants for external funding. An applicant is considered new if they have not submitted an application between 2020 and the year in question.

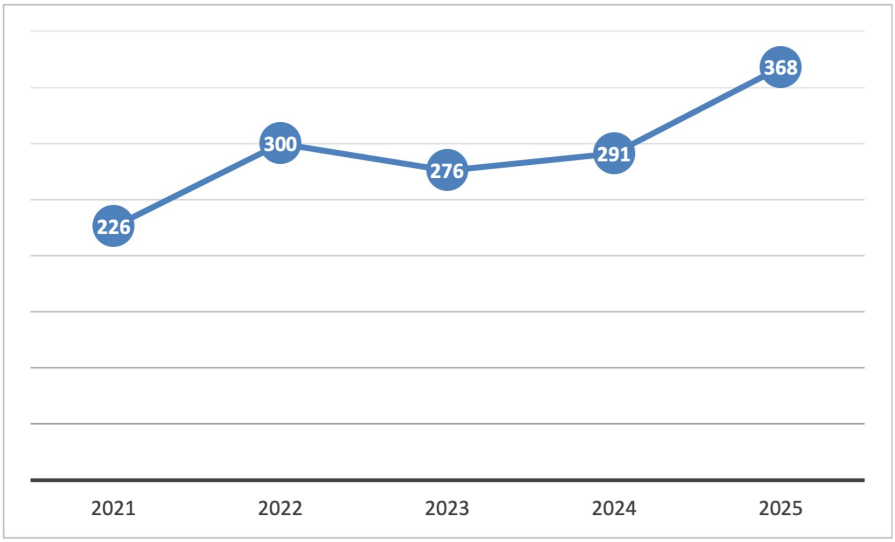


Figure 2.8: No. publications

- The coverage in Scopus is 90% on average for the period 2021–2025 indicating a high level of visibility of the published research. While Scopus does not provide a rich understanding of computer science research it suggests comparison with other disciplines.
- The Field-Weighted Citation Impact has increased from 1.40 (2021) to 2.18 (2024). This field-weight is based on Scopus.
- The department's publications in the top 10% of most cited publications is 17.6%.

Each year the AAU Library publishes an analysis of publications and on several related research topics in the university-wide research indicator, Computer Science Research Indicator, for the period 2020-2025. The Research Indicator is interactive, enabling users to explore extensive materials and data and to compare results with the other university departments. There are limitations as the Research Indicator cannot handle both old and new research groups at the same time, and also data on projects and sustainability goals are incomplete. The self-evaluations and visions of the research groups in the following sections are based on the complete data.

The Research Indicator is divided into Part A and Part B. Part A is the traditional metrics of publications, citations, and the calculations of field-weight. Part B is closer to what is asked for in CoARA, and in this case includes collaboration, visibility, and openness.

A few highlights from Part B as registered in the Research Indicator:

- Collaboration: The department's researchers have collaborated during 2021-2025 with 107 external partners, of which 104 are academic, and 20 are corporate. 68% of publications are co-authored with international partners.
- Openness: 70% of publication (2023) are open access either at the university's online library or with the publisher.
- Visibility: Two topics have a very high visibility with 'stochastic systems, traffic control, travel time' covering 9.48% of world publications, and 'timed automaton, model checking' covering 8.70% of world publishing.

2.3 Educations

The department provides a range of study programs. Teaching in these programs is carried out by the department's research groups. At present, the department offers 6 bachelor's and 7 master's educations.

Bachelor's Degree Programme

- Computer Science
- Software, Aalborg
- Software, Copenhagen
- Information Technology
- Interaction Design (closing 2026)
- Data Science (closing 2026)

Master's Degree Programme

- Computer Science
- Computer Science (International)
- Software, Aalborg
- Software, Copenhagen (started 2023)
- Interaction Design (closing 2029)
- Data Science (closing 2029)
- Digitalisation and Application Development

Common to all educations is a core of computer science subjects and projects, and in some cases combined with design, business, humanities, or social sciences. The intake on the educations in 2025 is shown in Figure 2.9. The intake has grown considerably since 2015, while in the last 2 years there has been a gradual decline in the intake on the educations in Aalborg but a steady growth in the Software education in Copenhagen. In 2015, the department's total student population was 941 and that has grown to 1288 in 2025. The prognosis for the future is that the decline in Aalborg will continue and that the growth in Copenhagen will reach an intake of 150 in 2030, with an ambition of eventually reaching an intake of 200 students.

It was part of the department's strategy to increase the gender diversity among students and improve the retention of students going from bachelor's to master's

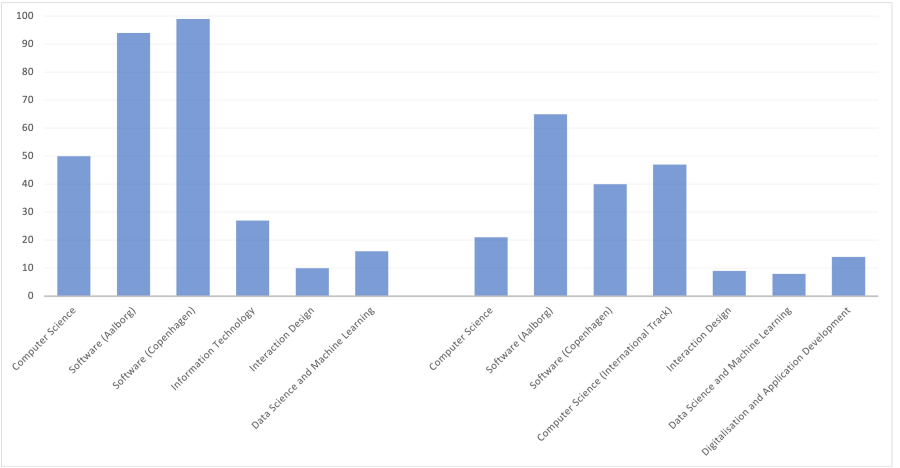


Figure 2.9: Student intake on bachlor's (left) and master's (right) educations 2025

programmes. There has been considerable effort in attracting female students. The ratio of female students in Copenhagen has increased to 25% while there has been a minor increase in Aalborg.

Aalborg University and also the department's educations all divide a semester into a few courses and a project conducted by the students in groups. The students' projects utilize problem-based learning, also known as PBL. This requires project groups to formulate the problem to be addressed, to devise solutions, and report on problem, method, solution, and its evaluation. Students are expected to apply knowledge gained in the courses when conducting their projects. This learning method is key to understanding the university and to appreciate the department's educations.

There are important linkages between research and educations. All teaching staff are active researchers engaged in research projects as well as publishing. There are a few exceptions where supervisors on the lower semesters are external teaching staff. All scientific staff are expected to contribute to teaching and that includes PhD students to full professors.

Teaching comes both in the form of course lecturing usually performed by assistant, associate, and full professors, and in the form of supervision of student projects. While the students are largely responsible for the problems they work on in the projects, it is also common that topic can be suggested by the supervisors. The most direct linkage between research and teaching is in the courses and project themes at the master's educations.

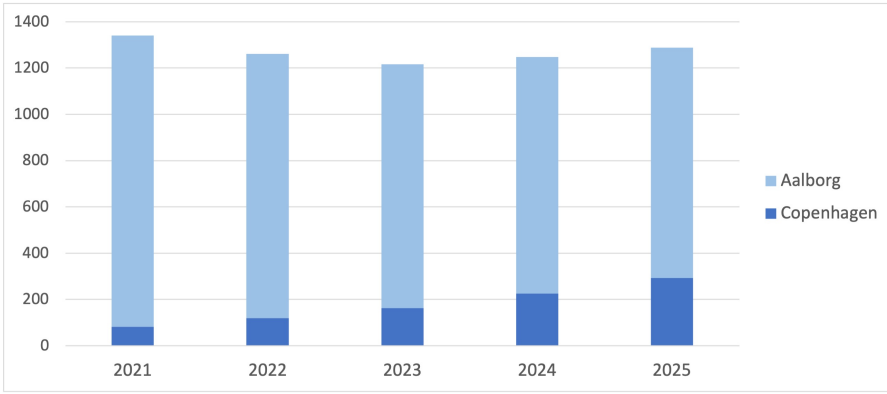


Figure 2.10: Student population

Strategically, the ambition has also included a major rethinking of the bachelor's programs in particular to increase the AI elements. This was implemented with the students starting in 2025. The master's educations are being revised subsequently. This coincides with a major reform of the structure of all master's educations in Danish universities. This reform has the aim of linking students to jobs by requiring that a significant percentage of students become part-time students employed simultaneously in a company.

2.4 Engagement with Society

A part of the department's research is conducted in collaboration with software companies or even wider with companies or public agencies in other domains. It has been part of the department's strategy to systematise this collaboration through industrial PhDs and joint projects with companies. This has been pursued to a large extent through application for external funding at the Innovation Fund Denmark. A substantial part of this has been through the national research center DIREC where many of the department's research have been active.

The university has in the last strategy period ending in 2025 set out to become a *mission-driven* university, Missions at AAU. The aim of a mission is to that work on complex challenges facing the world requiring new approaches and close collaboration. Three missions have established so far: a sustainable energy system, well-being among children and youth, and digital health. The department and a select group of researchers have been active in the missions. The effort will increase over the coming years.

2.5 Workplace

The department has a concern for the balance between research and teaching for all scientific staff. This is longtime concern that highlights the difficulty of finding a steady balance in a dynamic environment. There is variation over the years as to how much teaching the department will need to deliver. This is partly met by recruiting more staff. There is also variation as to how much effort is needed in externally funded research. On top of this comes an increasing demand for acquiring external research funds. It is not uncommon that the senior scientific staff experiences too many and too conflicting demands.

Teaching effort is measured in hours that follow an agreed set of norms. There is accounting of these teaching hours. The teaching capacity for an associate professor is set to approx. half their time, a little lower for assistant professors, and full professors teach half of associate professors. The norms, the accounting, and the set capacity is in place to control and regulate the effort on teaching over time and allow time for research and funding activities. Administrative tasks in the department are part of the same accounting.

Social events and meetings are arranged in the research groups with a few major events at the department level. The research groups socialize in various ways ranging from informal seminars, joint breakfast, sports & exercise, dinner in town, games night, and a junior club.

There has been an increasing focus on involving the younger staff in information and in influencing decisions and changes. This has primarily begun in 2025 in separate meetings for younger staff. Similarly, there has been meetings for younger female staff with a particular focus on gender diversity.

2.6 Committee Evaluation

First and foremost, the committee would like to congratulate the department on the impressive body of work that has been accomplished during the reporting period, as presented both in the report and in person during the site visit. The volume, quality and impact of research output is impressive and growing, as evidenced by the number of papers produced across the various groups, continued focus on prestigious publication venues, and the increasing number of citations of the department's work. This is particularly to be commended since the early part of this period was still pandemic-impacted.

In line with the department's stated research strategy, a strong balance can be

seen between foundational research in Computer Science and more applied research across a range of problem domains and emerging technologies. The research described during the evaluation includes both high quality foundational research contributions across Theoretical Computer Science, Data Management, Artificial Intelligence and other areas, and multiple instances of clearly articulated pipelines that drive theory-to-practice research and yield practical impacts through industrial collaborations, empirical and solution-oriented research on technology in use, and the development and distribution of software tools.

The committee noted an impressive range of international collaborations in the department's research, plus an array of links to industry as well as collaborations across faculties. Also evident was the standing of department members within their research communities, across all career stages, with many contributing through leadership and organisational roles. This includes the organisation of multiple major events, some being brought to Aalborg itself.

Research in the assessment period has been funded from a variety of sources, including multiple large, high profile grants. Despite a dip in the middle of the 5-year period, the recent trajectory for research funding looks very positive. The department's research output has also been enabled by a number of successful hires, including five full professors. This follows an active attempt to improve in this area through strategic changes made since the last review, such as the use of search committees (see below), and the support of the department funding office, which was very positively commented on by several department members.

The strong links between research and teaching are also to be commended. The problem-based student projects and themed semesters appeared to provide not only good learning opportunities for the students, but also opportunities for cross-research group collaboration and sharing, and for engaging students in research activities. Tangential to research, but reflecting the more general fairness values of the department, the transparency of the teaching workload model, including recognition of subsidiary teaching tasks, was particularly appreciated.

3 Data Engineering, Science, & Systems

3.1 Executive Summary

The Data Engineering, Science and Systems (DESS) group performs research in data management, data mining, machine learning, and artificial intelligence. The group embraces all activities concerning data-intensive systems and data-driven value creation. DESS aims to be an internationally leading research center within its areas of specialization.

The group performed very well during the period according to key performance indicators, including publications, external funding, Ph.D. education, scientific service, industrial impact, and dissemination.

The group published 532 refereed journal and conference papers during the period, including 285 in CORE/ICORE A* and 47 in CORE/ICORE A venues, ranking the group among the top worldwide and the very top outside Asia in the field of the group. Further, the group has embraced machine learning and AI during the evaluation period. Thus, 330 of the 532 papers present AI-related contributions, and 195 of the 330 appear in CORE/ICORE A* venues.

The group has participated in 31 externally funded projects and has received some DKK 78.88 million in funding from a wide range of sources. The project portfolio encompasses substantial industrial participation, and many projects involve other groups in the department or the university.

The group has trained a large number of young researchers, with 17 Ph.D. degrees having been awarded and 15 Ph.D. studies in progress. DESS researchers have received substantial peer recognition and have performed extensive service to the scientific community. The group has an extensive network of collaborators, encompassing outstanding researchers. Finally, the group was successful at attracting top scholars for positions in data management and machine learning.

In conclusion, the DESS group believes that it has demonstrated excellent research

performance in the reporting period.

3.2 Profile

The research in the DESS group covers a wide range of areas within data-intensive systems. The group's research approach is primarily constructive: theoretically well-founded, purposeful artifacts such as frameworks, data structures, indexes, algorithms, languages, tools, and systems are prototyped and subjected to empirical study. Thus, the research often involves labor-intensive software development and experimental studies.

The research is often driven by envisioned or existing real-world applications, the objective being to provide foundations for solutions or solutions that enable new or better applications. The primary application areas include intelligent transport systems, logistics, location-based services, energy grids, healthcare, and web querying. Central research topics belong to three areas:

- **Multivariate time series.** In 2025, the Internet of Things is expected to generate some 80 zettabytes of data, much of which is sensor data in the form of time series. Value creation from such data has been a key focus during the evaluation period, and many advances have been made that are documented in publications in top-tier outlets. Focus has been on multivariate time series with spatial correlations and on methods based on artificial neural networks, with the key goal of achieving highly accurate predictions. Further, focus has been on forecasting, while functionalities such as outlier detection and time series classification have also been studied. Key themes include the development of (i) methods that can be deployed on edge devices with limited storage and computational capabilities, (ii) neural architecture search, where the identification of purposeful neural architectures for specific data and tasks is automated, (iii) methods that reduce reliance on labeled training data and address privacy and trust, including unsupervised learning, federated learning methods, and model confidence, (iv) methods for compression, storage, and querying of time series, and (v) methods that are robust, e.g., to noisy training data. Most recently, few- and zero-shot methods, including methods that leverage foundation models, have been studied, as has the benchmarking of time series forecasting and outlier detection methods.

- **Trajectories.** A wide range of data-driven methods have been developed that leverage vehicle and vessel trajectory data to support diverse analytical

and decision-making tasks in transportation systems. These methods underpin core functionalities such as vehicle routing and navigation optimization, travel-time estimation under varying traffic and environmental conditions, and predictive modeling of future movement patterns. Beyond this, substantial research has focused on improving the quality and usability of trajectory data itself, including trajectory imputation, as well as on simplification and compression techniques.

In addition, trajectory analytics has enabled more advanced functionalities, such as trajectory quality assessment to evaluate data reliability, representation learning and embedding methods that transform raw trajectories into compact vectors, and similarity computation and search techniques that support pattern discovery and large-scale querying. These foundations further facilitate higher-level tasks including anomaly detection for identifying unusual movement behaviors, and forecasting models that anticipate future trajectories or traffic states.

- **Deep and extreme-scale analytics.** The group has worked on data analytics since the 1990s. In the evaluation period, the focus has been on deep (predictive and prescriptive) analytics and extreme-scale analytics on massive IoT time series. Prescriptive analytics adds mathematical optimization for a desired objective on top of predictive analytics. The extreme-scale analytics work considers mainly efficient management and analytics on massive IoT time series based on advanced lossy compression as well as extreme-variety data lakes with thousands of diverse datasets. The main application domain is digital energy, where focus has been on energy flexibility and massive energy time series, e.g., from wind and solar parks. In the evaluation period, new topics like digital twins emerged.

3.3 Staff

This section provides an overview of the staff by the end of 2025.

3.3.1 Current Staff

The following is a list of staff as of December 31, 2025. Part-time faculty members have full-time positions elsewhere. In brief, DESS has four professors and three associate professors, amounting to seven permanent faculty, in addition to four

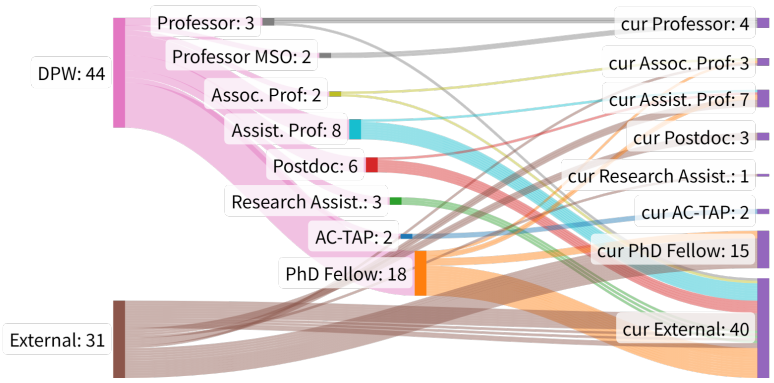


Figure 3.1: Staff evolution at DESS

tenure-track assistant professors. The remaining staff are employed in temporary positions.

Professors (4): Christian S. Jensen, Hua Lu, Torben Bach Pedersen, Kristian Torp

Associate Professors (3): Tianyi Li, Simonas Šaltenis, Christian Thomsen

Assistant Professors (7): Søren Kejser Jensen (tenure track), Tung Kieu (tenure track), Yushuai Li (tenure track), Yan Lin, Tiantian Liu, Yumeng Song, Sean Bin Yang (tenure track)

Postdocs (3): Liwei Deng, Hengyu Liu, Chuangtao Ma

Part-time Faculty Members: Chenjuan Guo (Associate Professor, 5%), Jilin Hu (Associate Professor, 5%), Arijit Khan (Associate Professor, 5%), Wolfgang Lehner (Professor, 20%), Bin Yang (Professor, 5%), Yan Zhao (Associate Professor, 10%)

Ph.D. Students (15 enrolled): Abduvoris Abduvakhobov, Jonas Brusokas, Sriom Chakrabarti, Zhen Chen, Carlos E. Muniz Cuza, Sarah Hasan, Subina Khanal, Mohammad Hadi Mehdizavareh, Ehsan Bonabi Mobaraki, Martin Moesmann, Ibraheem Taha, Frederik Marinus Trudslev, Sigmundur Vang, Jiachen Xu, Yu Zhang

Research Assistant (0.8): Christian Schmidt Godiksen (80%)

Academic Technical Staff (AC-TAP) (1.05): Kasper Fromm Pedersen, Laurynas Siksnys (5%)

3.3.2 Staff Development

Internal Promotion and Recruitment. Hua Lu first served as a Professor (MSO) at Aalborg University, then left for a Professor position at Roskilde University in

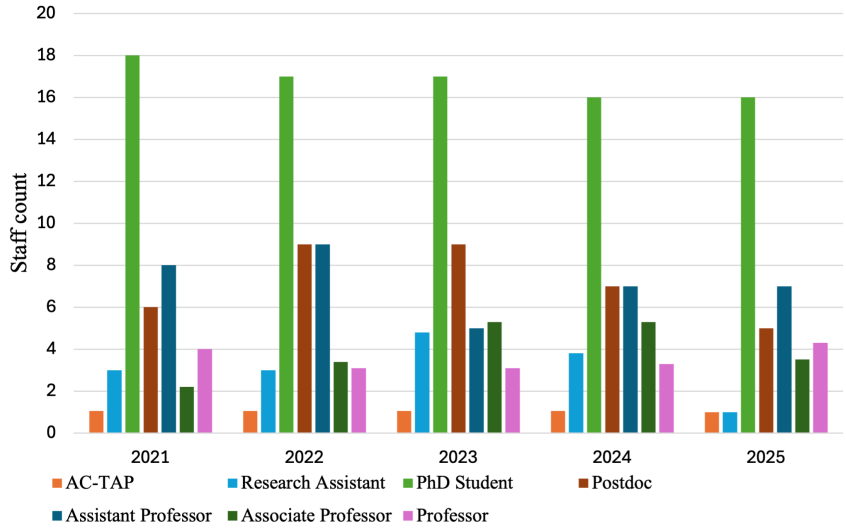


Figure 3.2: Staff count per year, weighted by percentage of employment

2020 and rejoined Aalborg University as a Professor in 2025. Tianyi Li received her Ph.D. degree from DESS in 2022, was promoted to Assistant Professor in the same year, then to Assistant Professor (tenure track) in 2023, and to Associate Professor in 2025. Yushuai Li joined Aalborg University as an Assistant Professor in 2024 and was promoted to Assistant Professor (tenure track) in 2025. Yumeng Song and Yan Lin, who were first Postdocs, became Assistant Professors in 2025. Kristian Torp was promoted from Professor MSO to Professor in 2024. Wolfgang Lehner joined Aalborg University as a part-time Professor in 2024. Sean Bin Yang received his Ph.D. degree from DESS in 2022 and joined Aalborg University as an Assistant Professor (tenure track) in 2024. Tung Kieu received his Ph.D. degree from DESS in 2021, was promoted to Assistant Professor the same year, and then to Assistant Professor (tenure track) in 2023. Søren Kejser Jensen, who was a Postdoc, became an Assistant Professor (tenure track) in 2024. Tiantian Liu received her Ph.D. degree from DESS in 2022, left for Roskilde University as a Postdoc in same year, and then rejoined Aalborg University as a Postdoc in 2023 and was promoted to Assistant Professor in 2024.

Departures and Leaves of Absence of Key Staff. During the evaluation period, 12 excellent faculty members, 5 female and 7 male, accepted full-time positions at other universities. Arijit Khan, who had joined as an Associate Professor, joined Bowling Green State University in 2025. Haomin Yu, who was an Assistant Professor, joined the University of Salford as a Lecturer in 2025. Yan Zhao joined

the Shenzhen Institute for Advanced Study, University of Electronic Science and Technology of China, as a Professor in 2025. Nguyen Ho, who was an Assistant Professor, joined Loyola University Maryland as an Assistant Professor in 2024. Dalin Zhang, who was an Associate Professor, joined Hangzhou Dianzi University as a Professor in 2024. Huan Li, who was an Assistant Professor, joined Zhejiang University as a Professor in 2023. Chenjuan Guo (Associate Professor) and Bin Yang (Professor) joined East China Normal University as Professor and Chair Professor in 2022, followed by Jilin Hu (Associate Professor) in 2023, also as Professor. Kaixuan Chen, who was an Assistant Professor, left in 2022. Peng Han, who was an Assistant Professor, joined the University of Electronic Science and Technology of China as a Professor in 2022. Miao Zhang, who was an Assistant Professor, joined Harbin Institute of Technology (Shenzhen) as a Professor in 2022. In addition to the above information, Simonas Šaltenis, originally an Associate Professor at AAU, was on leave at Vilnius University as a Research Professor from August 2019 to July 2023, while retaining a partial appointment at AAU (20% initially, later 30%). Since August 2023, he has returned to AAU as a full-time Associate Professor.

Figure 3.1 presents the overall evolution of the DESS staff composition during the research evaluation period. This figure does not include part-time faculty members, as they hold full-time positions at other universities. All other staff are counted as full-time (i.e., 100%). "DPW" (Database, Programming, and Web Technologies) was the group name used in the previous research evaluation period. The programming group was split off early during this period, and the web group was split off in January 2022. The remaining group was renamed "DESS." We do not cover the programming and web staff here.

Figure 3.2 shows the staff count per position category at the end of each year during the reporting period. Ph.D. students consistently represented the largest group. Research Assistants and Postdocs increased early in the period, peaking in 2023 and then declined. Assistant Professors fluctuated and then stabilized from 2024 onward. Associate Professors increased until 2024 and then decreased slightly. There were 3 to 5 full-time Professors (including Professor MSO) throughout the period. AC-TAP remained stable throughout the period.

Discussion. A key observation is that DESS was able to attract excellent faculty during the evaluation period. However, retention was challenging. Although the total number of staff and the count per category of staff remained stable throughout the evaluation period, a considerable number of staff joined and left, creating a very dynamic environment. During the evaluation period, 31 staff thus joined, and 40 left, including 12 faculty. The many departures resulted in the need for frequent hiring, which caused substantial uncertainties and threatened continuity. Only 4

permanent faculty were employed full time throughout the period. They played a key role in maintaining continuity and had substantial administrative and project-related responsibilities on top of other tasks, causing serious overload. Of those 12 faculty who left, 8 were so competitive that they obtained full Professor positions at their new universities. Only one of them was a full Professor at AAU.

3.4 Goals for 2021-2025

The detailed plan for the evaluation period may be found in the report for the previous evaluation period. The group conducted both fundamental and applied research and viewed these types of research as equally valuable. During the reporting period, the group focused on establishment of a new group, excellence and impact, realizing synergies, maintaining a robust and diverse funding portfolio, hiring highly qualified staff, obtaining laboratory support, and increasing its capacity for seizing new opportunities.

The group was envisioned as converging on five main topics: (i) spatial, temporal, and sensor data management and analytics, (ii) deep and extreme-scale analytics, (iii) semantic data management, graph databases, knowledge engineering, natural language processing, and recommender systems, (iv) data science in the context of interdisciplinary research, and (v) AI and machine learning.

Excellence and impact

The group valued both fundamental and applied research equally and aimed for excellence in both. For foundational research, key performance indicators included publications in top venues, citations, awards, invited talks, and other forms of peer recognition. For application-oriented research, key performance indicators included demonstrations, industry funding, technology transfer, spin-outs, software downloads, patents, and user adoption. The societal impact of both types of research was frequently assessed in relation to the UN Sustainable Development Goals (SDGs). The group's projects often addressed areas such as smart transportation, renewable energy, and bioscience, contributing directly to SDGs 3, 7, 11, and 13. The group planned to regularly monitor its societal impact using relevant performance indicators aligned with the SDGs.

Synergies

The group aimed to realize latent synergies within the group by (i) focusing selected activities around cross-cutting themes and (ii) encouraging cross-fertilization between foundational and applied research.

Cross-cutting themes. The group planned to bring together staff members working on similar techniques in different domains to leverage shared insights and improve research focus and innovation. Envisioned means included joint meetings, workshops, and shared PhD students or postdocs. For example, deep learning for time series was intended to be explored across both traffic and energy domains, capitalizing on complementary patterns and challenges. Similarly, data ingestion was planned to be addressed in contexts such as data warehousing and mobility analytics. Additional cross-cutting themes included scale-in/out, dimensional queries, predictive techniques, experimental practices, and open-source infrastructure.

Cross-fertilization. The group planned to promote synergy by sharing code, ideas, and techniques across foundational and applied research. While individual members specialized along different points of this spectrum, collaboration was expected to enable foundational work to inspire impactful applications, and application-driven work to benefit from theoretical advances. This was particularly envisioned in mobility and energy analytics, where the group aimed to combine top-tier publications with real-world prototypes, external collaborations, and spin-outs. Strengthening these synergies was a key goal for the period.

Robust and diverse funding portfolio

The group planned to maintain a robust and diverse funding portfolio, where many group members are able to obtain funding and where different types of funding, e.g., funding in the excellence and strategic pillars, can be obtained. The group planned to strive to maintain a robust and diverse portfolio in the current evaluation period.

Hiring

Recruiting highly qualified staff in the group's core research areas was identified as a challenge. The group planned to continue hiring highly qualified staff at all levels to compensate for departures.

Ability to Seize Opportunities

During the previous evaluation period, the group strengthened its research capacity and collaborations to expand into areas such as AI, big data, mobility, and renewable energy, outlining four research clusters for the next period.

Spatial, temporal, and sensor data management and analytics. The group planned to strengthen spatio-temporal research using Global Navigation Satellite System (GNSS) data from vehicles, bicycles, e-bikes, and trucks, addressing map-matching and irregular sampling while contributing to SDG 11. It would also use AIS ship data and integrate spatial and temporal sources such as fuel, radar, video, and air-pollution data to tackle large-scale management and mining challenges. Further work included explainable and robust time series analytics, data-intensive routing using reinforcement or imitation learning, and continued research on spatial crowdsourcing, entity linkage, and spatio-textual analytics.

Deep and extreme-scale analytics. The group planned to advance deep and extreme-scale analytics, extending previous work in advanced analytics and data warehousing. In deep analytics, it aimed to strengthen predictive and prescriptive methods for digital energy, applying machine and deep learning to IoT time series, expanding SolveDB on Spark, and extending FlexOffers to energy storage, conversion, and blockchain-based trading. In extreme-scale analytics, the group would improve IoT compression, enhance ModelarDB for edge computing, and explore mutual information for time series mining, while scaling the Danish National Data Lake for Energy and enabling semantic, data cube-based explorative analytics.

Data science in the context of interdisciplinary research. The group planned to expand interdisciplinary projects with Bioscience, Medicine, and Planning. With Bioscience, it aimed to improve microbial genome recovery using DNA sequencing, machine learning, and graph analysis. In medicine, it would continue work on entity similarity and graph embeddings.

AI and Machine Learning. Following the previous evaluation, the group launched a three-year BSc in Data Science in 2019 and planned a two-year MSc program. The programs focus on analytics, statistics, machine learning, data management, and related ethical and legal topics. Research efforts would expand toward applying machine learning to time series, spatio-temporal data, graphs, and energy data.

3.5 Activities and Results

This section provides a summary of the activities and results across five key research topics—four of which align with the topics in Section 3.4—as well as projects and funding.

3.5.1 Spatial, Temporal, and Sensor Data Management and Analytics

Time Series Analysis. We made substantial advances in time series analysis, with a focus on learning-based methods for temporal modeling, anomaly detection, and multivariate forecasting. We developed several transformer-based frameworks for time series, including memory-guided transformers (VLDB'2024), tree-based transformers (IJCAI'2022), and multi-scale adaptive pathways (ICLR'2024), which capture both local and global temporal dependencies to improve forecasting accuracy across diverse domains. We introduced TFB (VLDB'2024) and TAB (VLDB'2025), two large-scale benchmarking datasets that enabled fair and systematic evaluation of time series forecasting and anomaly detection methods. To facilitate reproducible evaluation, we developed EasyTime (ICDE'2025), a one-click framework that allowed researchers to conveniently assess new forecasting models on a wide range of datasets. In addition, we investigated robust time series forecasting, proposing methods that combined weakly guided adaptation with adversarial training to handle out-of-distribution data and noisy observations (VLDB'2023). For time series anomaly detection, we designed unsupervised approaches that effectively captured temporal dependencies from unlabeled data (ICDE'2021, WSDM'2023), and explored robust detection settings where training data was contaminated by anomalies (ICDE'2022, ICDE'2022). In the area of time series classification, we proposed LightTS (SIGMOD'2023), a framework that compressed large ensembles into lightweight models while preserving competitive accuracy. Complementing these efforts, we also advanced knowledge-enhanced and automated forecasting frameworks (VLDB'2021, SIGMOD'2023, VLDB'2024), embedding domain expertise into deep learning architectures and achieving end-to-end automation for correlated time series forecasting. To address the problem of lacking quality training data, we proposed a self-supervised approach to re-label time series datasets by inherently constructing candidate datasets (NeurIPS'2025). We developed a general framework that can wrap any encoder-decoder-based deterministic forecasting model into an outer energy-based model to allow so-called selective forecasting, avoiding forecasting in low-confidence scenarios (TMLR'2025). Finally, we published multiple papers about using mutual information for efficiently mining frequent (VLDB'2021), seasonal (ICDE'2023) and rare patterns (TKDE'2025) in time series.

Trajectory Modeling and Applications. Our research on trajectory modeling developed practical methods for intelligent transportation and location-based services. We focused on efficient, transferable, and semantically aware models for tasks including travel time estimation, trajectory recovery, path ranking, and mobility pattern understanding.

We proposed TrajMamba for efficient semantic extraction with travel-purpose-aware pre-training (NeurIPS'2025), TransferTraj for region and task transferability through multi-modal encoding and unified masking-recovery (NeurIPS'2025), and UVTM as a universal model with three independently maskable feature domains (TKDE'2025). For trajectory recovery and path applications, PLMTrajRec leveraged pre-trained language models with area-flow-guided prompts for scalable recovery (NeurIPS'2025), while Path-LLM integrated topological and textual road network data through contrastive learning, achieving substantial path ranking improvements (WWW'2025). These efforts advanced path-based applications. For semantic understanding, TrajCogn extracted movement patterns and travel purposes using LLM-based semantic embedders (IJCAI'2025), and Mobility-LLM analyzed check-in sequences through visiting intention networks (NeurIPS'2024).

Spatio-Temporal Data Analysis. We established a cohesive framework for modeling, forecasting, and uncertainty quantification in dynamic environments, with applications spanning crowdsourcing, traffic flow, and continuous data streams. We introduced a unified replay-based continuous learning framework to handle spatio-temporal prediction on streaming data, enabling adaptive model updates without catastrophic forgetting (ICDE'2024). For robust uncertainty quantification in traffic forecasting, we developed a unified understanding and practical approach to model uncertainty, enhancing prediction reliability (TKDE'2023, ICDE'2023). We also addressed bias in traffic prediction via a Spatio-Temporal Mixture-of-Experts (ST-MoE) architecture (CIKM'2023). In the context of crowdsourcing, we proposed an outlier detection method for streaming task assignment to ensure data quality and assignment robustness (WWW'2022). Together, these works formed an integrated suite of methods for accurate, reliable, and adaptive spatio-temporal intelligence in real-world streaming scenarios.

Toward a lightweight, scalable, and unified foundation model for paths (i.e., spatial trajectories) that generalizes across diverse downstream applications—such as travel time estimation, trajectory similarity computation, and path recommendation—we progressively advanced path representation learning from multiple perspectives. We first introduced an unsupervised path representation learning framework based on information maximization and curriculum negative sampling (IJCAI'2021). Building on this, we further explored temporal path representation learning through weakly

supervised contrastive learning (ICDE'2022). To enhance scalability and efficiency, we developed a lightweight path representation framework integrating relational reasoning and knowledge distillation (KDD'2023). Subsequently, we extended our research to multi-modal path representation learning to enrich semantic understanding, including path-textual representations (WWW'2025) and path-image representations (KDD'2025). Collectively, these efforts laid the foundation for a lightweight, scalable, and unified path representation model that could effectively empower transportation intelligence.

Spatial Crowdsourcing. We established a comprehensive framework for intelligent task assignment and recommendation, spanning geographic partitioning, preference learning, group and coalition-based allocation, fairness, profit optimization, and worker behavior prediction. We introduced an efficient geographic partition framework for scalable task allocation (TKDE'2024) and developed AdaTaskRec for adaptive task recommendation (TOIS'2023). Our work on federated preference learning enabled personalized task assignment while preserving privacy (TKDE'2023). We addressed group and coalition-based task assignment with priority-aware fairness (VLDBJ'2024) and game-theoretic approaches (ICDE'2021). For dynamic environments, we modeled worker churn using Context-LSTM (TKDE'2023) and incorporated loyalty-based assignment (CIKM'2022). Finally, we developed techniques for efficient and scalable time-continuous spatial crowdsourcing (ICDE'2021). Together, these contributions formed a robust and efficient foundation for reliable, fair, and scalable spatial crowdsourcing platforms in real-world applications.

Maritime Data Management and Analytics. We developed a data-to-insight stack across AIS warehousing, streaming analytics, data repair, multi-sensor fusion, behavior mining, prediction, and sustainability. We built a distributed spatial AIS warehouse with k-d tree sharding and dual trajectory or cell views (MDM'2024) and introduced trajectory and density views with the trident query for route analysis (SIGSPATIAL'2021). MH-GIN improved data quality via a multi-scale heterogeneous graph model (PVLDB'2026). We fused coastal cameras with AIS for location estimation and trajectory imputation (MDM'2024, MDM'2025). We detected complete fishing activities (MDM'2022) and benchmarked fleet-scale CO_2 emission models (SSTD'2023). Together, these outputs delivered a scalable and reliable stack for maritime safety, compliance, forecasting, and greener operations.

Data Management Systems. To address the dual challenges of time-series forecasting and scaling decision-making, we proposed MagicScaler (VLDB'2023)—a framework that integrated a multi-scale attentive Gaussian process predictor for uncertainty-aware time-series forecasting with an uncertainty-aware scaler for cost-efficient and reliable decision optimization.

Our works advanced the management and analytics of spatial, temporal, and spatio-temporal data through model-based, learned, and survey-driven systems research. We surveyed metric indexing methods with unified empirical analysis and guidance for index selection in diverse metric spaces (CSUR'2022), and modeled cost dynamics of space-filling curves with constant-time estimators and reinforcement-learning-based SFC optimization (VLDB'2025). For intelligent transportation, we designed efficient learned spatial indices enabling rapid reconstruction at scale (ICDE'2023). Beyond transportation, we built hybrid GNSS sampling and reachability indexing frameworks that balanced efficiency, accuracy, and scalability (MDM'2025, Inf. Syst. Front.'2022). Complementary advances included polynomial-based approximate aggregation (EDBT'2021), compression of floating-point time series for storage and query efficiency (SIGMOD'2024), and decentralized logging for extreme-scale time series systems (VLDB'2023). Finally, we introduced T-Assess, an automated quality assessment system for trajectory data (VLDB'2024), and surveyed geo-textual query processing paradigms (VLDBJ'2021). Together, these efforts established a comprehensive stack for efficient, reliable, and scalable spatio-temporal data management—spanning indexing, compression, quality assurance, and learned system design.

Our research investigated indoor spatial queries as a foundation for indoor location-based services (MDM'2022). The contributions included the indoor temporal-variation-aware shortest path query, which accounted for dynamic indoor topology changes using IT-Graph and IT-Index structures (TKDE'2021); a unified framework for crowd-aware path planning that leveraged indoor crowd models, time-evolving population estimators, and graph-based algorithms for fastest-path and least-crowded queries (VLDB'2021); the IKAROS system for top-k keyword-aware routing with browser-server support and route visualization (ICDE'2022); a framework for continuous indoor social distance monitoring that predicted and tracked pairwise distances between moving people in real time (VLDB'2022); and an extensive experimental study and benchmark of models, indexes, and algorithms on real and synthetic datasets, providing insights into their strengths, weaknesses, and optimal use cases (EDBT'2021).

Foundations, Causality, and Generative Models. We developed foundational frameworks and generative models for spatiotemporal data, advancing universal representation learning and data generation across trajectories and time series. We addressed challenges in creating unified models that generalized across tasks, extracted semantics from multi-view data, designed efficient architectures for long-range dependencies, and generated realistic sequences under structural constraints.

In foundational trajectory modeling, we proposed UVTM, which divided trajectory

features into three independently maskable domains for diverse tasks with partial features (TKDE'2025). UniTE provided a survey and unified pipeline that modularized pre-training methods into five key components (TKDE'2025). MMTEC introduced attention-based discrete and NeuralCDE-based continuous encoders to extract travel behavior and reduce biases in pre-trained embeddings (TKDE'2024). For time series foundations, WITRAN introduced water-wave information transmission with bi-granular pattern capture, achieving 5.80%/14.28% improvements and $O(\sqrt{L})$ complexity on long-range forecasting (NeurIPS'2023). DUET used dual clustering on temporal and channel dimensions to handle heterogeneous patterns and capture frequency-domain relationships (KDD'2025). In generative modeling, we developed a structure-aware diffusion model for road-network-constrained trajectories with hybrid discrete-continuous representation (TKDE'2024). STCDM proposed a spatio-temporal contrastive diffusion model with lossless encoding for variable-length check-in sequences (TKDE'2025). To support foundation models for spatial data and GeoAI applications, we proposed Poly2Vec (ICML'2025), a polymorphic Fourier-based encoding approach that unifies the representation of geospatial points, polylines and polygons. Together, these works established a systematic foundation for spatiotemporal data understanding through universal modeling, efficient architectures, and generative approaches.

Sensor Data Analytics. We advanced research on IoT, sensing, and spatiotemporal data analytics through a series of studies. We surveyed and enhanced sensor-based human activity recognition with a multilevel heterogeneous neural network and comprehensive analysis of datasets and challenges (CSUR'2021). We developed methods to improve indoor and IoT sensing accuracy, including attention-based data imputation (ICDE'2023), probabilistic population monitoring (TKDE'2025), and efficient continuous imputation for sensor streams (VLDB'2023). We designed a framework for efficient spatiotemporal quantile monitoring in edge computing (VLDB'2022), developed an open, extensible and developer-friendly testbed for edge-based query processing algorithms (SIGMOD'2025), and analyzed six decades of Brunt Ice Shelf data, revealing instability linked to ocean warming (ISPRS'2024). Finally, we proposed efficient methods for multi-dimensional probabilistic regression over imprecise data streams (WWW'2022).

3.5.2 Deep and Extreme-scale Analytics

Digital Energy. Digital energy emerged as a distinct research topic during the evaluation period. Here, our research focused on developing novel frameworks, models, energy management methods, and forecasting techniques for digital energy. We

primarily addressed challenges related to utilizing energy flexibility, ensuring system scalability, improving operational safety, increasing the accuracy of energy generation and consumption forecasting, and protecting the privacy of information sharing. The work on FlexOffers, our general and scalable technology for energy flexibility, was done according to the plan. FlexOffers were extended to support storage in the form of batteries (SmartGridComm'2021), conversion from electricity to heat and back (ACM e-Energy'2023), various types of uncertainty (ACM e-Energy'2023), a number of explicit a-priori metrics of energy flexibility (ACM e-Energy'2024), and peer-to-peer trading of both flexibility and energy based on blockchain (ACM e-Energy'2025, TLDKS'2025). FlexOffers were successfully used in a large-scale pilot with 500+ prosumers across three countries (ACM e-Energy'2022). In terms of frameworks, we proposed a four-layer framework for energy-computing integrated systems (Energy Internet'2025), a controllable energy planning architecture (ICCSIE'2023), two model-agnostic frameworks—i.e., multichannel network and twin network frameworks (TII'2024)—and an information-theory-based framework for quantifying fluctuations (TII'2024) to support the development of the Energy Internet. In terms of models, we proposed an energy dispatch model considering geo-data centers (J. Mar. Sci. Eng.'2024), a dynamic modeling method for electricity-gas systems with electric-driven compressors (TSG'2025), and a secondary control model for shipboard microgrids under disturbances (TTE'2024). In another line of work, an ontology was made to integrate Web of Things with smart buildings to enable smart energy services to search and discover building metadata and controllable devices (ESWC'2022, Procedia Comput. Sci.'2022). As a continuation of this, an extension of the standard ontology SAREF4ENER was proposed to integrate full support for the complete FlexOffer model (arXiv'2025). Work continued on the Danish National Data Lake for Energy at CenterDenmark (BigData'2020).

We proposed several distributed energy management methods, including resilient energy management methods against stealthy attacks (TCYB'2025) and DoS attacks (TNSE'2022), an energy-harvesting trading method (TGNC'2025), a privacy-preserving economic dispatch method (TII'2024), and a blockchain-based electricity data trading method (TII'2024). In terms of forecasting, we considered forecasting of energy flexibility for heat pumps (ACM e-Energy'2021) and extensions to federated domain adaptation (ACM e-Energy'2023) and so-called selective forecasting that avoided predictions when model confidence was low (ACM e-Energy'2025). Forecasting of short-term loads in an energy-efficient way (ACM e-Energy'2025), solar irradiance for photovoltaic panels (Sensor Letters'2022), energy use of electric vehicles (SSTD'2021), and energy savings and balancing in wireless sensor networks (IEEE Access'2024) was also considered. In addition, we proposed next-

generation time series management for large-scale renewable energy data (ADBIS'2023) and advanced spatial IoT data (SID) research on quality, analysis, and uncertainty through unified frameworks and benchmarks (CSUR'2022, Frontiers'2022, SIGMOD'2022). Finally, in collaboration with the HCC group, work was done on aligning developer assumptions and household expectations for the design of energy IT systems (NordiCHI'2022).

Prescriptive Analytics. As planned, the SolveDB platform for SQL-based prescriptive analytics was extended to support the full prescriptive analytics workflow with new modeling, prediction, and optimization features (EDBT'2021). Given the major trend towards energy-efficient computing, the planned Spark-based prescriptive analytics platform was not pursued. Instead, a major survey of prescriptive analytics applications and their methods and workflows was conducted (Inf. Syst.'2025).

IoT Data Management. Our open-source time series management system ModelarDB (ICDE'2021) (the old implementation is now referred to as ModelarDB Legacy) was extended with support for ingesting IoT time series on edge nodes, compressing them using new techniques, and efficiently transferring the compressed data to cloud nodes (TLDKS'2023). A complete rewrite of ModelarDB with support for edge nodes, cloud nodes, and clients was made. The rewrite was implemented in Rust using the lessons learned and new technologies such as Apache DataFusion and Delta Lake (VLDB'2025). The rewrite, a new model fitting method, and new model types significantly improved performance, e.g., storage use was reduced by up to 44%, while also removing parameters. The impact of ModelarDB lossy compression for machine learning was evaluated. For example, the results show that lossy compression with a low error bound has no or even a positive effect on wind turbine analytics (BigData'2022) and time series forecasting (EDBT'2024). This work also led to a novel autocorrelation-preserving time series compression method (EDBT'2026).

Much of this work was motivated by challenges from handling data generated by modern wind turbines (ICDE'2024, PVLDB'2024). ModelarDB was, however, also used and extended in our ongoing collaboration with researchers in wireless communication for end-to-end data management (ADBIS'2023) in future 6G networks (ICC'2025) based on a theoretical analysis (I&C'2025). In addition, work on a metric for query-aware data freshness named Query Age of Information was done (ICC'2021, TCOM'2022).

Digital Twin. Digital twins also emerged as a new research topic within the evaluation period. Our research developed novel frameworks and modeling methods for digital twins (DTs) as well as their applications. We addressed key challenges in creating high-fidelity DT models, considering dynamics representation, computational

and sampling efficiency, privacy preservation, and robustness to cyber-attacks.

In terms of frameworks, we proposed a "three layers + four attributes" reference architecture of a DT to support the development of Industrial Internet (Fundam. Res.'2024), a five-dimensional framework of networked DTs for Autonomous Vehicles (TIV'2024), and a DT-empowered autonomous driving framework for e-mobility (IEM'2024). In terms of modeling, we proposed a federated DT modeling method that could mimic the intrinsic dynamics and operational mechanisms of the physical world (TICPS'2025). By leveraging Gumbel-based policy improvement and a consistency-loss regularizer, we designed a DT model with enhanced computational and sampling efficiency (EI2'2024). By combining a digital physical model and a neural network model, we proposed a new DT model that was used to solve prediction problems with enhanced prediction accuracy (MPCE'2024). In terms of applications, we proposed a DT-empowered peer-to-peer energy trading method (TNSE'2025) and a DT-assisted economic dispatch method (TASE'2025) in cyber-physical energy systems, both of which achieved globally optimal solutions with theoretical guarantees. Finally, a comprehensive survey was provided to summarize the development and challenges of DTs (ICCSIE'2024).

Other Activities. Work continued on the programmatic Extract-Transform-Load framework pygrametl (TLDKS'2021). A tool was also made to do analytics with data cubes in Python (DaWaK'2024).

3.5.3 Data Science for Interdisciplinary Research

Neuroscience. Our works built a signals-to-insights stack for decoding cognitive and affective states from EEG and peripheral physiology. Outputs included MEMA, a multi-label attention dataset for online learning with a standardized paradigm and baselines (ICASSP'2025), and automated EMG-referenced labeling with a pseudo-online evaluation suite for self-paced movement EEG (KBS'2023). For affect, we localized emotion with hierarchical self-attention and channel selection (TAC'2022) and surveyed multimodal EEG emotion recognition with emphasis on fusion and incomplete modality learning (TIM'2024). Methodologically, AutoEER improved SEED and DEAP performance (JNE'2023), and cross-modal credibility modeling with intra-modal and inter-modal transformers plus sequential pattern consistency boosted DEAP and MAHNOB (JNE'2024). Together these outputs delivered a reliable multimodal pipeline for attention monitoring, affect-aware human-computer interaction, and online BCI deployment.

Medical Imaging and Health Monitoring Our work advanced low-cost cardiac monitoring and robust imaging analytics. We turned smartphones into ECG mon-

itors by converting chest-wall SCG to ECG with SWT denoising and a depthwise-separable encoder-decoder, achieving low interval errors across 30 users and enabling real-time arrhythmia/ischemia screening via a demo app (IMWUT'2023). For CT lung nodules, we paired ML-CNNs with HOUSES, a surrogate-assisted evolutionary tuner using a nonstationary GP kernel (spatial transforms + Kumaraswamy warping) and importance-guided mutation, outperforming TPE, grid/random, and stationary-kernel GP (TEVC'2021). Together, we provided a scalable pipeline from ubiquitous physiologic sensing to AutoML-optimized imaging for early detection and telehealth.

Materials and Chemistry. Our work enhanced crystal property prediction by tackling both data scarcity and physical invariances. CROP employed a mutually exclusive mask pre-training strategy to leverage unlabeled data and integrated multi-graph attention (MGA) and crystal knowledge-enhanced (CKE) modules to capture periodic patterns and domain knowledge. Experiments across eight datasets demonstrated that CROP delivered superior performance, particularly on small and medium datasets, where it achieved improvements ranging from 2.64% to 16.67%. These results confirmed our initial goal of addressing the challenge of limited labeled data in crystal property estimation (ECML-PKDD'2024). We advanced the inverse design of disordered materials through AMDEN (Amorphous Materials DEnoising Network), a diffusion-based framework for property-controlled generation of amorphous structures. AMDEN employed an equivariant graph neural network to preserve rotational and translational invariance, integrated desired material properties as conditions through Independent Condition Guidance, and generated valid structures via multi-step Monte Carlo denoising starting from Gaussian noise (NeuIPS'2025).

Education. Our works enhanced knowledge tracing with forward-looking and learner-aware models. DGMKT built dual-graph student profiles and modeled mastery with Mamba to overcome forgetting in long sequences, achieving SOTA on four benchmarks including KDDCup2010 and ASSIST2017 (ECML-PKDD'2025). Together these outputs provided trend-aware and student-aware KT for scalable personalization in intelligent tutoring.

3.5.4 AI and Machine Learning

Neural Architecture Search (NAS) / AutoML. We advanced principled differentiable search and task-specific automation. iDARTS scaled bilevel NAS via stochastic implicit hypergradients and yielded strong visual cells (ICML'2021). BaLeNAS treated architecture learning as Bayesian distribution optimization, improving sta-

bility and accuracy (CVPR'2022). We explained and fixed DARTS operation selection using influence functions (NeurIPS'2022), and modeled operator dependencies to shrink the search space with DaNAS (ECCV'2024). Beyond vision, AutoCTS, AutoCTS+, and AutoCTS++ jointly searched architectures and hyperparameters for correlated time series under resource and transfer constraints, with results (VLDB'2021, SIGMOD'2023, VLDBJ'2024).

Graph Neural Networks (GNN). This research direction focused on explainable and trustworthy frameworks for GNNs, making black-box predictions more transparent and actionable. We proposed new paradigms of explanation generation through optimization, user-friendly structures, and counterfactual reasoning, leading to multiple high-quality publications and collaborations. The first work, GVEX (ICDE'2024), introduced view-based explanations that represented interpretations as queryable graph views, offering finer-grained, configurable, and approximation-guaranteed solutions for domain experts. The second work, RoboGExp (SIGMOD'2024), developed robust explanations that remained reliable under adversarial perturbations. By integrating robustness verification with counterfactual reasoning, it ensured trustworthy insights in security-sensitive applications. The third work, Counterfactual Evidence (KDD'2025), identified similar yet counterfactual instances from the dataset to provide intuitive, comparative explanations, enabling direct contrast between factual and counterfactual cases. Together, these works advanced GNN explainability by balancing fidelity, robustness, and usability.

Reinforcement Learning. Our work targeted two categories: single-agent and multi-agent reinforcement learning. For the first category, we proposed a reward-sharing-mechanism-based reinforcement learning method by integrating potential-based and intrinsically motivated rewards, resulting in enhanced exploration efficiency and representativeness (TIM'2025). We proposed RobustZero, a novel MuZero-class framework that employed a self-supervised representation network and an adaptive adjustment mechanism to provide robustness guarantees against worst-case and random-case perturbations (ICML'2025). A query-aware deep reinforcement learning method was proposed to achieve application-timing-aware adaptive scheduling that improved both accuracy and efficiency (TCOM'2023). For the second category, we proposed a shared reward-function-based multi-agent reinforcement learning method that could balance the local goals of individual agents and the joint objective (EPSR'2025).

Federated Learning. Our works advanced the foundations and applications of federated learning across communication efficiency, uncertainty modeling, and fault-tolerant intelligence in distributed systems. FedAPT, FedAGL, and FedCDC introduced adaptive parameter control, bandwidth allocation, and channel-power

co-optimization to minimize communication overhead and enhance efficiency in federated vehicular networks (IoTJ'2024, TIV'2024, IoTJ'2025). To ensure robustness under unreliable or unlabeled clients, we proposed CFT-FSSL, a client-level fault-tolerant semi-supervised FL framework (TNSE'2025), and FedSI, a Bayesian subnetwork inference approach for scalable uncertainty quantification in personalized FL (TNNLS'2025). Together, these studies established a unified pipeline for privacy-preserving, communication-efficient, and uncertainty-aware federated intelligence across dynamic and heterogeneous environments.

AI for DB. Our research in "AI for Database Systems" focused on leveraging machine learning and deep learning to enhance core database operations, including query optimization, cost estimation, and efficient data processing. We proposed a graph representation learning-based model for answering approximate queries with multiple aggregate functions (VLDBJ'2025). We introduced a graph-based representation learning approach for efficient join order selection, significantly improving query planning (KDD'2022). To address query cost estimation, we developed a method that efficiently utilized pseudo-labels for robust learning (CIKM'2022). Our work also advanced data filtering through learned Bloom filters, enabling efficient multi-key membership testing (DASFAA'2023, DSE'2023). Collectively, these contributions showed a cohesive effort to infuse intelligence into database systems, driving forward their efficiency, adaptability, and scalability.

Large Language Models. Our research on large language models (LLMs) for spatiotemporal data mining developed frameworks that leveraged the semantic understanding capabilities of LLMs to analyze human mobility data and vehicle trajectories. We addressed challenges in extracting visiting intentions, travel preferences, and movement patterns from spatiotemporal sequences.

Mobility-LLM reprogrammed check-in sequences to understand human visiting intentions and travel preferences through a visiting intention memory network and human travel preference prompts, outperforming existing location-based service models (NeurIPS'2024). Path-LLM introduced multi-modal path representation learning that aligned topological and textual road network data using contrastive pretraining and dynamic fusion, achieving up to 61.84% improvement in path ranking (WWW'2025). TrajCogn incorporated a trajectory semantic embedder that enabled LLMs to extract movement patterns and travel purposes, demonstrating versatility across trajectory mining tasks (IJCAI'2025). TransferTraj achieved region and task transferability through a multi-modal encoder with spatial context mixture-of-experts, enabling zero-shot and few-shot transfer (NeurIPS'2025). PLMTrajRec used pre-trained language models for scalable trajectory recovery with area flow-guided prompts and road condition passing mechanisms (NeurIPS'2025). These

works advanced human mobility analysis, intelligent transportation systems, and path-based applications.

Computer Vision. Our research focused on person re-identification (re-ID), object tracking, and object detection by leveraging deep learning to enhance the feature representations. In re-ID, our research first explored Unsupervised Domain Adaptation (UDA). Our work proposed a novel body structure estimation (BSE) and label refinery mechanism to enhance reliable feature representations in the foreground areas (KBS'2022). We then researched re-ID on Unmanned Aerial Vehicles (UAVs), where a novel Multi-granularity Attention in Attention (MGAiA) network was proposed to satisfy the raised demands for aerial-based re-ID (VisualComputer'2024). In object tracking, we proposed a residual memory inference network (RMIT) to exploit the history of target states and last visual features (InformationScience'2022). In few-shot object detection (FSOD), we proposed Self-Supervising and Cooperative Classifier (FS3C) to consider the structural and semantic information of the image itself and solve the misclassification between data-abundant base classes and data-scarce novel classes efficiently (TNNLS'2024).

3.5.5 Unanticipated Research Directions

High Performance Systems. One line of this direction focused on distributed training of GNNs, yielding outstanding results. It addressed distributed training tasks for both static and dynamic graphs and proposed systematic optimization strategies in aspects such as communication optimization, optimal partitioning, batch training modes, distributed parallel architectures, sampling strategies, and caching strategies. These optimizations significantly improved the training efficiency of distributed GNNs. Our research drove advances in existing technologies and applications, resulting in multiple high-quality publications and new collaborations.

The first work introduced ADGNN, a hybrid online–offline sampling framework that reduced sampling overhead and information loss in distributed GNN training. By adaptively adjusting sampling frequency and minimizing aggregation errors, ADGNN greatly improved model convergence (SIGMOD'2023). The second work, DynaHB, was an asynchronous, communication-free framework for distributed temporal GNNs. With load-aware vertex partitioning, a hybrid-batch mode, and a reinforcement-learning–based batch size controller, DynaHB significantly boosted training efficiency (VLDB'2024). The third work presented SWASH, a flexible communication framework for temporal GNNs that lowered storage costs and communication overhead by enabling efficient data exchange, merging boundary nodes,

and sharing cache with a sliding-window mechanism (SIGMOD'2025).

We also developed a novel GPU-accelerated transaction processing system specifically designed for vectorized execution. The results of our research showed that the GPU-accelerated transaction processing system achieved excellent performance on industry-standard benchmarks (ICDE'2024). Although research in this area was still evolving, we foresaw its immense potential for high-performance transaction processing.

Data Management and Analytics for Blockchains. This research direction focused on data management, analysis, and verifiable queries for blockchain systems. It addressed both the fundamental challenges of blockchain data processing and the emerging need for trustworthy querying and verification in decentralized environments. Our work systematically explored efficient data management frameworks, advanced analysis methods, and verifiable query mechanisms, thereby extending the boundaries of blockchain data management, producing high-quality outcomes, and fostering new collaborations.

Specifically, in blockchain data management, we developed automated ETL and blockchain data mining methods for Ethereum, building scalable data organization and extraction mechanisms to support complex processing tasks (WSDM'2022). In blockchain data analysis, we conducted systematic studies of Ethereum blockchain graph datasets and methods (VLDB'2024, ICBC'2022, CIKM'2022), proposed a machine learning-based framework for blockchain data analysis (DLT:RP'2024), and introduced a trend detection method based on data depth and cores (Front. Blockchain'2024). These works revealed the structural properties of blockchain transaction networks and demonstrated the potential of machine learning and graph methods in blockchain data processing. In verifiable queries, we proposed the VGQ framework for verifiable graph queries on blockchain systems (ICDE'2025), designed the VeriDKG engine for verifiable SPARQL queries over decentralized knowledge graphs (VLDB'2023), and built the Pistis platform to support ownership-preserving decentralized knowledge graph queries (VLDB'2025).

3.5.6 Projects and Funding

Projects

We briefly describe the main selected projects active during the period. Note that this evaluation only reports projects whose periods overlap with the research evaluation by more than three months. The projects are sorted by start time in ascending order; if the start times are the same, they are sorted by end time in ascending

order. Some projects are collaborative; therefore, the DESS share is reported in addition to the total funding.

Villum Kann Rasmussen Annual Award, 2013–2021, DKK 1,974,226. This grant was used to provide back-up funding, enabling considerable agility in the hiring of temporary staff, notably postdocs, and Ph.D. students. This has had a very positive impact on hiring quality and volume.

Erasmus Mundus Joint Doctorate in Information Technologies for Business Intelligence - Doctoral College, 2013–2021, DKK 7,080,480. This is a doctoral programme addressing fundamental challenges in business intelligence. Upon completion, graduates are awarded a joint degree from two universities of the consortium.

NRP75 Relief Support, 2016–2022, DKK 1,085,000. This grant offers relief support in relation to Christian S. Jensen's service as president of the steering committee of the Swiss National Research Program 75 on Big Data.

RESPONS, 2018–2021, DKK 1,940,625. The purpose of this project is to increase the usage of demand-response transportation (DRT) in rural areas in the Baltic/Scandinavian area.

Analytics of Time Series in Spatial Networks, 2018–2021, DKK 2,556,000. The project aims at providing accurate and scalable learning algorithms for correlated time series analytics, such as forecasting and outlier detection.

SEMIOTIC, 2018–2022, DKK 2,045,858. The project aims to integrate concepts and techniques from wireless communication and big data analytics to enable integrated and optimized communication and analytics on massive amounts of IoT sensor data.

Data Management Foundations for Indoor LBS, 2019–2021, total funding: DKK 5,655,534, DESS share: DKK 2,764,551. The project is intended to create a prototype indoor data management system with general, systematic, and solid data management foundations upon which indoor location-based services (LBS) can be built to provide location-dependent information efficiently and effectively to users in a broad range of indoor scenarios.

Algorithmic Foundations for Data-Intensive Routing, 2019–2021, DKK 287,

986. This is a framework grant administered by Aalborg University that supports international networking activities in data-intensive routing.

EDAO: Example Driven Analytics for Open Knowledge Graphs, 2019–2021, DKK 1,544,474. The proposed research project has the goal to provide methods to support the understanding of the information represented by LOD repositories and to provide easy access to their content. To address this need, the researcher aims to develop an Exploratory Analytics System for LOD.

Flexible Energy Denmark, 2019–2023, total funding: DKK 6,400,000, DESS share: DKK 3,128,238. This project aims to create the next generation of intelligent, integrated energy systems based on Big Data and AI to pave the way for the green transition.

Light-AI for Cognitive Power Electronics, 2019–2023, total funding: DKK 2,996,278, DESS share: DKK 1,489,660. This project aims to design and develop light-AI, including computation-light AI and data-light AI, to enable cognitive power electronics.

A Data-Intensive Paradigm for Dynamic, Uncertain Networks, 2019–2023, DKK 5,882,400. The project aims at fleshing out a data-intensive paradigm to enable dynamic, uncertain networks, with a focus on applications in transportation.

MALOT: Managing Mobility Data Quality for Location of Things, 2020–2022, DKK 1,636,068. Location of Things is an IoT paradigm for mobility analytics, in which massive mobility data is being gathered, processed, and transmitted among heterogeneous data nodes in a decentralized architecture. This project aims to develop new data quality management techniques adaptive to the Location of Things.

Self-adaptive, Automated ETL Flow Management, 2020-2023, DKK 250,000. The project develops an adaptive framework for automating ETL processes, enabling dynamic adjustment to changing data sources and improving efficiency in data engineering.

FEVER, 2020–2023, total funding: DKK 4,188,000, DESS share: DKK 2,512,800. The project builds on the GOFLEX project and will further develop the FlexOffer concept and techniques in the GOFLEX platform to include more powerful flexibility aggregation and management, both central and P2P (blockchain-

based) flexibility trading, and increased use of AI. The resulting system will be demonstrated in 4 large trials in DE, ES, HE, and CY covering the residential, govermental, commercial, transport, and industrial sectors.

domOS, 2020–2023, total funding: DKK 4,304,000, DESS share: DKK 2,220,460. The project will develop and demonstrate an operating system for smart services in buildings where different IoT platforms and applications can be integrated seamlessly.

Management of Real-time Energy Data - MORE, 2020–2023, DKK 4,761,803. The project will extend the ModelarDB system to provide efficient model-based time series management on both edge and cloud and provide rich and fast analytics and machine learning functionality.

Data-based recruitment of football players, 2021–2022, DKK 500,000 from AAU and DKK 363,000 from Aalborg Boldspilsklub A/S. As an alternative or supplement to scouting, the project aimed to leverage widely available player tracking data for identifying potential football players for recruitment.

ISTeP: Enabling Industrial-Strength, Open-Source Temporal Query Processing, 2021–2022, Autonomous Province of Bozen-Bolzano, total funding: EUR 260,000. (DESS benefits through collaboration.) This project improves query processing for temporal alignment by adding operator-specific alignment primitives, better cost estimates, and new optimization rules to cut redundant intermediates and scale execution.

Qualified Workforce for Lighthouse South: Green Energy and Sector Coupling, 2021-2023, total funding: DKK 18,342,324, DESS share: DKK 407,000. The project aims to foster talent development and industrial advancement in green energy and sector coupling through innovative applications of data engineering and data science.

Explainable AI for Complex Microbial Community Interactions and Predictions, 2021–2024, DKK 2,995,778. This interdisciplinary project brings together microbiology and AI to develop interpretable machine learning models that uncover and predict microbial interactions in water resource recovery facilities. It aims to identify key drivers of community dynamics and support performance optimization of biotechnological systems.

Mobility Analytics Using Sparse Mobility Data and Open Spatial Data, 2021–2025, total funding: DKK 9,410,000, DESS share: DKK 1,775,598. A bridge project between academia and companies under DIREC, targeting mobility analytics from sparse mobility data and open spatial data to support efficient, predictable, and environmentally friendly mobility.

Data Engineering for Data Science (DEDS), 2021-2025, total funding: DKK 8,866,156, DESS share: DKK 6,649,617. This MCSA Joint Doctorate trains a total of 15 PhD's, of which 3 are hired and a further 2 hosted at DESS. The overall aim is to provide holistic support for the end-to-end management of the full lifecycle of data, from capture to exploitation by data scientists.

Digital Energy Hub, 2021–2025, total funding: DKK 20,400,000, DESS share: DKK 1,350,000. Funded by Industriens Fond, this project aims to build a data-driven innovation ecosystem for the Danish energy sector. The hub will operate a Data Lake-centered platform, host innovation sprints, bridge industry and research, and support SMEs and larger firms in developing AI/IoT-based energy solutions.

Multimodal Data Processing of Earth Observation Data, 2022–2025, total funding: DKK 12,270,000, DESS share: DKK 1,789,920. Funded by DIREC, this project aims to support the digital acceleration of the green transition by strengthening the data foundation for environmental data.

MobiSpaces, 2022-2025, total funding: DKK 65,700,000, DESS share: DKK 2,409,609. This project project develops sustainable data management solutions for the mobility sector, enhancing data-driven decisions to improve efficiency, safety, and sustainability in smart transport.

NNF Recruit: Data Management, Algorithms & Machine Learning, 2022–2027, Novo Nordisk Fonden, DKK 10,000,000. This recruitment grant supports a multi-year research program led by Arijit Khan on data management, algorithms, and machine learning within the Data Engineering, Science and Systems group at AAU.

Next Generation Spatial Data Management for Virtual Spatial Systems, 2023-2026, Australian Research Council, total funding: AUD 480,000; DESS in-kind funding: AUD 45,864. Covers travel for collaboration. The project investigates data retrieval methods that self-optimize for high query effi-

Table 3.1: External funding attracted by DESS (2013–2025)

Start Year	New Projects	Amount in DKK
2013–2020	17	43,160,629
2021	7	15,980,593
2022	3	14,199,529
2023	1	210,974
2024	2	2,155,411
2025	1	3,168,000
Total	31	78,875,136
Total new (2021–2025)	**14**	**35,714,507**

ciency and accuracy by utilizing underlying real-world data patterns. It will enable novel applications for virtual spatial systems with large-scale querying needs, benefiting location-based service providers and emergency management agencies.

6G-XCEL, 2024-2026, DKK 2,152,650, DESS share DKK 1,076,325. This project brings together EU-US partners to advance AI-native 6G networking, implementing the DMMAI (Decentralised Multi-party, Multi-network AI) framework across federated testbeds. It targets interoperable, secure and sustainable edge-to-cloud intelligence for future 6G systems.

Inverse Design of Materials Using Diffusion Probabilistic Models, 2024–2026, Villum Fonden, total funding: DKK 2,366,102, DESS share: DKK 1,079,086. This project explores the use of diffusion probabilistic models for inverse design in materials science. By integrating generative AI with materials modeling, the project aims to discover and optimize novel materials with desired physical and chemical properties.

Fair Task Assignment with Worker Preferences and Supply-Demand Prediction in Spatial Crowdsourcing, 2025-2029, Independent Research Fund Denmark (DFF), DKK 3,168,000. The project works on fairness-aware task assignment in spatial crowdsourcing, integrating worker-preference modeling and supply-demand prediction to improve efficiency and equity.

Funding

Table 3.1 lists funded projects grouped by starting year. As can be seen, the group has received funding from 31 projects during the period, with a total funding of

Table 3.2: Publications according to the CORE and ICORE categories

	A*	A	B	C
Journals	57 (30.81%)	1 (0.54%)	9 (4.86%)	2 (1.08%)
Conferences	228 (65.71%)	46 (13.26%)	28 (8.07%)	4 (1.15%)

Table 3.3: AI-related publications according to the CORE and ICORE categories

	A*	A	B	C
Journals	35 (33.65%)	1 (0.96%)	7 (6.73%)	1 (0.96%)
Conferences	160 (70.80%)	32 (14.16%)	14 (6.19%)	1 (0.44%)

DKK 78.88 million (EUR 10.57 million), a decrease of 26.15% over the previous period. Of these projects, 14, totaling DKK 35.71 million (EUR 4.79 million), started during the period. As can be seen, the amounts of projects and funding vary considerably from year to year, but were generally stable over the period.

Future Projects

Sustainable Water-based Cooling in Megacities (SWiM), 2026-2030, Poul Due Jensen (Grundfos) Foundation, total funding: DKK 60,000,000, DESS share: DKK 2,810,000. This project includes a large multidisciplinary consortium of 11 research groups across AAU, Aarhus University, and Nanyang Technological University. DESS will lead the work on sector coupling of the electricity and district cooling systems. Specifically, the FlexOffer technology will be extended to utilize energy flexibility for cross-sector optimization and trading between electricity and (district) cooling.

3.6 Own Evaluation

3.6.1 Scientific Output, Excellence, and Impact

The group prioritizes publishing its best research in leading general journals and conferences within its core scientific areas (mainly data management, but increasingly also in machine learning). Other results are published in top specialized venues in subfields such as spatio-temporal data management, mobile services, data warehousing, semantic web, and e-energy systems. Publications in general outlets with

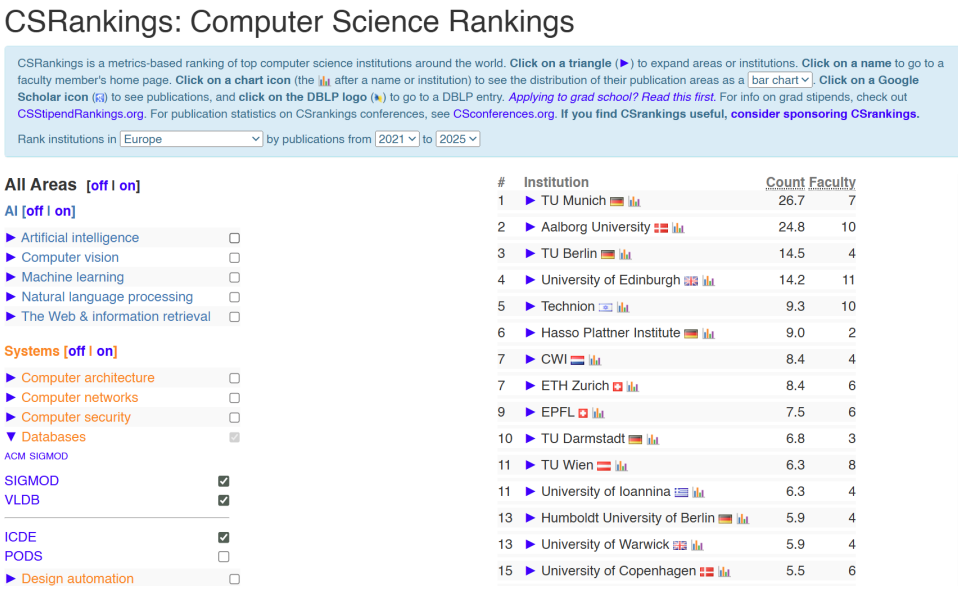


Figure 3.3: Ranking of universities in Europe, from csranking.org, based on full papers in SIGMOD, VLDB, and ICDE during 2021—2025

limited prestige and quality control are given the lowest priority. This strategy aims to improve the impact, visibility, and peer recognition of the group.

The group published 532 refereed journal and conference papers during the period. Table 3.2 reports the breakdown of conference and journal publications according to the ICORE and CORE rankings. As can be seen, a substantial number of papers are published in ICORE/CORE A* venues. Note that some journals and conferences have yet to be included in both ranking systems and that the percentages in Table 3.2 are relative to the total numbers of 185 journal and 347 conference publications.

The group published 330 AI-related refereed journal and conference papers during the period. A substantial proportion of AI-related papers are published in top-tier venues, with 70.80% of the conference papers and 33.65% of the journal papers appearing in ICORE/CORE A* venues. Again, some journals and conferences have yet to be included in both ranking systems, and the percentages in Table 3.3 are relative to the total numbers of 104 journal and 226 conference publications. This represents a major shift in the group's research compared to previous evaluation periods. Further, this development aligns with general developments in computer science.

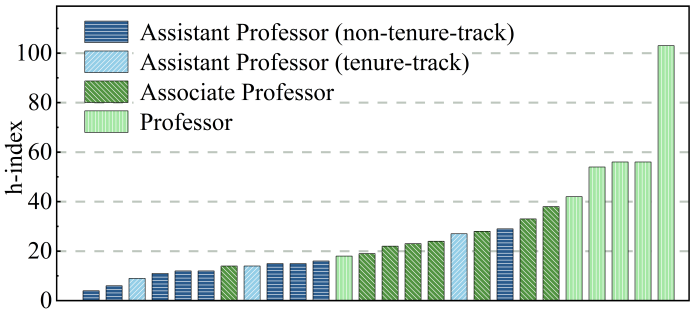


Figure 3.4: Google Scholar h-indices of DESS staff, assistant professor level and above

According to the widely used csrankings.org, focusing on publication of full papers in the top-3 database systems conferences (SIGMOD, VLDB, and ICDE), which align with the main focus of the group, the group ranks *number two* in Europe in the period, ahead of TU Berlin, ETH, and EPFL, as shown in Figure 3.3. In the same period, the group ranks *number eleven world-wide*, ahead of any North American group. Further, the group has good connections to the nine Asian institutions that rank higher.

The group's publications are frequently cited. According to Google Scholar, 105 publications have over 50 citations and 16 have over 100 citations. Figure 3.4 shows the group's scientific impact, measured by its Google Scholar h-index at the end of the reporting period.

DESS's members have given 20 keynotes, 31 other invited talks or lectures, and two tutorials. Members of the group have also received prestigious awards and recognition in the reporting period, such as ACM Fellow (the second in the group), Honorary Doctorate (dr. h.c.) of TU Dresden, IEEE Computer Society Distinguished Contributor, AAIA Fellow, AIIA Fellow, ACM SIGMOD Contributions Award, IEEE Senior Member, World's Top 2% Scientists, KDD 2025 Outstanding Reviewer, and VLDB 2025 Distinguished Reviewer.

Additionally, the group's publications have received top awards in leading venues such as IEEE EI^2 2024 Best Theoretical Paper Award, MDM 2024 Best Paper Runner-up Award, MPCE 2024 Best Paper Award, VLDB 2024 One of the Best Papers Award, DASFAA 2023 Best Student Paper Runner Up Award, ICCSIE 2023 Best Paper, APWeB-WAIM 2022 Best Paper Award Runner Up, ICDE 2022 Best Paper Award, MDM 2022 Best Industry, Systems and Apps Award, NDBC 2022 Best Student Paper, and SSTD 2021 Best Paper Nomination.

3.6.2 Synergies

Over the past few years, we have witnessed remarkable advances in technologies based on artificial neural networks, and today the most competitive methods for the data management and analytics functionalities targeted by the group now often involve neural networks. In alignment with this general development, the group has embraced neural technologies and now often develops methods that are essentially neural methods or involve neural methods as components. The group has seen considerable collaboration on such methods that have been applied to solve problems in the different application domains, where the group has been active. Thus, the joint focus on neural methods has created synergies among foundational research topics, as well as between foundational and applied research. For example, the latter is seen in the use of neural technologies for challenges in relation to the area of vehicular transportation, the maritime domain, and the energy domain. Specifically, a range of solutions employ joint expertise in deep learning in the group across different foundational topics and across the foundational/applied boundary.

- Within the transportation domain the group has significant experiences with handling GPS and fuel consumption data. This has led to synergies across multiple projects relating to data from cars and ships. The synergies are at the data-engineering level where overlap in modeling movements at different levels of granularity and the overall ETL data flow, e.g., PygramETL, has been a common denominator. Ideas from data integration used for cars have been reused in the maritime domain. The land and maritime domains also overlap with respect to data imputation, data cleaning, movement predictions, and estimation of CO_2 emissions.

- Within the energy domain, the group has significant experience handling both massive time series, e.g., from wind turbines, as well as data related to energy flexibility, e.g., energy consumption, production, prices, and trades. This has led to synergies between the application area of digital energy and foundational data management research. For example, time series data and analytics for wind turbines have inspired compression algorithms, forecasting models, and their interaction, as well as the design of the second generation of the ModelarDB time series management system. Flexibility forecasting for heat pumps has inspired general-purpose ML research on so-called selective forecasting (only forecast when model confidence is high), which was then, in turn, applied to improve flexibility forecasting for heat pumps.

3.6.3 Robust and Diverse Funding Portfolio

As it is important to always have a healthy funding portfolio, the group strives to maintain a robust capacity for maintaining such a portfolio. To achieve robustness, it is important that multiple staff members are able to attract funding as (co-)PI and that staff members are able to attract funding from diverse sources. Figure 3.5 shows the number of projects attracted as (co-)PI for DESS staff. As can be seen, 13 staff members have attracted funding as (co-)PI, and 6 staff members have attracted more than one project as (co-)PI. Thus, many staff members, junior as well as senior, are able to attract their own funding. Thus, the future success of attracting funding is spread across many staff members, which is very encouraging.

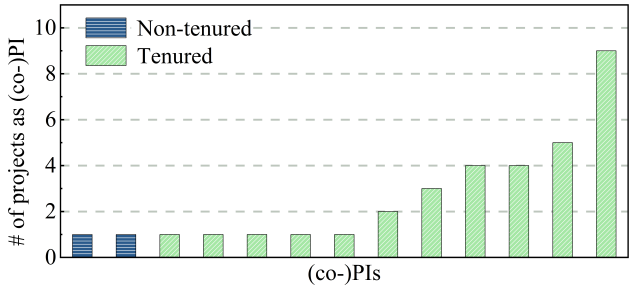


Figure 3.5: Number of projects attracted as (co-)PI across DESS staff

The funding sources are diverse and exhibit balances between Danish versus European sources, public versus private sources, as well as sources that fund independent versus application-oriented research. Figure 3.6 shows the total amount of funding attracted per category.

Danish public excellence pillar councils, including the Independent Research Fund Denmark, account for 8.9% of the funding. Danish strategic councils, including DIREC, the Danish Business Promotion Board (REACT-EU programmes), and AAU framework / industry collaborations, account for 13.5%. European excellence pillar sources, namely the EU Horizon 2020 MSCA Joint Doctorate (DEDS), account for 18.6%. European strategic sources, including EU Horizon Europe collaborative projects (MobiSpaces under Pillar II; 6G-XCEL under the SNS JU) and a regional Italian grant (ISTeP), account for 15.2%. International strategic sources (Australian Research Council) account for 0.6%. Private Danish organisations (foundations including the Villum Foundation, Novo Nordisk Foundation, and Industriens Fond) account for 43.2%. There is a reasonable balance between independent and application-oriented research, with the former category being the largest, driven

primarily by the NNF recruitment grant and Villum-funded basic-research projects. In summary, the group is very satisfied with the level of funding and the fact that it has acquired more large projects from attractive sources than previously.

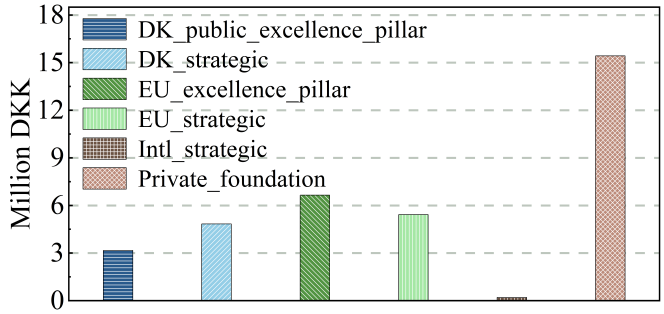


Figure 3.6: Amount of funding attracted per funding category

3.6.4 Ability to Seize Opportunities

As shown in Section 3.5.1, our group performed well across all research topics defined for this evaluation period (see Section 3.4). In addition, we have successfully seized several key opportunities.

- The Villum Synergy Programme provides funding to strengthen interdisciplinary data-driven science in Denmark. DESS successfully seized this opportunity through three collaborative projects.

  The first project Light-AI for Cognitive Power Electronics is a collaboration between Computer Science and Energy on profiling and estimating the energy consumption of SQL queries. It combines data management and software optimization expertise to develop methods for energy-aware query processing and benchmarking. The project aims to advance sustainable software design by providing tools and models that quantify and reduce the energy footprint of data-intensive applications.

  The second project Explainable AI for Complex Microbial Community Interactions and Predictions is a collaboration between Computer Science and Bioscience on explainable AI for modeling and predicting complex microbial community interactions. It integrates explainable machine learning methods with bioscience expertise to develop systems for managing and controlling microbial processes in Danish wastewater treatment plants.

The third project Inverse Design of Materials Using Diffusion Probabilistic Models is a collaboration between Computer Science and Materials Chemistry on the inverse design of glass-ceramic materials using diffusion probabilistic models. It combines advanced machine learning methods with materials science expertise to develop frameworks for designing novel materials with desired properties.

- Digital Research Centre Denmark (DIREC) was established in 2020 as a national research and innovation centre for advanced digital technologies, in a unique partnership between all eight Danish universities and the Alexandra Institute. With funding from public sources, DIREC supports world-class research throughout Denmark. In the period between 2021–2025, DESS secured several grants from DIREC. The grants supported the creation of robust software prototypes for both the maritime and land transport. These prototypes are the foundation for several research papers and external collaboration. A most recent grant GREENSQL will support research on profiling and estimating energy consumption of SQL queries in software, under DIREC's Next-Generation AI program.

- Large Language Models (LLMs) emerge as a new paradiam for spatio-temporal data and time series data analytics. Empowered by the powerful generalization capabilities of LLMs, we propose serial research methods for effective spatio-temporal data and time series analytics. First, we propose a Parameter-efficient Federated Anomaly Detection framework named PeFAD (IEEE TMC'2025) with the increasing privacy concerns, which bridges the gap between the decentralized time series data and the centralized anomaly detection algorithms. Further, we introduce TimeKD (ICDE'2025), an efficient multivariate time series forecasting framework that leverages the calibrated language models and privileged knowledge distillation. TimeKD aims to generate high-quality future representations from the proposed cross-modality teacher model and cultivate an effective student model. Additionally, Multi-source Irregular Time-Series Transformer (MITST) (CSBJ'2025) is a pre-trained model for healthcare time series that represents irregular Electronic Health Record (EHR) data using hierarchical attention within each timestamp and across sources such as laboratory tests, medications, and vital signs. MITST aligns events from multiple sources without hand-crafted aggregation and learns end-to-end representations suitable for transfer to downstream clinical tasks.

3.6.5 Scientific Service and Recognition

Members of the group have served the scientific community in a number of leadership roles that indicate substantial peer recognition, including member of Springer Nature European Research Advisory Council, member of the ACM SIGMOD Advisory Board, Associate Editor of IEEE Transactions on Intelligent Vehicles, IEEE Network Magazine, IEEE Transactions on Industrial Informatics, IEEE Transactions on Automation Science and Engineering, IEEE Systems, Man, and Cybernetics Magazine, Data Science and Engineering, Journal of Modern Power Systems and Clean Energy, IET Cyber-Physical Systems: Theory & Applications, and Area Editor of IEEE Transactions on Big Data and Springer Encyclopedia of Database Systems. They have served as program committee co-chairs, vice chairs, and general chairs for a range of conferences, including ICDE, ACM e-Energy, SIGSPATIAL, IJCNN, PAKDD, SSTD, DASFAA, MDM, and NDBC, and have co-organized several workshops. This is in addition to other leadership services and a very substantial number of program committee memberships for ICORE A* conferences such as SIGMOD, VLDB, ICDE, WWW, KDD, and NeurIPS. Group members have also served on award committees, including test-of-time award committees for MDM in 2021, 2022, 2023, and 2024, best paper award committees for EDBT in 2021 and 2024, and best paper award committee for SIGMOD in 2022. In particular, Wolfgang Lehner was elected an ACM Fellow in the 2025 selection round, doubling the number of ACM Fellows in the group.

They have also taken on broader governance roles through the Board of Directors of the Danish National Research Foundation, serving as member, Acting Chair, or Vice Chair 2021 to present. In addition, they also contribute to research evaluation and funding decisions through service on major committees and panels, including the evaluation committee and mid-term evaluation committee for Future Software Systems (Swedish Foundation for Strategic Research) October 2021 to April 2022 and September to November 2025, the ERC Consolidator Grants panel PE6 Computer Science and Informatics 2025, chair of the CHISTERA Call 2023 MultiGIS evaluation panel May to November 2024, assessment panels for Research Council of Norway collaborative projects in Digital Security and Artificial Intelligence, Robotics and Autonomous Systems December 2021 to February 2022 and in Service Industries December 2020 to January 2021, and the evaluation committee for the midterm evaluation of HEIBRiDS (Helmholtz Foundation) October 2022.

3.6.6 Education of Researchers

The group has maintained a strong focus on researcher training. In total, 21 Ph.D. students started their studies during the reporting period, including students from top universities worldwide (e.g., Peking University). Most Ph.D. students have been highly productive, typically publishing at least three high-quality papers in top venues during their studies.

During the same period, 17 Ph.D. students successfully defended their theses, and 15 remain active as of December 2025. Graduates now hold positions at leading national and international institutions, including the National University of Singapore, The Hong Kong Polytechnic University, the Technical University of Berlin, Fiftytwo A/S, Norlys Energy Trading A/S, and Arla A/S.

The group attracted nine visiting Ph.D. students during the reporting period, specifically from Zhejiang University, Beijing Jiaotong University, Northeastern University, Southwest Jiaotong University, and the University of Electronic Science and Technology of China.

In addition, 12 postdoctoral researchers were hired during the evaluation period. Of these, nine have continued within the group as postdocs, assistant professors, or associate professors; one holds an academic position at the University of Electronic Science and Technology of China; one holds an academic position at the King Abdullah University of Science and Technology; and another has joined the University of Salford as a Lecturer. Overall, the group has been highly successful in educating new researchers and expects this area to gain even greater importance in the future.

3.6.7 Hiring

The group has continued to attract high-caliber researchers. A total of five highly qualified associate professors (one external and four internal) and 13 highly qualified assistant professors (eight external and five internal) were recruited (including six tenure-track assistant professors). Among them, three assistant professors were later promoted to associate professors. Furthermore, one professor (MSO) was promoted to full professor, and one full professor and one part-time professor joined the group.

The group recruited assistant, associate, and full professors from a diverse range of countries, as shown in Figure 3.7. AU denotes Australia, CN denotes China, DK denotes Denmark, SA denotes Saudi Arabia, SG denotes Singapore, and US denotes the United States. Among the 17 hires for assistant, associate, and full

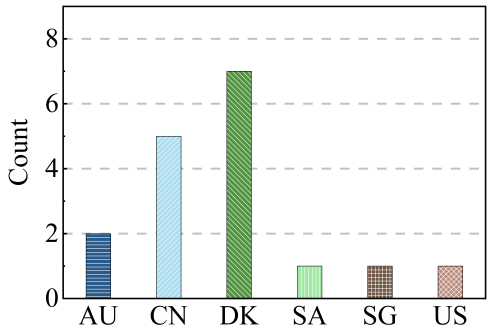


Figure 3.7: Country issuing the latest diploma of the new Assistant Professor, Associate Professors, and Professors

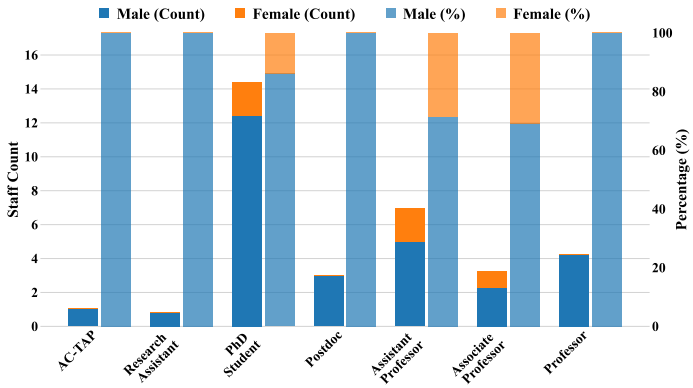


Figure 3.8: Gender distribution per category, weighted by percentage of employment

professor positions during the reporting period, three are graduates of universities ranked in the top 100 of the QS World University Rankings 2026, including the National University of Singapore (8th), University of New South Wales (20th), and University of Technology Sydney (96th).

Figure 3.8 shows the gender distribution across position categories at the end of the reporting period. Although the number of male hires exceeds that of female hires, the group has made dedicated efforts to ensure gender balance in recruitment. These efforts are reflected in the steady inclusion of female faculty, as shown in Figure 3.9.

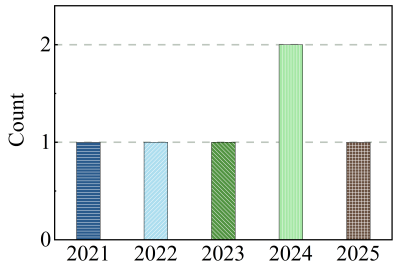


Figure 3.9: Gender—new female recruitment

3.6.8 Industrial Impact and Dissemination

The work on digital energy, in particular FlexOffers, has achieved significant industrial uptake, being deployed in more than 25 large R&D projects—including the key Danish project in this area. It led to the creation of the spinout company FlexShape, which was acquired by the EWii group, one of the Danish frontrunners in the Green Transition, during the period and now optimizes and trades a substantial portfolio of assets, including the largest battery in Denmark.

The Efficient Short-Term Electricity Load Forecasting ML model, developed in the Digital Energy Hub project, is open source and used by the energy trader EWII for responsive and energy-efficient load forecasting in the Danish electricity market, supporting daily operational decisions.

The work on model-based time series management has received much interest from industry practitioners. In the H2020 project MORE, ModelarDB was used on large volumes of data from renewable energy sources (RES), particularly wind turbines and photovoltaic modules, and collaboration continues with several large wind industry companies. The spin-out company ModelarData helps companies adopt ModelarDB in practice.

The work on programmatic ETL is actively used in industry. For example, the Danish transport company FlexDanmark, which handles demand-responsive transport, uses SimpleETL and pygrametl for loading a data warehouse containing around two million coordinates collected daily from 5,000 vehicles. The pygrametl ETL framework is now used by more than 7,400 users across over 14 countries, both from official and non-official repositories.

The predictive autoscaling framework MagicScaler has been adopted in practice as a unified solution for optimizing cloud resource allocation under uncertain and dynamic user demands. It integrates a multi-scale attentive Gaussian process pre-

dictor for uncertainty-aware time-series forecasting with an uncertainty-aware scaler for cost-efficient and reliable decision optimization. Extensive experiments on Alibaba Cloud clusters demonstrate its superior prediction accuracy, decision quality, and overall performance compared to existing autoscaling approaches.

3.6.9 Collaboration

The group maintains extensive collaborations with a large number of international colleagues, as reflected by coauthorships of papers published during the reporting period. These collaborations span Asia, Australia, Europe, North America, and Denmark, highlighting the group's global engagement and scientific visibility. The international collaboration groups are listed alphabetically, and the universities within each group are also listed alphabetically for both international and national collaborations.

International Collaborations

The group has built substantial academic partnerships with colleagues at leading **Asian universities**, including City University of Hong Kong, Hong Kong Polytechnic University, Hong Kong University of Science and Technology, National University of Singapore, Nanyang Technological University, The Chinese University of Hong Kong, The University of Hong Kong, Tsinghua University, and Zhejiang University.

Collaborations with **Australian universities** include Griffith University, Monash University, RMIT University, University of Auckland, University of Melbourne, University of New South Wales, University of Queensland, and University of Waikato.

In **Europe and the Middle East**, the group collaborates with institutions such as Aalto University, Free University of Bozen-Bolzano, Hamad Bin Khalifa University College of Science and Engineering, Inception Institute of Artificial Intelligence, King Abdullah University of Science and Technology, NOI Techpark Südtirol / Alto Adige, Qatar Computing Research Institute, Stockholm University, Technical University of Berlin, TU Dresden, TU Eindhoven, Università degli Studi di Cagliari, Université Libre de Bruxelles, University of Amsterdam, University of Cambridge, University of Cyprus, University of Malaga, University of Navarra, University of Oslo, University of Salzburg, University of Sheffield, University of Stuttgart, University of Twente, University of Warwick, University of Zurich, and Utrecht University.

In **North America**, the group has worked with researchers from Arizona State University, Emory University, George Mason University, Iowa State University, Pur-

due University, University of California, University of California Riverside, University of Illinois Chicago, University of Massachusetts Boston, University of Minnesota, University of Pittsburgh, University of Southern California, and York University.

National Collaborations

Within Denmark, the group collaborates closely with other leading universities, including Technical University of Denmark, IT University of Copenhagen, Roskilde University, and Aarhus University.

Internal Collaborations

Collaboration within the department has continued and even strengthened during the reporting period. Ongoing joint efforts address topics such as energy certification of software and software installations, embedded time-critical software, human–computer interaction for flexible energy systems, and data-intensive cyber-physical systems.

Interdisciplinary collaborations with other departments have also expanded. For example, the project Light-AI for Cognitive Power Electronics—conducted with **AAU Energy**—focuses on computation-light and data-light AI for adaptive and self-aware power electronics. Another collaboration, Inverse Design of Materials Using Diffusion Probabilistic Models—with the **Department of Chemistry and Bioscience**—explores ML-driven discovery of novel glass-ceramic materials.

Such broad and deep collaborations are expected to further strengthen in the coming years.

3.6.10 Teaching

The members of group invest substantial amounts of time in teaching, and in this way, the group achieves a high impact through teaching. Members of the group teach across regular educations offered by the Department, e.g., Software, Computer Science, as well as continuous educations, e.g., IT Vest. Courses taught by the group range from core courses with large numbers of students and specialized courses with a high connection to the research topics investigated by the group. Moreover, members of the group have led the development of the Data Science education. Notably, members have received teaching awards during the evaluation period, specifically the AAU Pedagogy Prize 2023 and the AAU Supervisor of the Year 2023/2024.

3.7 Committee Evaluation

DESS is a large and well-established group performing research in data management, data mining, machine learning, and artificial intelligence. The group embraces all activities concerning data-intensive systems and data-driven value creation.

Commended

The group has demonstrated strong research excellence, maintaining a prolific publication record with well over 500 refereed papers reported over the evaluation period. More than 50% of these papers appear in CORE/ICORE A* outlets. Notably, the group ranked second in Europe according to csrankings.org for full papers published in SIGMOD, VLDB, and ICDE, placing them ahead of leading institutions like TU Berlin, ETH Zurich, and EPFL.

In terms of research strategy, the group aims to cover the full range from long-term to applied research through topical pipelines: particularly digital energy and spatio-temporal analytics. Group members find positions along these pipelines that best align with their interests and expertise. The panel found this an original and constructive way of both organising and reflecting on the research going on in the group. Recognising that many data problems now involve AI, the group has successfully embraced AI and machine learning, with over 60% of the publications being AI-related.

The research is backed by a solid and diversified funding portfolio totaling approximately DKK 79 million across 31 projects. Fundraising and project management responsibilities are distributed healthily across more than 13 staff members acting as PIs or co-PIs, rather than being concentrated among a few individuals.

Operationally and culturally, the group has shown remarkable resilience and cohesion. The senior staff has a clearly articulated leadership approach, based around shared values such as treating everyone with respect, fair and transparent decision making, empowerment through trust and recognising achievements. Senior staff invested significant effort into coordinating and supporting members through a turbulent period, a dedication that reflected directly in the experiences of early-career researchers, who reported feeling strongly supported in areas like grant writing and paper reviews. Despite notable staff turnover, the group has remained coherent and stayed together, a testament to its underlying internal cohesion, while continuing to attract top-tier new hires due to its strong global reputation.

The group also reported a strong PhD training record, with 17 degrees awarded during the period and another 15 currently in progress, with graduates consistently

securing placements at strong institutions.

Challenges noted

Staff retention has emerged as the central challenge for the group over the evaluation period. A total of 36 staff members departed, including 12 faculty, which slightly outpaced the 32 new arrivals. The competitive caliber of the team is evident in these departures, as 8 of the 12 exiting faculty members moved directly into full professorships at other institutions, highlighting the external poaching pressure the group faces.

This high turnover meant that only four permanent faculty members remained in post full-time for the entirety of the period, creating a risk of administrative and academic overload for those individuals.

It came up in discussion that there would be value for a group like DESS to participate in larger national or international consortia (e.g., the UCPH-led bid for the Pioneer Centre), but that the process to join a consortium as it is forming is often highly political and opaque. The panel thought it might be helpful for the department as well as the faculty to reflect on this and consider developing a strategy for future consortium opportunities where DESS and other research groups could make a meaningful contribution.

4 Data, Knowledge, & Web Engineering

4.1 Executive Summary

The Data, Knowledge, and Web Engineering (DKW) group was established in 2022 as a result of the previous research evaluation conducted over the 2016-2020 period. The group was established based on a core group of researchers from the previous DPW group, centered around Prof. Katja Hose. The following section describes the research activity at DKW during the period of its operation, i.e., from January 2022 to June 2025, together with the activity of its founding researchers in 2021 up to its establishment.

The DKW group has facilitated the establishment of the new Natural Language Processing (NLP) group. This sub-group has grown rapidly since 2020 from a single early-career researcher to a thriving, independent research group with a full professor, two assistant professors, a postdoc, and currently seven PhD students, supported by strong funding successes. The group's research spans linguistically informed Large Language Models (LLMs), computational linguistics, factuality and question answering, multilingual and low-resource NLP, and – most notably – the emerging field of NLP security. The group has published extensively in top-tier venues, especially in the latest years of the evaluation period. Furthermore, the group has secured several prestigious grants and engaged in impactful collaborations with industry and academia. By combining linguistic theory with cutting-edge AI, the group addresses timely challenges in factuality and security, beginning to position AAU as a leader in NLP security research nationally and internationally.

The recruitment of Prof. Torben Larsen from his previous faculty-level position as vice-dean of digitalization led to the establishment of a university-wide Quantum Computing research center. This activity was consolidated under the DEIS research group at the beginning of 2025.

The Web Science and Engineering area was temporarily weakened by an extended leave by Associate Prof. Peter Dolog between February 2022 and Jul. 2024,

but has recently been strengthened by the recruitment of two assistant professors (Rodrigues and Çelikkanat). The main results are centred around graph-based methods for recommendations, but also work on knowledge graph creation from datasets. The research in this area resulted in publications at reputable venues, particularly towards the end of the evaluation period.

In the core research area of Data and Knowledge Management, the group secured substantial funding through several large collaborative and career research grants, resulting in numerous publications, public datasets, conference presentations, demonstrations, posters, and invited keynotes at our core conferences (ISWC, ESWC, EDBT). At its peak, the research area comprised a professor (Hose), two Associate professors (Montoya, Dell'aglio), and three assistant professors (Lissandrini, Sagi, Aebeloe). The departure of Prof. Hose to TU Wien in early 2023, together with the departure of Assoc. Prof. Gabriela Montoya, and Asst. Professors Matteo Lissandrini and Christian Aebeloe left this research area depleted, and the remaining staff joined the newly formed database and web research groups in late 2025.

4.2 Profile

The DKW group conducted research in Natural Language Processing (NLP), Knowledge Management, Web Science, and Quantum Computing. The group's researchers participated in several cross-disciplinary research efforts spanning healthcare, bioscience, education, and security, in close collaboration with other groups and departments. The stated joint ambition of the group was "To bring meaning to large amounts of heterogeneous data and leverage it effectively for a broad range of use cases and applications."

Research Area Profiles

Natural Language Processing (NLP) DKW contributes to fundamental research in Natural Language Processing, with a particular focus on multilinguality, low-resource languages, and NLP Security. Our work bridges computational linguistics, AI, and data science to address real-world challenges, promoting equitable language technology and robust AI systems.

Knowledge Management DKW researches knowledge engineering and machine learning, with a particular focus on knowledge graphs, representation learning, data integration, and data privacy, with applications in healthcare, biol-

ogy, and more. We study how to derive actionable knowledge and enhance decision-making.

Web Science Our focus in this area is on AI-based methods for learning user preferences from user explicit and implicit data, from side information, and methods for recommending items and users for different tasks on the Web. We are actively advancing the state of the art in Recommender systems, Personalization, User Modeling, (Personalized) Information Retrieval, and Web social networks analytics. The main directions are complemented with the publication, linkage, and alignment of open data with other datasets on the Web. We develop new methods, algorithms, and software to address fundamental problems in this area.

Quantum Computing DKW has been working in quantum computing and quantum information since late 2022. The activity was transferred to the DEIS research group in early 2025. We refer the reader to the DEIS chapter of this evaluation for further details.

4.3 Staff

4.3.1 Current Staff

As of June 2025, the DKW group comprised one full professor, three associate professors, three assistant professors, and three post-doctoral researchers. Professor Katja Hose is in a partial position (10%), and Professor Torben Larsen moved on April 1st 2025 to the DEIS research group together with Post-doctoral researcher Rajnish Kumar.

Professors (1.1) Johannes Bjerva (Head of Section for the new Copenhagen Section) and Katja Hose (PhD-supervision only - 10% FTE).

Associate Professors (3) Daniele Dell'Aglio (group coordinator), Peter Dolog, and Tomer Sagi

Assistant Professors (3) Juan Manuel Rodriguez, Abdulkadir Çelikkanat, and Russa Biswas

Postdoctoral Researchers (3) Mike Zhang, Mohammad Yaqoob, Heather Christine Lent (assistant prof. from autumn 2025)

Ph.D. Students (14) Ernests Lavrinovics, Rasmus Thyge Aavang Jensen (Industrial), Esther Ploeger, Marcell Richard Fekete, Luca Fabbian, Yiyi Chen, Martin Pekár, Theis Erik Jendal, Yeasmin Ara Akter, Frederik Marinus Trudslev, Ikhtiyor Nematov, Antheas Kapenekakis, Thomas Heede, and Mads Corfixen.

Research Assistants (2) Franciska Alves and Frederik Marinus Trudslev

4.3.2 Staff Development

Figure 4.1 summarizes the number of full-time senior staff by position per year from the establishment of DKW in January 2022 to the eve of the department structural changes in June 2025. Overall, the number of staff has remained stable with about seven FTE in Professor positions and three post-doctoral researchers throughout the period. However, the overall figure does not capture the substantial personnel changes that occurred during the period; we detail the significant changes and their context in the following section (see also Figure 4.2).

Recruitment of senior staff to establish the NLP research Domain Starting with the promotion of Johannes Bjerva to an associate professor position in 2022, and to full professor in 2024, DKW has consistently expanded its abilities in this field by recruiting four post-doctoral researchers and seven PhD students and promoting two of the post-doctoral researchers to assistant professor.

Establishment of the Quantum Computing Research Center In Oct. 2023, Professor Torben Larsen, previously the AAU TECH Faculty Associate Dean of Digitalization, joined DKW to establish a Quantum Computing research center. In April 2025, it was decided to consolidate Quantum research in the department into the DEIS research group, and Prof. Larsen and post-doctoral researcher Rajnish Kumar moved there. Regrettably, at the end of 2025, Prof. Larsen died after a prolonged illness.

Internal Promotion and Recruitment to Strengthen Core Research Areas During the period, there were several recruitments and internal promotions to strengthen the core research topics of knowledge management and data integration

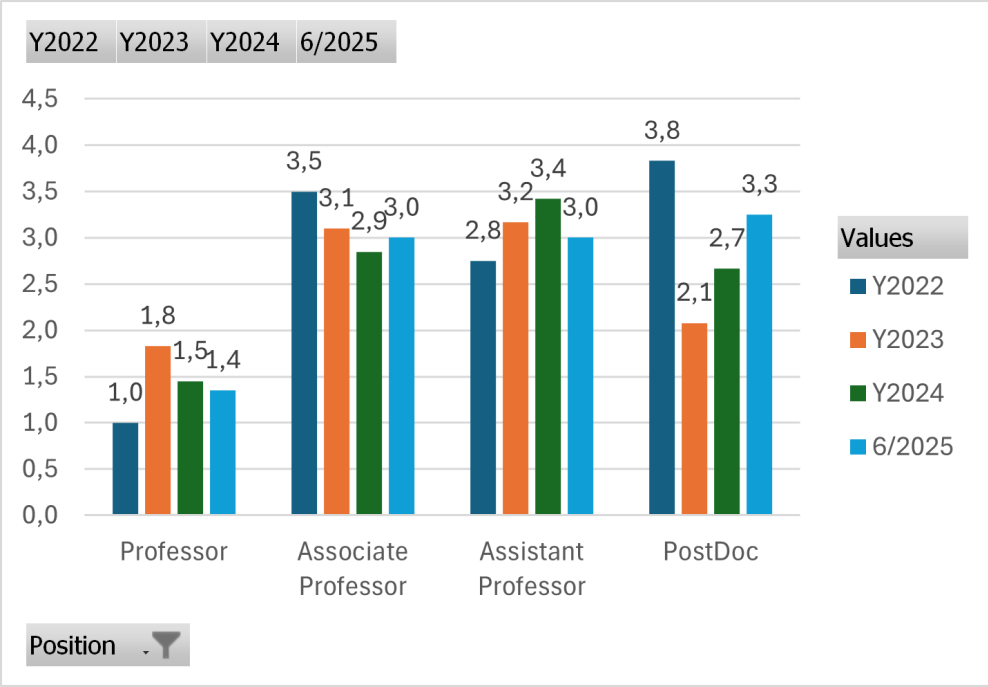


Figure 4.1: Staff Position Count per Year

at DKW. Tomer Sagi was recruited as an Assistant Professor (2022) and later promoted to Associate Professor (August 2024). Assistant Prof. Daniele Dell'Aglio was promoted to Associate Prof. (August 2022), and Christian Aebeloe was recruited as Assistant Professor after completing his Ph.D. in September 2022.

Departures and Absences of Key Staff Founding research leader of DKW, Professor Katja Hose, elected to take a position at TU Wien starting March 2023 and remains in a limited (10%) capacity. Associate professor Gabriela Montoya took an equivalent position at Nantes University (Sep. 2024). Assistant professor Matteo Lissandrini took an associate professor position at the University of Verona (Oct. 2023). Assistant professor Christian Tovgaard Aebeloe moved to Industry in July 2024. Associate Professor Peter Dolog was on an Extended sabbatical during 2023 and most of 2024.

Figure 4.2 presents a summary of recruitment sources and career paths at DKW throughout the period. PhD student recruitment is balanced, with about half coming from AAU master's programs.

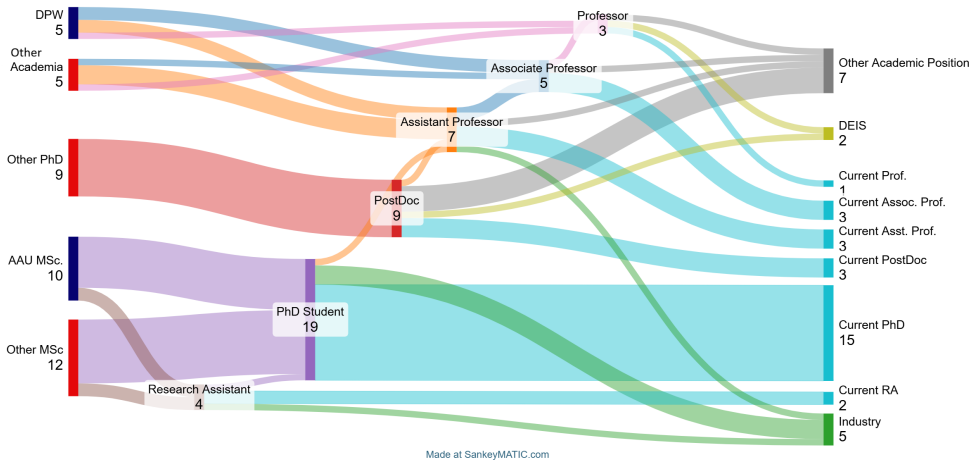


Figure 4.2: Staff sources and career development paths

4.4 Goals for 2021-2025

The following presents a summary of the goals set for DPW, the previous research group from which the founding members of DKW originated, in the previous evaluation period. For additional details, the reader is referred to the previous research evaluation. We focus on those goals relevant to the newly established DKW group.

Establishment of a new group With the growing group size and increased activities within certain areas, the Department of Computer Science aimed to establish a new group (incubator) to represent these areas within research and teaching. The ambition is to establish a new group on an equal footing with the three established groups that will reach a sustainable size within the next 3–4 years. The new group focuses on Web-scale data management, knowledge engineering, and Web intelligence.

Excellence and impact The group views fundamental and applied research equally valuable and targets excellence in both kinds of research. In terms of foundational, or long-term, research, performance indicators include publication in top scientific outlets (excellence) and citations (scientific impact), as well as awards, invited talks, and other forms of peer recognition. In terms of application-oriented research, we aim for demonstrations, industry funding, industrial uses of results

and software, spinouts, software downloads, patents, and system and service users. Additionally, the societal impact of both fundamental and applied research is evaluated in relation to the SDGs. In DKW group, applications are often related to health, privacy, and bioscience, thus contributing to SDGs 3, 11, and 13.

Synergies: cross-cutting themes We aim at realizing latent potentials for synergies in the group by identifying and focusing some of our activities around selected, cross-cutting themes. Cases exist where group members study the same types of techniques in different settings or application domains. Envisioned means include meetings, talks, and workshops and also shared Ph.D. students and postdocs.

Synergies: cross-fertilization We aim at realizing latent potentials for synergies by means of sharing of data, code, concepts, and knowledge and collaboration between foundational and applied research.

Robust and diverse funding portfolio The group strives to maintain a robust and diverse funding portfolio, where many group members can obtain funding and where different types of funding, e.g., funding in the excellence and strategic pillars, can be obtained.

Hiring Hiring highly qualified staff in the core research areas of the group remains challenging. In addition, some current members may leave for other positions. Thus, the group plans to continue hiring highly qualified staff at all levels.

In the 2020 evaluation, DPW identified three clusters of envisioned research topics for the upcoming period, of which the following two are relevant to DKW.

- **Semantic data management, graph databases, knowledge engineering, natural language processing, and recommender systems** Building upon our previous work in this area, we will continue our research on decentralized knowledge graphs to enable efficient query processing, availability, provenance, and collaborative updates. As knowledge graphs are evolving and old versions typically become unavailable, we will investigate how archiving and versioning can be enabled efficiently while keeping the data queryable. Considering knowledge graphs with high update rates, so-called dynamic knowledge graphs, our research will cover aspects such as anomaly detection, vandalism attempts, and embeddings and link prediction. Furthermore, we plan to work on aspects of privacy, such as privacy-preserving

querying of knowledge graphs and privacy-aware data integration in general. Moreover, we plan to continue our research on semantic data integration, ETL, (spatial) OLAP, and example-driven graph analytics, which we will expand to new applications and use cases. We plan to intensify our research efforts in the area of Natural Language Processing by developing methods that can efficiently use language similarities and differences, particularly to support truly low-resource languages. Finally, we plan to continue developing new models for recommendation based on embedding methods (both matrix factorization and neural methods) with information from multiple views.

- **Data science in the context of interdisciplinary research** Our interdisciplinary efforts will be strengthened in the next period in the context of several upcoming or just starting projects. First, with colleagues from Bioscience, we will improve microbial genomes' recovery rate by leveraging, expanding, and combining DNA sequencing, machine learning, and graph-based analysis. Second, we plan to continue our work in the Medical domain in the context of entity similarity and graph embeddings. Third, in collaboration with the Department of Planning, we will work on extracting, organizing, learning, searching, and using knowledge to assist the environmental assessment process.

4.5 Activities and Results (2021-2025)

In this Section, we provide an overview of our activities as members of DPW in 2021 and as a separate research group since January 2022. We provide a summary of the activities by research topic, followed by a review of research performed in specific application domains.

4.5.1 Natural Language Processing (NLP)

Large Language Models (LLMs) Our group investigates (multilingual) Large Language Models (LLMs) with an emphasis on linguistically informed modeling, but also applied settings. By integrating linguistic insights, we address fundamental challenges related to model interpretability, generalizability, and robustness. Our research in LLMs has led to publications in CORE A(*) venues such as (ACL'2024, ACL'2025), (NAACL'2025, NAACL'2025), (CHI'2025), and (AAAI'2025). Moreover, we have publications on the usage of LLMs in education at relevant venues related to a Villum Synergy grant (e.g., (SEFI'2024), (EDUCON'2025)).

Computational Linguistics (CL) We integrate computational methods with linguistic theory, contributing to both methodological advances and theoretical understanding in computational linguistics. Our research covers linguistic typology, analysis of language representation, and multilingual NLP. Our research in CL has led to publications in CORE A(*) venues such as (ComputationalLingu'2025, CL journal'2024, ACL'2025, EMNLP'2024, EACL'2024, EMNLP'2023), mainly in the context of a career grant awarded by the Carlsberg Foundation, under the Semper Ardens: Accelerate programme, and a range of associated dissemination activities.

Factuality & Question Answering Our research addresses the critical challenge of ensuring factual correctness and reliability in text summarization and question answering by effectively integrating LLMs and Knowledge Graphs (KGs). This includes work on the evaluation and improvement of NLP outputs in domains such as finance and healthcare. Our work has led to publications in top-tier conferences like (EMNLP'2024), as well as in journals (Journal of Web Semantics'2025), and workshops (ALVR'2024), an Industrial Ph.D. project funded by Innovation Fund Denmark, and the co-organisation of the 1st Workshop on Knowledge Graphs and Large Language Models (KaLLM 2024) co-located with ACL 2024.

Multilingual & Low-Resource Languages We focus extensively on enhancing NLP capabilities for multilingual and low-resource languages by developing robust cross-linguistic transfer methods and creating new datasets. Our research in multilinguality and low-resource NLP has led to publications at top venues like (TACL'2024), (ACL'2025), as well as highly-relevant local venues for NLP in the Nordics (NoDaLiDa/Baltic-HLT'2025), the award of a Google Award for Inclusion for our work with Creole languages, and a prestigious Elite Research Travel Grant from the Danish Ministry of Higher Education and Research.

NLP Security In 2024, we identified a new research niche, allowing us to be first movers in the area of NLP security. Our pioneering research in NLP security specifically targets vulnerabilities in large language models, addressing risks such as adversarial attacks and data poisoning. As many security vulnerabilities are exacerbated by poor multilingual performance, our proposed strategies for meeting these challenges are grounded in linguistic theory and expertise in low-resource and multilingual NLP. Furthermore, we have been able to establish concrete collaborations with NVIDIA and with the Cybersecurity research group at the Department of Electronic Systems at AAU. In a short span of time, this highly promising new direction has led publications in (TACL'2025), (ACL'2024, ACL'2025),(AAAI'2025),

and (NAACL'2025). Furthermore, it has led to two external career grants in the span of 6 months – a Novo Nordisk Foundation Ascending Data Science Investigator, and an Independent Research Fund Denmark Sapere Aude – in addition to an AAU-internal AI:X Labs award.

4.5.2 Data, Knowledge, & Web

Knowledge Graph Engineering & Management DKW conducts research in data management primarily through the prism of the knowledge graph paradigm, where data is modeled as a set of related facts, semantically grounded by resource identifiers, classes, and properties from ontologies in the RDF data model. We cover the research in this domain from multiple perspectives, with work performed on RDF Triplestore engineering, SPARQL Query Optimization, Knowledge Graph Change Management, Graph constraint validation using SHACL, and Knowledge Graph Evolution. A smaller part of the research in data management focused on other data representations, including Relational models, Data Warehouses, Property Graphs, and Data Lakes, where topics included data exploration, stream processing, and temporal data management. Our research has led to six Ph.D. projects (four completed and two in progress), as well as over thirty peer-reviewed publications. These include papers, demonstrations, and posters at Semantic Web and Web Data Engineering conferences such as (WWW'2023), (SIGIR'2024), and (ESWC'2025), as well as their satellite workshops (e.g., (ISWC/MEPDaW/QuWeDa'2023)), journal papers in the premier journals of the field - (Semantic Web Journal'2023), (International Journal of Semantic Computing'2025), and the (JoWS(b)'2022), as well as conference and journal papers in highly-ranked general data management venues - (VLDBj'2022), (CIDR'2022), (SIGMOD'2023), (EDBT'2023), and (Information Systems'2022). Our research led to several recognitions, including a best paper award at ESWC 2023, best paper awards at the NLP4KGC and DL4KG workshops, a challenge award at the BioASQ workshop, and a best paper runner-up at TPDL 2025. This line of research was supported by a number of grants, including Data Engineering for Data Science (DEDS), Example Driven Analytics for Open Knowledge Graphs (EDAO), the Poul Due Jensen Professorate in Big Data and Artificial Intelligence, and RelWeb: A Reliable Web of Data, all obtained before 2021, but put into effect only in the evaluation period.

Ontology Engineering We research methods and approaches for the automated generation, evaluation, and change management of Ontologies. The work on this topic is done through international collaborations, where our researchers have

co-supervised two Ph.D. students, leading to publications, e.g., (AAAI Symposium'2024), and prototype systems (OntoEval'2023, JoWS(a)'2022)

Data Integration Our research in data integration is driven by challenging application domains such as scientific data, medical data, and multi-lingual historical data. Our work has led to two new grants - (HEREDITARY'2024) (Heterogeneous semantic data integration for the gut-brain interplay) and (ARISTOTELES'2023) (Integrating AI for Personalized Risk Assessment and Streamlined Clinical Interventions in an Integrated Care System), and several publications in application venues, e.g., (DH'2023) and computer science venues, e.g., (LRE'2025, SWJ'2024, JoWS'2023).

Recommender Systems. In this area of work, we have studied the impact of (knowledge) graph structure of side information, reviews, and clustering on recommender systems, including inductive methods. We have also contributed components that could handle such information and improve the accuracy of recommender systems. We have also studied review–based explanations for recommender systems which could better utilize aspects of interest in such reviews and improve explanations. From the evaluation perspective, we have studied recommenders beyond accuracy and user fairness, and in biological research with a method for finding proteins. We have created a bibliographic dataset for recommender systems and created a knowledge graph for Yelp dataset with almost full coverage for items. Our research led to: Publications at top-ranked venues including The ACM Web Conference (ACM Web'2024), VLDB (VLDB(a)'2025), Data Mining and Knowledge Discovery (journal track of ECML/PKDD) (ECML/PKDD25'2025), ACM Transactions on RecSys (ACM Trans. on RecSys'2025), ACM RecSys (RecSys'2024), ECIR (ECIR'2024), CIKM (CIKM'2025) as well as some RecSys workshops for example (KaRS'2023, HealthRecSys'2024). The recognition for the quality of this work is reflected in the funding support for research stay at Vienna University awarded by Carlsberg Foundation and senior PC memberships for Peter Dolog at IJCAI and ACM UMAP conferences as well as PC memberships at other major venues.

Representation Learning The research activities in this area focused on developing representation learning methods for genomic and biomedical data, with an emphasis on analyzing complex mixtures of DNA fragments from biological samples. A core component of this work addressed metagenomic binning, where novel machine learning approaches were developed to cluster DNA sequences and identify microbial species present in a sample. In parallel, representation learning techniques

were employed to uncover latent relationships between environmental variables and microbial community structure. Bayesian modeling frameworks were integrated to explicitly capture ecological dynamics while accounting for uncertainty in the inferred representations.

Moreover, the research activities were extended to the medical domain, where patient data representations were studied for medical analytic tasks. These activities resulted in a series of peer-reviewed publications in leading journals and conferences, including (Bioinformatics'2022, IEEE Access'2023, Health Informatics Journal'2024, ICML'2023, NeurIPS'2024), demonstrating the applicability of advanced machine learning techniques to genomic and biomedical problems.

4.5.3 Unexpected Research Directions

The following are some unplanned research directions undertaken for various resaons in the evaluation period.

AI Explainability In collaboration with researchers from the Free University of Brussels, an ongoing Ph.D. project on AI explainability in information extraction tasks has resulted in two publications to date on example-based AI explainability (AIES-24'2024, AIMLAI@ECML'2024).

Computer Vision As a result of collaborations with industry and academic partners, two computer vision projects were undertaken in video classification (Image and Data Fusion'2025) and text-to-image retrieval (ECIR'2024).

Quantum Computing As previously mentioned, the arrival of Prof. Torben Larsen to DKW brought about an unexpected research focus on quantum computing, as this activity was consolidated under DEIS, the details can be found in the DEIS chapter.

Data Privacy Initiated through two funded research projects, Data Engineering for Data Science (DEDS) and (HEREDITARY'2024), this line of research focuses on privacy-preserving techniques for data science, with a focus on differential privacy. We developed collaborations with academic partners (University of Zurich, ATHENA Research Center, University of Hong Kong) and Aalborg University hospital, and two PhD students are currently researching on this topic. This direction has

so far led to six publications, including techniques for privacy-preserving representation learning of knowledge graphs (JoWS(b)'2022), data privacy for the blockchain infrastructure (Blockchain'2025, Front. Phys.'2021) and privacy-preserving synthetic data generation (VLDB(b)'2025, BigData'2024, ADBIS'2025). In September 2025, one of the publications on synthetic data generation was awarded the best paper at the 29th European Conference on Advances in Databases and Information Systems.

4.5.4 Application Domains

Much of DKW's research was performed in the context of an application domain in collaboration with industrial or academic domain experts. Here, we describe the activity and impact of our work in these domains.

In the Digital Humanities domain, the **MEHDIE project** (MEHDIE'2022, 2022-24) provided new methods for cross-lingual entity resolution over historical records of people and places in the Middle East. The research led to the development of new methods that were widely disseminated and adopted as part of the World Historical Gazetteer.

In the Health Domain, the group made a concerted effort to create and expand collaborations in the health domain, resulting in two new grants (HEREDITARY'2024, ARISTOTELES'2023), and a series of publications, in Medicine (Nature Communications'2021, JEADV Clinical Practice'2024, Genome Medicine'2022), and AI in Medicine venues (AIME 22'2022, AIME'2023, JMIR'2025). HEREDITARY aims to develop novel solutions for safe and private federated analytics and learning of gut-brain disease data. The project is a joint effort of several universities and research centers across Europe and the USA. We participate in the project with a specific focus on ontology-driven federated analytics and privacy-preserving methods for data sharing and analysis. ARISTOTELES is developing AI-based solutions for Atrial Fibrillation prognosis and care management. Our role in the project involves providing AI-based data integration solutions based on the OMOP common data model and an AI-robustness suite to assess the robustness of the developed models against identified error patterns in the data.

In the Bio-Science domain, our primary focus has been on addressing the problem of metagenomic binning, i.e., grouping DNA fragments according to their respective, yet unidentified, genomes or clusters. This line of research has resulted in several publications (Bioinformatics'2022, IEEE Access'2023, ICML'2023, ICML-Biology'2023, NeurIPS'2024). Additionally, we have also explored the integration of geographically annotated microbial data with relevant environmental datasets.

This integration aims to facilitate joint analyses, enabling a more comprehensive understanding of the spatial and ecological patterns underlying microbial communities (CEUR'2024, Uncertainty Processing'2025).

In addition, synergy projects and collaborations were carried out in several domains, including finance (EMNLP'2024), legal documents (NoDaLiDa/Baltic-HLT'2025), cyber security (AAAI'2025), ocean science (ODINI'2022), environmental assessment (ESWC-JP 23'2023), and radio astronomy (ICDE 21'2021).

4.5.5 Projects and funding

Out of 66 submitted applications in the evaluation period for which a verdict was delivered, DKW members won 23 competitive, externally funded grants totaling 47.9 million DKK (35% success rate). Of these, five projects (374K DKK) were travel grants, two scientific event grants totaling 150K DKK, and the rest were research grants. Notable among these are the LM2-SEC project (9.9M DKK), Microbial Dark Matter (7.5M DKK), a Sapere Aude grant (6.2M DKK), the (HEREDITARY'2024) EU Project (6M DKK), and a Semper Ardens: Accelerate grant (5M DKK). See Table 4.1 for a summary.

Year	Tenured Staff (FTE)	Awarded Grants	In DKK	DKK/Staff member
2021	3	3	3.656.069	1.218.690
2022	4,5	3	12.517.808	2.781.735
2023	4,9	6	2.447.540	499.498
2024	4,4	6	16.811.247	3.820.738
2025	4,4	5	12.480.171	2.836.403

Table 4.1: Tenured Staff, Awarded Grants, and Financial Data from 2021 to 2025

In addition, as part of the AI:X initiative at AAU, the group won two grants totaling 6M DKK for the establishment of AI-based research labs in collaboration with non-computer science researchers. AI:SECURITY with Johannes Bjerva in collaboration with the Department of Electronic Systems and AI:EcoNet with Abdulkadir Çelikkanat and in collaboration with the Department of Chemistry and Bioscience.

4.6 Own Evaluation

4.6.1 Evaluation of specific goals from 2020 Goals

Here, we assess the progress made towards achieving the goals set for DKW in the previous research evaluation.

Establishment of a new group The DKW group was established during the period of this research evaluation as planned. The group has experienced reasonable growth but also faced some staff departures, particularly towards the end of the research evaluation period. Due to the department's overall restructuring, the remaining members of this group will continue their research activities under the umbrella of new sections and groups. Notably, the group served as an incubator for two successful new research topics at the department: NLP, now a thriving research group on the Copenhagen campus, and Quantum Computing.

Synergies: cross-cutting themes The focus on health-related applications was a cross-cutting theme in the evaluation period and was a stated focus of the research group. This was formalized by the appointment of the then-head of the group, Katja Hose, to lead department-level efforts on the topic. This focus led to multiple projects and subsequent publications, as listed in the previous section.

Hiring As discussed in Section 4.3.2, while the group did manage to hire and promote several substantial additions, this was offset by the loss of key group members over the period. The goal of hiring additional staff to offset potential losses was thus met.

Excellence and impact In the following section, we detail the impact of our work by order of the research topics listed in the previous evaluation goals. We then summarize our scientific output and its impact in terms of publications and their venue quality in Section 4.6.3.

4.6.2 Research-topic-specific Evaluation

Semantic data management, knowledge engineering, and graph databases. Our work on semantic data management and knowledge engineering advanced the state of the art in both topics, as highlighted in the goals for this period in the previous evaluation, including management of evolving knowledge graphs, archiving and versioning, and new topic areas such as data quality and knowledge-driven machine learning.

As detailed previously, our research on semantic data management, graph databases, and knowledge engineering has achieved very good results, with novel algorithms and systems that outperform state-of-the-art solutions and have resulted in multiple publications. We consolidated existing collaborations with research partners and expanded our network through new collaborations with academic and industrial institutions. We secured new funding to support our research and integrated new junior and senior researchers into our team. We can therefore conclude that we have successfully followed the plan presented in the 2020 evaluation.

Data science in the context of interdisciplinary research. In the previous research evaluation, we had planned to expand upon our interdisciplinary collaborations by both applying for synergy projects funding and hiring staff with an interdisciplinary portfolio. In terms of hiring, we expanded our interdisciplinary base by hiring Tomer Sagi, who brought with him his existing projects in Oceanographic Data Integration (ODINI'2022) and Digital Humanities (MEHDIE'2022), and a medical-data expertise contributing to securing grants for the (COVID-19'2020) and (ARISTOTELES'2023) projects, as well as several collaborative publications (e.g., (AIME 22'2022)) with colleagues from Aalborg University Hospital and Region Nord. We further hired Juan Manuel Rodriguez, with a background in collaborative projects with industry (e.g., (ECIR'2024)) and expanded our collaborative research in bioscience (DarkScience'2022) and planning (DREAMS).

Recommender Systems. The **publication** strategy in this area was to give higher priority in targeting publications in the top venues (ICore A* or A categories of conference venues, as well as Q1 in SJR ranking). This strategy was followed and mostly successful, as evidenced by papers published at the Web, RecSys, and CIKM conferences. From a dissemination perspective, we also had some papers accepted for workshops, especially when submitted in collaboration with students. As for the volume, as stated above, the work in this area was influenced by a core member being on long-term leave and supported by hiring only in the latter part of the period by an additional assistant professor.

The members of this area maintained their level of **service to the scientific community**, serving as senior PC members or PC members of major conferences such as ACM WEB, ACM RecSys or ACM UMAP as well as reviewing for journals such as ACM Trans. Rec. Sys. or Springer UMUAI journals.

In **funding acquisition**, similar to publications, this activity was influenced by staff on leave or hired only in the latter part of the period. In this area, the funding

support received was for one person going on sabbatical.

Representation Learning. The research conducted in this area has contributed novel methodological advances at the intersection of machine learning, genomics, and biomedical data analysis, and their acceptance at leading venues reflects their relevance and rigor. The research has strengthened interdisciplinary collaboration, including closer ties with the Department of Chemistry and Bioscience, supported by the hiring of an assistant professor to further develop joint activities.

The visibility and recognition of the work are further evidenced by invitations to present at major machine learning venues and by service as a peer reviewer for conferences such as AISTATS, ICLR, and NeurIPS. Moreover, the success of this research program is reflected in the ability to attract external funding for collaborative and interdisciplinary projects, including the (DarkScience'2022) project and the (AI:Econet'2025) Lab. Together, these outcomes indicate a sustainable and impactful research direction that effectively bridges machine learning methodology with applications in bioinformatics.

Natural Language Processing. Pursuant to the 2020 goal of intensifying our research efforts in the area of NLP, we have made marked progress in this area. Our work has focused on linguistically informed approaches, with a focus on multilinguality and the emerging field of NLP Security. NLP at AAU has grown from a single researcher to the establishment of a new research group comprising three faculty, one postdoc, and seven PhD students, with funding secured for further growth from 2026. In the evaluated period, our efforts have led to over 25 million DKK in external funding, primarily in excellence-based career grants from the Carlsberg Foundation (Semper Ardens: Accelerate), the Novo Nordisk Foundation (Ascending Data Science Investigator), and the Independent Research Fund Denmark (Sapere Aude) – in addition to an AI:X lab (AI:SECURITY). In the period, our work has been published at all top core-NLP venues. Finally, the group has carried out a broad range of dissemination activities, including invited talks, conference and workshop organization, and public media appearances (e.g., news, podcasts).

Based on this track record, the goal of intensifying research efforts in NLP is judged as highly successful.

Conference Rank	A*	A	B	C	Unranked	Total
NLP	12	7	1	1	18	39
Data, Knowledge, & Web	16	9	7	4	45	81
Total	28	16	8	5	63	120

Table 4.2: Conference publications by research area and rank (CORE 2023 ranking)

Journal Rank	Q1	Q2	Q3	Unranked	Total
NLP	6	1	1	1	9
Data, Knowledge, & Web	25	12	1	5	43
Total	31	13	2	6	52

Table 4.3: Journal publications by research area and rank (SJR ranking)

4.6.3 Scientific Output and Impact

As seen in Tables 4.2 and 4.3, members of the DKW group published an impressive 172 peer-reviewed publications in the evaluation period, with 75 of those in A/A* conferences and Q1 journals at an average of about four and a half publications per senior staff member (assistant professor rank or higher) per year.

We separate NLP from the rest of the DKW research topics to emphasize the strength of this research topic, which has emerged as an independent and productive research group.

Beyond peer-reviewed publications, DKW members have created open-source datasets (e.g., MultiHal, benchmarks (e.g., LSQB), GitHub repositories (e.g., SHACTOR), and Python packages (e.g., translit-me) to benefit the scientific and software communities. Furthermore, our members have organized workshops, participated as program members, and chaired programs in the central scientific conferences and workshops of our field.

In addition to scientific output and impact, DKW members have been interviewed several times in popular science (e.g., ing.dk and inputmag.dk and general news venues (e.g., tv2.dk) on the emergence of AI as an economic and societal force to be reckoned with.

Finally, we value the impact on society in the form of our teaching activities. DKW members have been active contributors to AAU teaching at all levels, responsible for teaching database, web information, graph analytics, and big data processing topics

in a variety of courses at all levels. We have supervised bachelor's and master's level project groups and theses, including some resulting in scientific publications and some even awarding the students with travel opportunities to research conferences to present their work (e.g., at International Journal of Image and Data Fusion, ESWC, Sci-K Workshop @ WWW '23). Beyond providing teaching hours, we have actively shaped curricula by adding courses to the Software, Computer Science, and Data Science and Machine Learning programs, and pioneering a multi-project course that allows students to experience working in a scrum environment with multiple interrelated development teams.

4.7 Committee Evaluation

DKW was established in 2022 in response to the previous evaluation. The main active research areas were in NLP, knowledge engineering, data science, recommender systems and representation learning, with web science recently becoming more active again through some strategic hires.

We note that the short operational life of the group (Jan 2022 – mid-2025) makes its evaluation different in character from the other three, longer-established groups. This also makes the overall achievements commendable, to have been able to achieve these within this shorter time period, and with the resourcing challenges noted below.

Commended

The DKW group covers a broad range of research topics related to data, knowledge and web engineering, reflecting the strengths and interests of particular members of the group. However they have also done well in identifying machine learning and how to give heterogenous data meaning as cross-cutting themes. Health-related applications was also a cross-cutting application domain..

DKW have also demonstrated a pragmatic agility to respond to new opportunities that have arisen from both strategic hiring decisions and from domain-specific challenges to establish new research directions, such as quantum computing (see below), computer vision, AI explainability and data privacy. This expansion of topics from those set out at the beginning of the period can be seen as a strength.

A particular success story is the establishment and rapid growth of the NLP group from a single researcher to a full professor, multiple assistant professors/postdocs, and 7 PhD students. This is a genuine organisational success and incubation story.

DKW was also able to successfully nurture a quantum computing and quantum information activity through the strategic hire of a full professor. This initiative led to DKW being instrumental in establishing a university-wide Quantum Computing research centre.

DKW members have been successful in attracting strong excellence-based funding, e.g., NLP (Carlsberg Semper Ardens, Novo Nordisk Ascending Investigator, DFF Sapere Aude) plus AI:X lab funding. Overall this represents a good level of funding relative to the group size: 23 grants, approximately DKK 47.9M, with a 35% success rate, albeit with a dip in 2023 in successful funding.

The focus on application domains, and collaborations with industrial partners and interdisciplinary domain experts, are strengths of the DKW work. There is evidence of some significant real-world impact, whether for historical records or medical diagnosis and management, or open-source data sets.

The research has also resulted in a high number of publications with a conscious effort to publish in CORE A* and A conference venues, across all sub-areas of research represented by the group. Members of the group also perform key service roles in their peer communities, as recognition of their standing.

The support culture within the group is to be commended. The mentoring and support of one senior person was mentioned as being particularly appreciated, along with the peer review process in place to support grant proposals. Early-career researchers also reported feeling supported.

Challenges noted

DKW had a number of significant challenges related to personnel changes that in turn impacted the focus and level of activity in particular research areas.

The departure of the founding leader of DKW (Prof. Katja Hose to TU Wien, 2023) and subsequent loss of several other key staff significantly depleted the core Data & Knowledge Management area.

The Web Science activity was also weakened by an extended sabbatical of a core member, although there is evidence of some recovery via late-period hires.

The staffing profile of the group is also largely skewed towards more junior or mid-career people and would have benefited from having more full professors to both contribute to the work of the group and to represent the group at departmental level discussions, e.g., around resources and funding.

5 Distributed, Embedded & Intelligent Systems

5.1 Executive Summary

The research activities of the DEIS group focus on the modelling, analysis, and realization of computer programs, with particular emphasis on distributed, embedded, and intelligent systems. The group's contributions span foundational theory, verification and optimization tools, validation methodologies, programming technologies, security, probabilistic graphical models, and machine learning, addressing both classical and quantum systems. DEIS research combines strong theoretical foundations with practical and experimental work.

During the evaluation period, DEIS performed very strongly with respect to key performance indicators, including scientific publications, external funding, PhD education, scientific service, dissemination, and academic and industrial collaboration.

DEIS produced 466 peer-reviewed journal and conference publications, being a 86% increase compared to the previous period. The publications include 58 publications in top-tier journals and 106 publications at top-tier conferences. In the period the group aquired 38 new external projects with at total funding volume of 79.271.581 DKK, ranging from prestigious individual grants to large-scale industrial collaborations and dissemination projects, with the majority of funding from basic and strategic research programmes. Several projects address one or more UN Sustainable Development Goals and are conducted in close collaboration with other groups at the department and university levels. DEIS also played an active role in the Danish National Research Center for Digital Technologies (DIREC) and serves as a leading partner in the newly established Basic Research Center CLASSIQUE: Communication in the Quantum Era.

The group has maintained a strong international profile through the development and sustained support of state-of-the-art model checking tools, including UPPAAL

and TAPAAL. These tools have achieved wide industrial uptake, exceptionally high download numbers, and multiple gold and silver medals at international model checking competitions, with the release of UPPAAL 5.0 being a particular highlight.

DEIS has successfully promoted new full professors and attracted outstanding researchers in foundational theory, automated verification, machine learning, and quantum systems. Despite the departure of two key members, close research collaboration has been maintained. The group has received substantial recognition through best paper awards, prizes, honours, and extensive service to the research community. In conclusion, the DEIS group considers its research performance during the evaluation period to be excellent. Its publication output in leading venues, contributions to verification tools, level of industrial collaboration, and impact on societal challenges compare very favourably with peer groups across Europe.

5.2 Profile

The research of the DEIS group concerns modelling, analysis and realization of computer programs, with the emphasis on distributed, embedded and intelligent systems. The research contributions of the group cover foundational theories, verification and optimization tools, validation methodologies, programming technology, security as well as probabilistic graphical models and machine learning focusing on distributed, embedded, intelligent systems and quantum systems.

The research of DEIS spans the entire range from foundational research, strategic research to industrial application and includes the following key research areas:

Foundational Theories Here, the group continues its long track record within Concurrency Theory, with focus on mathematical and logical theories for modeling, specifying and verifying concurrent processes, quantitative aspects, in particular timing stochastic aspects. Our work in the period includes metrics for approximate behavioral equivalence, logic including new areas like hyperlogics and automated theorem proving, monitoring with emphasis on timed and hyperlogics, extensions of timed automata with energy variables focusing on problems concerned with existence of energy-constrained runs. We have developed methods using EM (expectation maximization) to learn probabilistic behavioral models. In addition, the group has opened new applications for history-deterministic automata.

Verification and Validation In the period, we have successfully improved the efficiency and extended the capability of the tools UPPAAL and TAPAAL. In UPPAAL,

new extrapolation techniques have been developed yielding an order of magnitude improvement, with extension to the setting multi-player timed games.

We have advanced verification techniques for Petri nets and Petri games and their extensions with time and colors, focusing on state-space reduction, unfolding of colored nets.

Over the last decade, the DEIS group has had a leading role in developing the theory of dependency graphs that facilitate such on-the-fly model checking in a unified framework with wide range of applications. A major contribution has been the introduction of abstract dependency graphs.

UPPAAL has been extended with *randomized* algorithms providing efficient falsification methods, and TAPAAL has been extended with an SMC engine.

Other significant research addresses synthesis and theorem proving.

Quantum Systems During the period, DEIS has consciously expanded the scope of research to include quantum computing. We have focused on contributions to the area of design automation for quantum circuits – an area that has long benefited from formal methods in the classical domain – to reduce the effort of bringing quantum software into practice. The research has been conducted in collaboration with TUM and Aarhus University.

Security The focus has been on strong security and privacy guaranties, applying the theory, tools, and technology that are developed in DEIS. The research includes verification of secure protocols, use of string solving to analyze security breaches due to "injection" of code into programs, glitch attacks and side-channels as well as study of security in socio-technical systems. Early work on Attack-Defense Trees has been continued.

Artificial Intelligence To address the lack of safety guarantees of reinforcement learning, DEIS has made several contributions to explainable strategy representation, formal verification and shielding.

Within automated planning, the focus has been on domain-independent methods which can automatically analyze and exploit the structure of a model of the environment to make efficient decision making on any given domain. We have introduced the notion of Contrastive Analysis as a new way of identifying and exploring planning models.

Within probabilistic methods and models, a central focus has been to deepen the

theoretical foundations of generalization in modern neural models with special attention to ensembles and posterior tempering. In our research on probabilistic modeling, we have continued our work on flexible frameworks for modeling hybrid domains. Building on our extensive expertise in statistical relation learning (SRL), a main theme has been the transfer of SRL methods to the field of graph neural networks.

Distributed Systems and Networks Here, the research contributions have focused on distributed computation, software engineering aspects and model-driven design of SoS, blockchains supporting trust policies and to manage crowd-sourced efforts, agent simulation for energy-efficient motion planning, as well as schedulability and performance analysis.

Another line of research concerns the modeling, verification, synthesis of resilient rerouting under link-failures as well as efficient updates of network protocols. Most of the research contributions involved the development of tool prototypes and experimental evaluation in collaboration with companies.

Programming Language Technology Completing work from the previous reporting period, the research includes a cost semantics of spreadsheets completing the funded project P3 (Popular Parallel Programming). Also type systems has been developed for a functional scripting language respectively a subset of Java.

In August 2020 members of the programming technology subgroup in DPW joined the DEIS group following many years of strong collaborations on embedded systems development and parallelization of spreadsheet computations, now focusing on Energy Aware Programming. This area has been subject to intensive activities during the current period.

Finally, a series of papers develops and exploits operational semantics for a variety of languages of calculi, often with student involvement and a teaching perspective.

Educational Science The activities on education research have concentrated on the setting of higher education and have been motivated by concrete teaching experience among members of the DEIS group.

Tools The groups effort in developing, maintaining and distributing validation and verification tools has continued in the period.

The release of UPPAAL 5.0 was a major achievement integrating several of the

previous branches of the tool. UPPAAL downloads come from more than 1600 user domains that span academic and industrial users. The development of the TAPAAL tool has focused on improving the core verification algorithm. An important achievement was the introduction of a colored modelling formalism, hyperLTL logic and a statistical model checking engine.

Applications and Impact areas include water management systems (storm surge barriers, storm water detention ponds, waster-water treatment), autonomous systems (robot swarms, drones), satelites, intelligent transport, energy-aware systems (heat-pumps, district heating,..), green ICT, health, and epidemics (COVID19).

5.3 Staff

We report on the DEIS staff per december 2025. Currently DEIS consists of 3 full professors, 1 professor MSO, 21 full-time associate professors, 6 assistant professors, 7 Postdoc, 12 PhD students. These are complemented by 1 affiliated professor, 1 Special Consultant/Tool Developer, 2 research assistants, and 1 senior researcher. Eight of the staff members are now part of the Copenhagen section (marked with gray in the listing).

Professor Kim Guldstrand Larsen, Thomas Dyhre Nielsen, Jiri Srba

Professor MSO Bent Thomsen

Affiliated Professor Anders Læsø Madsen

Associate Professor Michele Albano, Giovanni Bacci, Giorgio Bacci, Daniel Fišer, René Rydhof Hansen, Lukas Holik, Hans Hüttel, Manfred Jaeger, Peter Gjøl Jensen, Josva Kleist, Andres Masegosa, Marius Mikučionis (20%), Brian Nielsen, Ulrik Nyman, Danny Bøgsted Poulsen, Marco Antonio Muniz Rodriguez, Christian Schilling, Anders Schlichtkrull, Arne Skou, Lone Leth Thomsen, Alvaro Torralba, Martin Zimmermann

Senior Researcher Per Printz Madsen

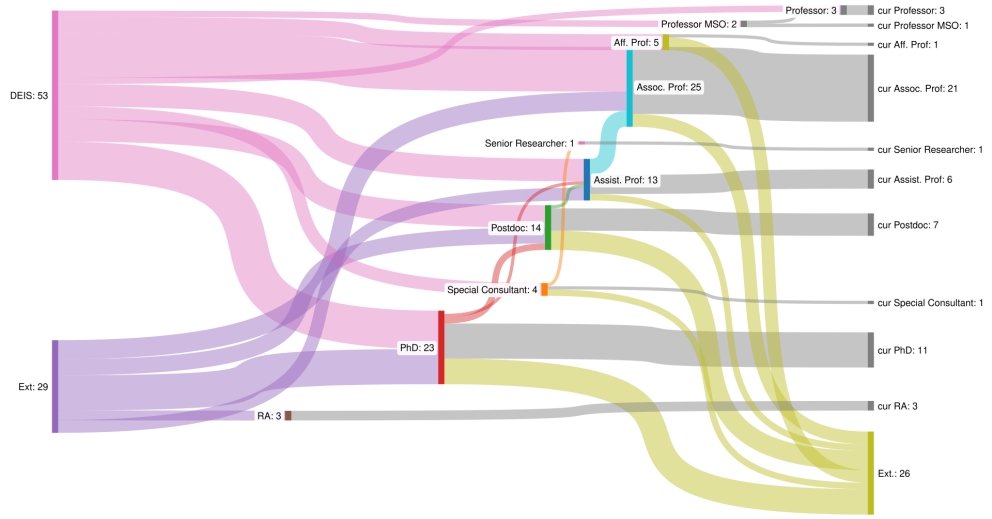


Figure 5.1: DEIS staff development

Assistant Professor Elli Anastasiadi, Levs Gondelmans, Jonas Kastberg Hinrichsen, Morten Konggaard Schou, Suman Sourav, Daniele Toller

Postdoc Xinyu Ge, Thomas Møller Grosen, Jonas Hansen, Nicolaj Østerby Jensen, Antheas Kapenekakis, Esther Hahyeon Kim, Martin Kristjansen

PhD Fellow Suhaib Al-Rousan, Andreas Kjeldgaard Brandhøj, Asger Horn Brorholt, Tobias Worm Bøgedal, Maria Fernanda Salerno Garmendia, Sean Kristian Remond Harbo, Thomas Heede, Andreas Holck Høeg-Petersen,Raffaele Pojer, Fouzi Tabouri, Rasmus Grønkjær Tollund, Michal Šedý

Special Consultant Marius Mikučionis (80%)

Research Assistant Laurits Brøcker, Dragos Ionescu

5.3.1 Staff development

As shown in Figure 5.1, the number of DEIS scientific staff members remained essentially stable throughout the evaluation period, only marginally increasing from

53 at the beginning to 54 at the end. In the following, we report the most significant staff development events that occurred during the 2021-2025 period.

Full Professor: During the period, Thomas Dyhre Nielsen was promoted from Professor MSO to Full Professor. He is now also serving as Vice-Head of the Department with responsibilities for Research.

New Associate Professors: During the period, we were fortunate to hire 5 new associate professors in DEIS: Andres Masegosa (Machine Learning, CPH), Christian Schilling (Validation&Verification, Quantum Systems), Martin Zimmermann (Foundational Theory), Daniel Fiser (Planning, CPH), Lukas Holik (Validation&Verification, Quantum Systems). The high qualification of these new staff members is witnessed by their several best paper awards and acquiring of prestigious grants such as Sapere Aude and Villum Synergy during the period.

New Assistant Professors & Promotion of Associate Professors Three new Assistant Professors have been hired during the period, two of whom are located at the Copenhagen Campus. Also, five Assistant Professors have been promoted to Associate Professors.

Loss of Associate Professors: 5 Associate Professors left DEIS during the period, two of them due to retirement. Max Tschaikowski, who was a key contributor to Foundational Theory and the emerging area of Quantum Systems, left for a position at Sapienza University Rome. Also, Peter G. Jensen, a key contributor to Validation&Verification, is on an extended leave to set up the company CEDAR, which optimizes control of heat-pumps. Also two of the leaving members, Thomas Bøgholm and Kurt Nørmark, were key contributors to Programming Technology.

Loss of Tenure Track Assistant Professors: Two tenure-track Assistant Professors, Florian Lorber and Martijn Goorden, left us during the period. We are sad to see them leave but also proud that they are now in a successful and permanent position at SAL (Silicon Austria Laboratories) and TU/e (Eindhoven University of Technology) and are still collaborating (e.g. in the Interreg project STORM-SAFE and in European project proposals).

Loss of Tool Development Lab People: During the period four people has left the DEIS Tool-Demonstratrator Laboratory, including Kenneth Yrke Jørgensen (chief developer for a 3 year period), Falke Otker Carlsen (developer

or demonstrators), Thorulf Neustrup (Main developer of UPPAAL), Jakob Guldhammer Jensen (developer of UPPAAL).

In conclusion, the total number of scientific staff as well as the number of permanent staff has remained unchanged throughout the evaluation period. We have managed to hire five highly qualified new permanent staff members within Artificial Intelligence, Planning, Foundational Theory, and Validation&Verification. However, we have lost a similar amount of permanent staff members, 2 of which are from the key area of Programming Technology. Also, we lost one of the key persons founding the new area Quantum Systems. Finally, the staff allocated to tool development, maintenance and demonstrators has significantly been reduced – in contrast to the stated plan of consolidating and expanding the DEIS Tool-Development Laboratory. The goal for the coming years of the new DEIS Section is to continue hiring excellent new scientific and technical staff to strengthen the Section, with an ambition of closing the gaps in Programming Technology and Tool-Development, while pursuing opportunities in all areas of DEIS.

5.4 Goals for 2021-2025

In the following, we present a condensed version of the goals set for DEIS at the end of the previous research evaluation.

Tools and Model Checking We will strengthen our focus on tool development as this will sustain the bridge between foundational research and applications. We shall continue the effort in combining symbolic model checking with machine learning to obtain improved performance. Also we shall consolidate and expand the DEIS Tool-Development Laboratory, aiming for joint effort and knowledge sharing across individual tools, as well as further exploit the Commercialization effort.

Foundational Theories Our influential work on behavioural metrics and their logic characterization will be expanded to deal with infinite-state dynamical systems. In particular, and continuing initial research of the current period, we want to use metrics in the theoretical study of guarantees that can be made by various methods for learning behavioural models from sampled observations (time-series) even in settings of partial observability. We are currently collaborating with Reikjavik University on using EM (expectation maximization) for learning probabilistic behavioural models. It is also planned to continue our successful line of work on

the reduction of nonlinear biochemical models. Ongoing research is concerned with on-the-fly and optimality-preserving reduction algorithms for nonlinear differential equations and involves collaborators from the University of Oxford, IMT Lucca and Sant'Anna Pisa.

Programming Technology Research on Programming Technologies will now be part of the groups profile as members of the programming technology subgroup has joined the group. Work will build on semantic foundations, static analysis and abstract interpretation, as well as constructive and imperative approaches, which can be applied on programs but also on models.

We expect to pursue research in energy aware software development and ICT Infrastructure (e.g. data center), where models can be used e.g. by viewing data centers as a component in a complete energy system.

Security This is an important research area with significant industrial interest and teaching responsibilities given the new Master's education in Copenhagen on Cyber Security. So far the contributions from DEIS has been offered by a few core members. Within the next period we want to grow substantially in this area, in terms of staff and research productivity. Initial focus will be on security of IoT and embedded systems exploiting our existing strong competences in model checking and static analysis. We expect to also involve theorem proving exploiting the competence of our new staff member Anders Schlichtkrull.

Artificial Intelligence and Machine Learning We intend to increase staff and research activity significantly within this area. In the next period we plan to investigate various combinations of planning and reach out to other departments in the university working with operations research.

Other directions to be pursued includes verification (of robustness) of learning-enabled systems (e.g. deep Neural Networks), explainability through learning of explainable models (e.g. Bayesian networks, Decision Trees, Automata of various types). Complementing the symbolic methods we will further pursue the use of reinforcement learning as a way of synthesizing strategies for (infinite-state) Markov Decision Processes. Here collaboration with Professor Bin Yang and the DKW group is envisaged.

Network Modelling and Verification At the end of 2018 Stefan Schmid left the group accepting a Full Professorship position at the University of Vienna. The

collaboration with Stefan Schmid is still active through the DFF project Quantitative Analysis and Synthesis of Network Protocols as well as through the Vienna Research Project WHATIF and we intend to strengthen our activities and staffing in this area in the next period.

Methodology and Applications We intend to continue to engage in having our generic methods and tools being applied within the ICT-sector itself (e.g. embedded systems) but also in other application areas. To achieve a higher level of impact additional effort needs to be made to make our methods and tools accessible for researcher and practitioners from other fields, possibly requiring domain specific customization – expected to be done with the DEIS Tool-Development Laboratory – and demonstrators – expected to be done with the Departmental Demonstrator Laboratory. Effort needs to be taken to ensure that these activities produce a significant number of publications.

Research Collaborations and Projects We want to maintain the current balance between basic research and application-oriented projects. Also, we will continue to pursue successful big collaborative projects but still have attention to individual projects, as these are crucial for the academic careers of young research members. We also intend to balance between applying for (hard to get) individual prestigious grants (ERC, Villum YIP, DFF Sapere Aude) and more accessible funding opportunities.

Research Management and Staff In the next hiring rounds we hope to attract more highly qualified applicants at all levels, with a particular focus on attracting an increased number of highly qualified applicants to our PhD position. We aim to make more aggressive use of personal networks and advertise more clearly the "tenure track" possibility.

Concerning future growth of the (new) DEIS group, we have particular focus on the areas of Artificial Intelligence and Machine Learning, Security, Network and Programming Technologies. The staffing of the DEIS Tool Laboratory needs to be made permanent, and as for the staff of the Departmental Demonstrator Laboratory we seek two main competences 1) digital twins and virtual demonstrators and 2) IoT and physical demonstrators.

We intend to identifies ways to decrease the drop-out of PhD students, by introducing mentoring support functions, more extensive use of study groups, as well as social arrangements. In the likely situation of a continued lock-down due to Corona

this should have even more attention.

For Assistant Professor that do not hold a tenure-track position, we will try to establish a principle of a 1-2 year extension based on involvement in external projects. First agreements of this type has already been made with the Department. In the same manner we want the mentoring offered to tenure-track Assistant Professors to be extended to non-tenure track Associate Professors.

The research activities are increasingly relying on the availability of the computing facilities, in particular the presence of the Model Checking Cluster. Whereas the staff of CLAAUDIA provides ample support for the general set and operation of these computing facilities, it is important that we within DEIS have own permanent staff, whose responsibility include interfacing to CLAAUDIA.

5.5 Activities and Results

5.5.1 Foundational Theories

Behavioural Metrics and Bisimulations The DEIS group has a long tradition in notions of exact and approximate behavioural equivalences which allow one to compare quantitative systems exactly and approximately. In this reporting period, we continued our success story, as outlined below.

Building on its existing work, DEIS introduced novel notions of behavioral equivalences, expanding to application domains in systems biology, quantum computing and data mining. Specifically, (LICS'2021, LICS'2023) introduced novel algorithms for the computation of behavioral equivalences and applied them to published Boolean network models. This allowed one for instance to compute biologically relevant attractors whose computation was previously infeasible. In a similar vein, (CMSB'2024) introduced approximate behavioral equivalences to speed-up the simulation of published chemical reaction networks. Instead, (TACAS'2024) introduced behavioral equivalences for quantum circuits. This allowed to efficiently simulate and debug, on classic computers, published quantum programs which are too demanding for the currently available quantum hardware. At last, (ICDM'2024) used approximate behavioral equivalences to efficiently obtain graph embeddings of benchmark networks, outperforming state-of-the-art data mining approaches. This aligns to (IEEE Trans. Automatic Control'2025, IEEE Trans. Automatic Control'2024) which allow for efficient verification and optimization of uncertain networks. The aforementioned techniques have been implemented in the software tools ERODE and CLUE. In a similar vein, (IEEE Trans. Automatic Control'2023) introduced a behavioral equivalence for Markov decision processes and evaluated

its applicability on benchmarks from performance engineering and systems biology.

In addition to expanding into new domains, DEIS has continued its influential work on the computational foundational aspects of behavioral metrics. For example, in (LMCS'2021) we introduced the first practical algorithms for computing distances of probabilistic automata (the conference version being selected among papers from CONCUR'19). Subsequently, we introduced in (QEST'2024) computational methods for metric distances of linear dynamical systems. In the works (CALCO'2021, LMCS'2024, MFPS'2023), we further investigated the algebraic and logical foundations of behavioral distances. Notably, (CALCO'2021) was awarded Best Paper at CALCO 2021, for developing the theory of commutative combination of quantitative effects, which was used to provide the first algebraic axiomatizations of labelled Markov processes and Markov decision processes.

Logics The DEIS group has continued its strong and influential work on logic in computer science while also expanding into new areas like hyperlogics and automated theorem proving.

In a series of works (kicked off by (LMCS'2025)), we settled the complexity of the most important verification problems for several synchronous and asynchronous hyperlogics, which allow the specification and verification of information-flow properties for security and privacy. Many problems are shown to be highly undecidable, thereby motivating and guiding further research into tractable fragments. Furthermore, DEIS developed game-based algorithms for model-checking HyperLTL (Acta Informatica'2025, CONCUR'2025), arguably the most important hyperlogic. These algorithms also yield explanations for the satisfaction or violation of a specification, thereby increasing the usefulness of HyperLTL model-checking considerably.

In another line of work, DEIS studied robust semantics for temporal logics, including CTL and CTL*, probabilistic CTL and CTL*, ATL and ATL*, and extensions of LTL. All these works have in common that the complexity of the model-checking problem for the robustified logic is as hard as for the non-robust variant, i.e., robustness can be added for free. Finally, DEIS showed that robust semantics also increase the usefulness of model-checking: While 44% of LTL formulas of a standard benchmark set are not monitorable under standard semantics, all formulas are monitorable under robust semantics (Formal Methods in System Design'2022).

We also continue a successful line of work on string constraint solving, implemented in the constraint solver Z3-Noodler. Z3-Noodler took the first places in SMT-comp competition of SMT-solvers, string constraint solving sub-category, in the last two years (in a strong competition with large research groups and with industrial grade

solvers such as cvc5). The recent works were concerned with improving scalability and generality of the core string constraint solving method and its implementation in Z3-Noodler. For instance, we pinpointed a class of positional constraints, which includes several practically relevant constraints such as string disequality, and proposed an NP algorithm for them, significantly improving the previously known doubly exponential one.

We have formalized in the proof assistant Isabelle/HOL results on the meta-theory of proof systems for several logics including first-order logic, epistemic logic, public announcement logic, second-order logic and higher-order logic. We have also built a general framework in Isabelle/HOL for completeness proofs for logics. The framework makes it easy for logicians to prove completeness of new and old logics and proof systems. We demonstrate this by using it to formalize the completeness of a very recent hybrid logic.

Monitoring and Monitorability In the reporting period, DEIS increased its efforts on monitoring. In the timed setting and in a series of works – initiated by (FORMATS'2022) accompanying our keynote talk at FORMATS'2022 – DEIS revisited the monitoring of real-time specifications expressed in MITL, including monitoring under delayed observation and monitoring under assumptions. Here, DEIS has developed uniform foundations, general-purpose algorithms, as well as a prototype implementation for all three settings. Two of the three conference papers introducing the settings have been invited to special issues of journals dedicated to the respective conference. Most recently, DEIS settled the complexity of the monitorability problem for real-time specifications (CONCUR'2025).

Complementarily, in a pair of papers, DEIS studied the complexity of basic verification problem for `nfer`, an event-stream abstraction language developed by engineers at NASA to evaluate telemetry logs: Our results show that the full language is very expressive and thus computationally hard to verify, again guiding the search for tractable fragment. Both of these papers were invited to the respective special issues dedicated to the conferences.

Finally, DEIS also studied the monitoring problem for hyperlogics, developing algorithms to construct both centralized and decentralized monitors from specifications (CONCUR'2024).

Theory of Timed and Energy Automata In the reporting period, we have continued investigation of the theory of timed automata, as well as the extensions with cost and resources. We have considered parameter synthesis for real-time

systems modeled as stop-watch and timed automata, where we demonstrate (Fundamenta Informaticae'2021) that refinement of trace abstraction provides solutions in contrast to current state-of-the-art methods.

Energy Timed Automata (ETA) extends PTA by allowing the rates of the cost-variable to be negative, making it possible to capture energy consumption as well as harvesting. A key decision problem is whether there exist infinite plans (runs) during which the energy-level will always remain within some given safety bounds. Previously we proved this problem – so-called energy-constrained infinite-run problem – to be undecidable for generic energy timed automata. In (Formal Aspects of Computing'2021) the energy-constrained infinite-run problem was proved decidable in settings with both certainty and uncertainty of the energy rates for the subclass of flat segmented energy timed automata. In particular, this work was selected for a special FM18 journal issue, where the article received the best paper award.

We have revisited the energy-constrained infinite-run problem in the setting of multiple cost variables providing a fixed point characterization of energy-levels allowing energy-constrained infinite run. This paper was invited to the special issue journal dedicated to TASE'2024.

During the last 25 years, DEIS has played an internationally central role in establishing Compositional Specification Theories (CTS) for interacting systems. Such a theory allows specifications to be logically combined (e.g. conjunctively) as well as structurally combined (e.g. combined in parallel). Also, the dual operator to parallel composition, quotienting, should be expressible. It may be shown that a CST supports assume-guarantee reasoning. During the past period, DEIS has revised and substantially extended the CST based on Timed I/O Automata (arXiv'2023) that underlies the UPPAAL branch ECDAR. Also a CST for Hybrid Systems has been developed and applied to analyse flexoffers between prosumers (producers and consumers) in an energy system

Automata Theory In a series of influential papers, DEIS has opened new applications for history-deterministic automata, i.e., non-deterministic automata which still possess many of the desirable properties of deterministic automata. These applications include infinite-state synthesis (LMCS'2022, LMCS'2024) (the latter being based on work winning the best-paper award at MFCS 2021) and quantitative specifications (Trans. Comp. Logic'2025).

5.5.2 Verification and Validation

Timed Automata In the evaluation period, we have successfully improved efficiency of existing symbolic analysis as well as extending their applicability to significantly more general settings.

Zone-based on-the-fly analyses of timed automata require additional abstractions in order to guarantee termination. Over the years, DEIS have contributed with several so-called extrapolations ensuring termination, as well as increased performance. Most importantly, intricate proofs of their correctness have been provided. In the period DEIS has developed novel extrapolation methods for extended timed automata with expressions in guards and updates over integer variables (FORMATS'2021, ICFEM'2023). The resulting extrapolation reduces the zone graph sizes by 34.7% overall compared to a classic location-clock-based extrapolation. Also novel extrapolation techniques have been deviced for model checking of multi-player timed games against TATL specifications (CONCUR'2025). Having implemented this on top of UPPAAL, this provides our first zone-based based full TCTL model checker for timed automata. Also, after implementing our new abstraction in UPPAAL TIGA (synthesis for two-player timed games) we improve its performance by almost an order of magnitude.

Introduced 25 years ago Priced Timed Automata (PTA) extends TA by a single cost variable that may evolve according to location-specific non-negative rates. PTA allows optimal planning problems to be solved efficiently through a cost-optimal reachability analysis using priced zones. Already 3 years later it was shown that optimal infinite plans in terms of minimal mean payoff were also decidable, in fact PSPACE-complete. However, it is only now—after an additional 20 years—that we have succeeded in presenting a (efficient) algorithm using priced zones (ICAPS'2024).

DEIS has made several contributions to the monitoring of timed systems, as already described in the Foundational Theory section. In particular, given a Timed Büchi Automaton (TBA) presentation of a property to be monitored, effective zone-based, fixpoint computations were developed for pre-computing crucial state-sets of the TBA (FORMATS'2022). Zone-based methods for maintaining state estimates during monitoring were also developed, which proved highly non-trivial in the setting of parameterized delays (IFM'2024).

Petri Nets In the past five years, we advanced verification techniques for Petri nets and Petri games and their extensions with time and colors, focusing on state-space reduction, unfolding of colored nets, and application of the theory

to case studies. In particular, we optimized the unfolding algorithm of colored Petri nets (RP'2021, Fundamenta Informaticae'2023) by introducing static analysis methods to group equivalent colors into classes and overapproximate feasible color sets per place, significantly shrinking the size of the unfolded nets. These techniques outperform existing unfolding tools like MCC, Spike, and ITS-Tools in size reduction and query resolution on the Model Checking Contest benchmarks. Most recently, we developed algorithms, implemented in the tool TAPAAL, for explicit verification of colored Petri nets (ICTAC'2025), avoiding the expensive unfolding process.

Another prominent direction involves the continuation of our work on stubborn set reductions extended to game-theoretic and timed settings. In (FORMATS'2021, LMCS'2021) we adapt the classical stubborn set reduction technique to timed-arc Petri net games, pruning interleavings in reactive systems under hostile environments and yielding possibly exponential savings in time and memory on scaled case studies. Complementary works published in (TACAS'2025) propose static and dynamic marking reductions for Petri nets based on transition effects, reducing explored configurations by up to 40% on average in CTL benchmarks, and in (SPIN'2023) we improve the state-space search by avoiding irrelevant subgraphs in fixed-point computations, further enhancing on-the-fly algorithms for CTL model checking and Petri game synthesis. The efficiency of the reachability search was further improved by introducing a random search strategy with dynamic potency assignments tied to heuristic distances (SPIN'2023), outperforming classical strategies across diverse Petri net models.

Finally, Petri nets/games were leveraged for practical applications in computer network updates. We translated the SDN (software-defined networking) update problem into Petri games (PETRI NETS'2021) in order to find efficient update schedules via the synthesis engine implemented in our tool TAPAAL, outperforming competing approaches on large network topologies while at the same time preserving security policies during the transient updates. The follow-up work Kaki (IFM'2022, Formal Aspects of Computing'2023) introduces further optimizations like subproblem decomposition and update batch identification, yielding provably minimal concurrent batches of updates while maintaining waypointing and chaining policies, with superior runtime and sequence lengths compared to the tool FLIP as demonstrated on the Topology Zoo benchmarks. Most recently, we designed and implemented HyperLTL verification engine (ATVA'2025) for Petri nets and used it to analyze congestion in computer networks.

Dependency Graphs On-the-fly model checking (also called local model checking) is an efficient approach to formal verification that explores complex systems incrementally, enabling analysis of large models without necessarily constructing their entire state-space upfront. Over the last decade, the DEIS group has had a leading role on developing the theory of dependency graphs that facilitate such on-the-fly model checking in a unified framework with wide range of applications. A major contribution of the DEIS group was the introduction of abstract dependency graphs (STTT'2022) that generalizes the fixed-point computation from Boolean to arbitrary value domains that satisfy the Noetherian ordering axioms. More recently, we applied dependency graphs for the verification and synthesis of (untimed) alternating-time logic (ATL) properties in concurrent games with multiple players (GandALF'2023)as well as for the timed variant of ATL that allows us to specify player-coalitions (CONCUR'2025). We also improved the performance of the generic algorithms by a light-weight but practically beneficial variant of the pruning approach, the so-called "elimination of detached regions" in the dependency graph (SPIN'2023) showing promising experimental results. The technique of inclusion checking that formalizes a version of on-the-fly pruning of the state-space has been defined in the dependency graph framework (CONCUR'2025), further improving the performance of the algorithms. We also suggested a new reduction technique for Petri nets that is applicable to CTL model checking of Petri nets via dependency graphs (TACAS'2025). The importance of this line of work on dependency graphs was further confirmed by a keynote talk at CONCUR 2025 (CONCUR'2025) providing a survey of the research conducted on the topic of dependency graphs over the past 20 years.

Statistical and Randomized Model Checking Statistical Model Checking (SMC) is an analysis technique that combines simulation and statistical inference to estimate the probability that a stochastic system satisfies a given behavioral property. SMC has been available in UPPAAL since 2011 and has been used in numerous applications since then, including analysis of extremely large agent-based models of the Northern Jutland population to give advice on suggested lockdown measured with respect to Covid-19 during 2020-2022.

In the evaluation period, DEIS has made several contributions that significantly improve the performance of SMC in UPPAAL. Often, the properties of interest are rare in the sense that they occur with very small probabilities. In (IsoLA'2022) we have developed and implemented the rare event simulation technique importance splitting in UPPAAL, significantly reducing the number of system executions needed to obtain a highly confident estimate of a rare property. In (Festschrift'2025), we

have investigated the possibility of accelerating SMC using GPUs: in collaboration with NVIDIA, we have developed a prototype tool for GPU-based SMC, which in time-wise vastly improves single-core SMC while demonstrating substantial energy savings.

During the period, we also extended the UPPAAL SMC engine to support hyperlogic HPSTL for stochastic hybrid and timed systems (SPIN'2022). The extension was applied to analysis of a number of side-channel attacks.

A major contribution of DEIS has been the extension of TAPAAL with an SMC engine (PETRI NETS'2025). The work includes a first race-based stochastic semantics for TAPNs. The practical applicability of our modeling formalism and its SMC implementation is demonstrated in several examples. This work won the Best Paper Award at the Petri Nets conference 2025.

Complementing the work on SMC a line of randomized algorithms has been developed and implemented in UPPAAL providing efficient (falsification) methods for refinement, reachability, and cost-optimality. The work on randomized reachability was selected for a special journal issue related to FMICS21 (STTT'2022). Also, randomization was key to a method ranking counter-examples according to usage and risk of a Cyber-Physical System (FORMATS'2023).

Finally, the SMC engine of UPPAAL has been applied to a large number of industrial energy-consuming and -harvesting cases, with particular focus on sensor networks. Several of these studies were carried out in collaboration with industrial partners. (DATE'2021, ECBS'2024, ISCC'2021).

The recognition of UPPAAL SMC is confirmed by the Invited Talk at the Isaac Netwon Institute Summer Event on Verified Software in July 2022 and the Keynote Talk at TAP 2023.

Synthesis and Shielding Synthesis is the automatic construction of a system (controller or program) from a formal specification describing how it should react to all possible inputs from its environment. During the period, DEIS has made contributions to synthesis in the setting of timed and energy timed games. In (CONCUR'2025), we have developed strategies for multi-player timed games with respect to TATL specifications, resulting in order-of-magnitude improvements of UPPAAL TIGA. Also, in (Formal Aspects of Computing'2021), quantifier elimination for first-order logic over linear arithmetic was applied to synthesize strategies ensuring energy-constrained infinite runs of an energy timed game.

In a series of work, we deployed BDD-based methods for efficiently solving a number of synthesis problems from computer networking (TASE'2022, SCP'2023, IN-

FOCOM'2024, DSN'2024). More details are given in a dedicated section below.

DEIS has significantly progressed shielding in the context of Reinforcement Learning (RL). In ordinary RL, an agent learns through trial and error, which can lead to unsafe actions while exploring. Shielded RL adds a (synthesized) safety shield that monitors and corrects the agent's actions in real time to guarantee that safety constraints are never violated. Several contributions address shielding for Euclidean MDPs (i.e., continuous and hybrid domains) using analytical solutions (CCTA'2023) and compact, partition-based strategy representations (AISoLA'2024, AISoLA'2024) resulting in the COSHY tool extension of UPPAAL (RP'2025). Additional work on combining shielding with automata-learning has been made .

Most recently, a novel, highly scalable approach for shielding multi-agent systems has been developed. The method is based on an assume-guarantee proof rule decomposing a global safety specification into local obligations for the shields of the individual agents. Applying the shields during reinforcement learning significantly improves quality within a given budget (AAMAS'2025).

BDD Based Methods We have deployed the Binary Decision Diagrams (BDDs) for a number of problems from the computer networking domain. The research contributions in (TASE'2022) focus on advancing BDD-based symbolic synthesis for network updates, ensuring transient correctness during network reconfigurations. This allows us to synthetise network updates while preserving a broad range of policy properties expressed in linear temporal logic (LTL), such as waypoint enforcement and loop freedom. This approach uses parameterized BDDs to compactly represent all feasible and cost-optimal solutions, enabling efficient exploration of the update space without exhaustive enumeration. In the extended journal version (SCP'2023) we further enhance the scalability through a two-level BDD structure that improves performance on real-world topologies, providing formal guarantees of correctness.

Building on BDD techniques for network resilience, a series of papers including (DSN'2024, INFOCOM'2024) contributes to efficient synthesis and repair methods for local fast re-routing (FRR) forwarding tables in highly dependable networks. We deploy BDDs to repair existing routing tables or synthesize new ones from scratch using hybrid heuristics, achieving resilience to multiple link failures with up to three orders of magnitude speedup over state-of-the-art approaches. Complementing these, our recent work (VMCAI'2025) applies BDDs to a different problem of light path scheduling in elastic optical networks, introducing a method for routing and spectrum allocation that ensures resilience to multiple link failures without double spectrum usage, demonstrating BDDs' effectiveness in model checking and optimizing resource-constrained network problems.

Theorem Proving In the reporting period we have worked on formalizing in Isabelle/HOL a number of algorithms and tools for verification and validation. In particular we have now a formalized correctness proof for a reachability algorithm in pushdown systems as well as a verified implementation (FMCAD'2022). We have also generalized this to weighted pushdown systems. Additionally we have built a tool for the verification of cryptographic protocols. This tool produces security theorems in Isabelle/HOL for the verified protocols (CSF'2021). Another development we have in this direction is in program analysis where we have verified an encoding of program analyses into stratified Datalog. This required an existence proof of least models (SAC'2024).

Quantum Systems During this period, DEIS has expanded the research scope to new emerging technologies. One of the most prominent ones is quantum computing, which is of particular strategic importance in Denmark. DEIS have been active in founding the AAU Quantum Hub with both the founding chair and a regular member in the steering group. In terms of research, we have focused on contributions to the area of design automation for quantum circuits – an area that has long benefited from formal methods in the classical domain – to reduce the effort of bringing quantum software into practice (once the hardware is ready). In one direction, we applied dimensionality reduction to quantum circuits (TACAS'2024), which allows for efficient simulation on a classical computer. This paper was invited for a special issue. In a follow-up work with Robert Wille's group (TUM), we combined this approach with their decision-diagram package to achieve even greater reduction in running time (Trans. Quantum Comt.'2025). In another line of work, we proposed a verification approach of quantum algorithms against general specifications, which encodes the problem as a first-order formula over the reals – a fragment for which δ-complete decision procedures exist (FM'2023). When compiling quantum circuits to a hardware platform, compilers apply optimizations, which motivates the problem of checking equivalence between two quantum circuits. This problem is co-NQP-complete (the quantum version of NP). Based on a master thesis, we proposed a new approach to integrate tensor network contraction (which is often used for simulation) with (tensor) decision diagrams, achieving state-of-the-art performance (Entropy'2024). In terms of funding, we secured one of the six PhD projects funded by the Danish e-infrastructure Consortium (DeiC); in this EQuaL project, we extend our equivalence-checking approach with heuristics and machine learning. In the recent basic research center CLASSIQUE funded by the Danish National Research Foundation, we lead the "research thrust" on Reliability and trustworthiness. This interdisciplinary center combines expertise on communi-

cation in the quantum era. To support a sustainable growth from within, we are teaching the new Quantum Information and Computing course for MSc students and organized two PhD courses on the topic. We also co-organized the Workshop on Formal Methods in Quantum Computing, co-located with CONFEST 2025 in Aarhus, and are active in the quantum activities of the Royal Danish Academy of Sciences and Letters as well as the Danish Quantum Community.

5.5.3 Security

The unique challenges of security, most notably an active and knowledgeable attacker, combined with the increased societal and industrial need for high-assurance systems, giving strong security and privacy guarantees, make it ideally suited for the theory, tools, and techniques that are developed, applied, and implemented in DEIS.

Protocol Verification Secure protocols are necessary to protect communication between (sub-)systems and/or users. Experience shows that it is difficult to define, design, and implement secure protocols, hence the need for high-assurance protocol verification. In (CSF'2021), the authors present first steps towards highly automated formalised proofs of stateful (security-)protocols.

In (ICISSP'2022) the authors give an analysis of the Lightning protocol used in Blockchain settings. The analysis, which uses the ProVerif tool, shows that the Lightning protocol fails to satisfy an authenticity property.

In (FMICS'2024) statistical model checking is used to analysing energy draining attacks on devices implementing the DTLS protocol, e.g., to drain the battery of IoT devices, as well as modelling and exploring the efficacy of potential countermeasures.

String Solving Many attacks involve some form of "injecting" code into a program, and that injection is only possible due to unsanitised user inputs (strings) used in insecure ways. String Solving is thus an important research area as it (combined with symbolic execution) allows analysing which string patterns are used in different parts a program. That is, we can determine if the programs allows an unescaped string to be used in a SQL-query.

In the current reporting period, we have developed the tool Woorpje that solves Word Equations with length constraints (the decidability of which was uncertain for long) and showed how SMT-solvers (CVC4 and Z3) could benefit from solving techniques as a pre-processing step. In parallel with developing Woorpje we also

created the (to our knowledge) first framework for automating the comparison of String Solvers (Journ. Found. Comp. Scien.'2025, CIAA'2023).

Glitch Attacks and Sidechannels By intentionally injecting faults deep into a system, also called a glitch attack, the assumptions underlying both security and functionality design may be broken, leading to a full system compromise.

In (AISoLA'2024, FMICS'2025) it is shown how statistical model checking can be used to evaluate the effects of glitch attacks and potential mitigations, e.g., by hardening bools, in security critical code, i.e., code authentication and authorisation.

In (SPIN'2022) a probabilistic hyperlogic is developed and, among other examples, used to detect a timing channel in cryptographic code. A UPPAAL-based model checker for the hyperlogic is developed and further used to examine if random delays can be used to mitigate the timing channel.

Socio-Technical Systems Systems where humans and human interaction are essential to the system, it often becomes unclear or ambiguous what security actually means as well as who security should benefit and how.

In (NSPW'2022), based on a study of the CHERI development process, it is argued that participatory practices are used throughout the hardware/software stack in order to improve (user perceived) security.

Models are often essential for defining, analysing, and verifying the security of a system. But even the term and concept of "model" varies greatly in different security (sub-)communities making models and insights difficult to share and collaborate on. In (Journ. Cybersecurity'2024) we define a framework, called MORS, for exploring various aspects of different model types and classes for working within, between, and across various model types.

Misc Earlier work on Attack-Defense Trees (ADTrees) has been continued, resulting in a tool for defining and analysing ADTrees (in (STTT'2021)), as well as preliminary work on using ADTrees for guiding system refinement with a focus on security (in (FMICS'2023)).

In (ICDCN'2021) a compiler fuzzer was designed and implemented to verify that the P4 compiler (for software defined networks) did not contain or introduce security vulnerabilities in P4 code.

We also mention the Keynote Talk given at Cyberwall in Galaxia, ESA, Belgium, 2024.

5.5.4 Artificial Intelligence

Safe and Verifiable Reinforcement Learning Reinforcement learning (RL) has long proven its ability to learn effective decision-making and control strategies automatically - often exceeding human performance - without explicit programming. However, RL lacks correctness and safety guarantees because of how it learns and represents strategies. In the period, DEIS has made several contributions to strategy representation, verification and shielding, three complementary approaches that address the challenge of correctness and safety.

From a safety/explainability perspective, Decision Trees (DT) are preferred over Neural Networks (NN) as control policies for (dynamical) systems. In UPPAAL STRATEGO, a revision of the DT-based partition-refinement Q-learning algorithm for Euclidean Markov Decision Processes has been developed with proven convergence guarantees (AISoLA'2024). Here, the potential explosion in size of the learned DT is addressed by our CAAP semantic-preserving DT-reduction algorithm (RP'2025), which often yields orders-of-magnitude reduction. In (AAAI'2025) an alternative approach explores the exponential space of DTs using a novel trace-based pruning mechanism drastically reducing search complexity, while synthesizing compact and optimal DT policies from black-box environments and specifications.

In (NeurIPS'2023), we presented the first algorithm to directly verify a system controlled by a DT in continuous time. We demonstrated the effectiveness of our approach by verifying the safety of several DTs distilled to imitate NN policies for nonlinear systems. The paper was distinguished as a "spotlight" presentation at NeurIPS'23. In (AAAI'2022), we studied the verification problem for closed-loop dynamical systems with NN controllers ((NNCS). Our implementation delivers state-of-the-art performance and was the first to successfully analyze all benchmark problems of the annual ARCH-COMP verification competition for NNCS. In (AAMAS'2025), we have developed a novel approach to compose RL control policies in environments with a two-level structure, while giving probably approximately correctness (PAC) guarantees.

A very active line of research within RL - with several contributions from DEIS - is that of shielding. Here, traditional RL is combined with a formally verified safety layer (the shield) that prevents unsafe actions during both learning and execution. During learning, the agent can still explore, but only within the boundaries of the safety region. By avoiding unsafe and unproductive regions, the agent also learns faster and uses fewer samples. One line of contributions is that of shielded RL for Euclidean MDPs (AISoLA'2024, AISoLA'2024) resulting in the COSHY extension of UPPAAL STRATEGO (RP'2025). Most recently, shielded RL for multi-agent sys-

tems has been developed based on an assume-guarantee proof rule (AAMAS'2025). Experiments demonstrate effectiveness and scalability, with a reduction of computation time from hours to seconds and a significantly faster convergence of learning.

Within this research direction, DEIS has contributed to the research community in terms of initiating and (co-)organizing events such as SAIV 2024: First International Symposium on AI Verification, DIREC Workshop on Verifiable and Robust AI, 2023, as well as D3A Workshop on Verifiable, Robust and Explainable AI, 2025.

Automated Planning The area of automated planning deals with how to determine the best course of action (in the form of a plan or a policy) to achieve a given goal. The focus is on domain-independent methods which can automatically analyze and exploit the structure of a model of the environment to make efficient decision making on any given domain.

In this period, we have developed several algorithms and approaches to advance the state-of-the-art in the area. A prominent example is symbolic search techniques that perform exhaustive state-space exploration by efficiently representing sets of states as Binary Decision Diagrams (BDDs). Even though it was believed that these techniques were only suitable for exhaustive search, we showed that there is a family of heuristic functions that can effectively be used to guide symbolic search towards a goal (AI'2024), greatly improving the performance of a method that was already state of the art for cost-optimal planning in deterministic settings. Furthermore, we extended symbolic search techniques to support more expressive action models with conditional effects, axioms, and state-dependent action costs (JAIR'2025). And also adapted them to settings beyond classical planning. For example, we showed that symbolic search can be used on problems with multiple potential goals in order to find states that are as close as possible to as many goals as possible (ICAPS'2024). Our techniques are currently the state-of-the-art for Stackelberg planning (AAAI'2021), a class of adversarial game that has applications for network verification (IFIP Networking'2022) and verification of meta-actions (IJCAI'2023), among others.

Another important line of research is how to automatically create abstractions of a given problem that can be used to extract useful properties and/or guide the search for a plan. In that direction, we have explored how to improve the CEGAR process that is currently used to guide search in cost-optimal classical planning (AAAI'2024, ECAI'2024), we have explored how to efficiently use abstractions in the context of decoupled-search algorithms (ICAPS'2023, SoCS'2022, ICAPS'2022). And we have set the foundations and practical approaches for several abstraction methods in probabilistic planning (ECAI'2024, ICAPS'2023, ICAPS'2022, ICAPS'2021). All

of this has significantly advanced the state-of-the-art in optimal planning both in deterministic and probabilistic environments.

Finally, we introduced Contrastive Analysis (AAAI'2023), a new way of identifying and exploiting structure in planning models. The key idea is to be able to compare states according to their goal distance, by introducing techniques that can prove a state to be at least as close to the goal as another. In that direction, we have analyzed the implications of performing dominance pruning in A* search(AAAI'2021), strengthen the methods to prove dominance, and introduced new methods that go beyond dominance by explaining what a state lacks to be at least as good as another.

Probabilistic Methods and Models A central focus of our research has been to deepen the theoretical foundations of generalization in modern neural models, with special attention to ensembles and posterior tempering. We derived a Chebyshev–Cantelli PAC–Bayes–Bennett inequality for the weighted majority vote, which bounds one-sided deviation risk by combining Chebyshev and Bennett arguments—this yields bounds that are tighter and more adaptive than classic PAC–Bayes inequalities in many settings (NeurIPS'2021). We then introduced PAC–Bayes–Chernoff bounds for unbounded losses (leveraging Cramér–Chernoff theory), which extend the applicability of PAC–Bayes methods to loss functions without bounded ranges. This enables new regularization techniques adapted to the model's geometry (e.g. via log-Sobolev inequalities) (NeurIPS'2024). In the direction of neural network ensembles, we formulated a diversity–generalization trade-off theory, characterizing how diversity measures in ensembles contribute to improved generalization under different aggregation rules and loss regimes (PMLR'2022). We also revisited the cold posterior phenomenon, showing that its empirical success is symptomatic of underfitting in the standard posterior. Adjusting posterior temperature is thus not a heuristic tweak but a principled Bayesian mechanism to reweight evidence and mitigate model misspecification (Trans. Machine Learning Research'2024).

In our research on probabilistic modeling, we have continued our work on flexible frameworks for modeling hybrid domains using mixture models based on truncated basis functions (PMLR'2022) as well as the integration of NN components for increased model expressivity (Entropy'2021). These developments have also been explored within a genome representation learning context, where we have proposed light-weight and scalable models for latent representation learning (NeurIPS'2024) and demonstrated how structural domain constraints can be leveraged for learning latent variable models (ICML-Biology'2023, ICML'2023).

Relational and graph learning. Graph learning has emerged as a key area of interest within machine learning during the reporting period. Building on our extensive expertise in statistical relational learning (SRL), a main theme of our research has been the transfer of SRL methods to the fast developing field of graph neural networks (GNNs). In particular, we have developed methods for more powerful classes of aggregation functions (IJCAI'2021), and for interpretable feature construction in multi-relational domains (LOG'2023). We have shown that GNNs can be encoded as modules in the SRL framework of relational Bayesian networks (RBNs) (LOG'2023). The combination of GNN modules with the general RBN modeling capabilities leads to a neuro-symbolic framework that can harness the predictive power of GNNs for solving a wide range of reasoning tasks beyond the specialized prediction tasks GNNs are typically trained for. The RBN-GNN integration has been implemented in a new release of the Primula tool (ECMLPKDD (demo track)'2025) and we have explored applications of GNNs for both metagenomic binning (Bioinformatics'2022) and intelligent traffic systems (Trans. Spat. Algo. Systems'2022, IEEE Trans. Intelligent Transportation Systems'2024).

5.5.5 Distributed Systems and Networks

Internet of Things The research work on the Internet of Things led to the completion of 1 PhD thesis, and to the publication of 9 peer-reviewed papers on international conferences and journals, including on flagship conferences such as IoT, and top ranked conferences such as Mobiquitous.

1. The main research line was the analysis of leading communication protocols such as LoRaWAN and Sigfox by means of model checking (ISCC'2021, MECO'2021, IEEE Sensors Journal'2023) and system simulation (Proc. Workshop ns-3'2022, ECBS'2024, MobiQuitous'2022), and the optimization of its usage to improve the lifetime of IoT devices. Some of the results were included as modules in the leading simulator software Network Simulator 3.

2. Another research line involved the programmability of IoT devices, and code generation from formal specification of the IoT device service interfaces (SAC'2022, IECON'2021, ASOCA'2023, EDGE'2022). The results allowed the generation of service API and monitoring subsystems for Arduino-based platforms, and were included into the OpenAPI-Generator code generator.

Distributed Systems The research work on Distributed Systems achieved scientific results on a number of aspects, and led to the publication of 23 papers at leading international conferences and journals.

1. A research line focused on distributed computation, and in particular to different aspects of the edge-cloud continuum. Its fundamental characteristics were investigated (DCAI'2022, SATrends'2024). Different approaches to task orchestration were investigated, such as energy-aware auctions (EDGE'2023), resource provisioning (SEAA'2024) and fault-tolerant orchestration and computation offloading (EDGE'2023, eSAAM'2023). Finally, tools to visualise deployment scenarios (Eware IoT'2024) and edge-to-cloud offloading (JSS'2024) were studied.

2. Software engineering aspects of distributed systems were investigated (Models'2022, SCP'2024, SoSE'2021) and led to the extension of Papyrus for model-driven design of structured systems of systems.

3. Work on blockchains (OID'2021, DAPPS'2023, Blockchain'2023) supported the programmability of trust policies for businesses and organizations in distributed virtual world, and applied blockchains to manage crowd-sourced efforts to AI model training, and to disseminate security advisors in a non-repudiable manner.

4. Another research line focused on agent simulation. We pushed forward the state-of-the-art of energy-efficient motion planning (TASE'2024) and of online map exploration using independent agents (ICAART'2022, ICAPS'2022, ALR'2023, ICAART'2025).

5. Some work (DATE'2025, Festschrift'2024) has been devoted to more theoretical aspects of distributed systems, such as schedulability and performance analysis.

Verification of Network Protocols The achieved scientific results in computer networks where published in more than 20 peer-reviewed international conferences and journals, including top ranked conferences and journals like DSN, INFOCOM, CoNEXT, TACAS, TON, including a patent application on recursive protection of MPLS networks. The results can be sumarized into the following five categories, most of the research contributions involved the development of tool prototypes and experimental evaluation in collaboration with the companies NORDUnet and BENOCS.

MPLS networks modelling and analysis under link failures. We provided a formal model of MPLS networks and highlighted its connection for pushdown automata (ATVA'2021, Trans. on Networking'2022)and we suggested novel algorithm for increasing resilience in MPLS networks using a recursive fail-over protection (CoNEXT'2022) for which AAU decided to file a patent application due to its potential impact on the industry. We created MPLS verification framework AalWiNes popularized at `https://aalwines.cs.aau.dk/` and we improved its scalability by novel algorithms for pushdown automata verification (ATVA'2022)

that we also formally verified the approach using theorem provers (FMCAD'2022). We have developed an advanced MPLS simulation tool that has been extensively used in the evaluation of the developed techniques.

Fast-reroute protocols and the question of perfect resilience under link failures in computer networks. We suggested dynamic and memory-aware fast reroute algorithm and improved the scalability of the methods by employing BDD technology (DSN'2024, INFOCOM'2024).This allowed us to represent all perfectly resilient routings in a BDD and perform various optimizations.

Quantitative aspects of network protocols were studied with respect to congestion avoidance for capacity-aware routings (TACAS'2021) followed up by introducing the hazard value for quantitative network properties (DSN'2022).

Synthesis of correct and efficient updates in SDN networks.This line of work studied the use of formal methods for automatic synthesis of correct-by-construction network updates by using Petri nets and its time extensions (see e.g.(IFM'2022, Formal Aspects of Computing'2024)) as well as via the deployment of BDD technology (TASE'2022). In collaboration with an industrial Internet analytics company BENOCS, we conducted experiments on real network data from a major European Internet Service Provider and used quadratic linear programming to reconstruct the splitting ratios for routing paths, even in case of measurement noise (PRDC'2023).

5.5.6 Programming Language Technology

Static Analysis In the last reporting period researchers from DPW, the DEIS group and researchers at the IT University participated in the DFF funded Popular Parallel Programming (P3) project. Although the project was completed in 2020 a joint paper on the cost semantics of spreadsheets (Journ. of Computer Languages'2022) was published in 2021, to some extent this work inspired work on Energy Aware Programming.

Other activities concern type-based analyses of program properties that involve notions of aliasing.

The paper (EPTCS'2024) proposes a type system for dataflow and alias analysis in the setting of the functional scripting language Rescript and proves that the type system is sound.

The paper (FtfJP'2021) presents a behavioural type system for a subset of Java using notions from separation logic.

Energy-Aware Programming In the research evaluation 2015-2020 the topic Energy Aware Programming was reported as an emerging activity.

Energy aware programming is the practice of designing and writing software with the explicit goal of minimizing energy consumption. It involves making conscious decisions during the software development life cycle to optimize for energy efficiency, rather than simply optimizing for performance or functionality. This approach can lead to more sustainable software solutions, especially in resource-constrained environments like mobile devices and embedded systems, but it can also contribute to reducing energy consumption in data centers and will hopefully contribute to reducing the environmental impact of AI.

During the reporting period there has been a collaborative effort on building a tool based on UPPAAL for estimating energy consumption of web based IT systems and on building tools for measuring energy consumption of software.

A collaboration (arXiv'2025) with RUC and AU has developed advice on teaching energy aware programming.

Several interviews and a number of invited presentations at various industry events and online has been given.

Several papers have been or are in the process of being published in this area (Festschrift'2023, CERCIRAS'2022).

During the reporting period a large number of applications for external funding has been written, some with positive outcomes. We refer to subsection 5.5.10.

Operational Semantics A series of papers propose an editor calculus that describes syntax-directed editing for a functional programming language. The paper (PEPM'2021) introduces the calculus and its type system. In (SYNASC'2021) a notion of undo/redo is studied, and in (IFL'2022) the original calculus is extended with a notion of cut/paste and the resulting type system is proved sound. Finally, in (PEPM'2025) the editor calculus is encoded in a typed λ-calculus and the encoding, which is proved sound, is then uses as the basis for an implementation in Elm of a prototype editor. All of these papers are the result of collaboration with students.

The paper (EPTCS'2022) links programming language theory, programming language tools and education research. It gives an analysis the threshold concepts that one must face when teaching structural operational semantics and uses it to identify the requirements for a tool that uses techniques from program analysis to assist in the teaching of structural operational semantics.

In (EXPRESS/SOS'2024) the authors link the study of process calculi to functional array programming. The paper considers a subset of the Futhark programming language due to Henriksen, Oancea et al. and shows how one can give a sound encoding of this subset of Futhark into a version of the π-calculus.

In (EPTCS'2022, Information and Computation'2024) the authors study a higher-order version of the psi-calculus proposed by Bengtson, Parrow et al. and show that it is possible to formulate and give non-trivial instantiations of a generic type system for this higher-order process calculus.

In (NWPT'2021), the authors give a formalisation of the CYK algorithm for context-free parsing in Agda and prove that the algorithm has polynomial time complexity. This provides a formal proof that the class of context-free languages is contained in the complexity class P.

5.5.7 Educational Science

Education research The activities on education research have concentrated on the setting of higher education and have been motivated by concrete teaching experience among members of the DEIS group.

The papers (Trans. PBL Hybrid'2021) and (ECEL'2021) focus on how the move to online teaching activities at AAU during the COVID-19 lockdowns in 2020 and 2021 affected problem-based learning (PBL). They constitute an analysis of a university-wide survey among staff and students at the time and focus on issues of the social aspects of PBL and on the perspectives in the setting of flipped and blended teaching.

The paper (For the Learning of Mathematics'2023) considers different views of problem-based learning in degree programmes in the natural sciences and mathematics. Based on a qualitative survey, the paper gives a classification of student projects that allows one to understand the spectrum of projects from those that consider applied settings to those that take a pure theoretical perspective.

The paper (EPTCS'2022) straddles the border between programming technology and education research. It gives an analysis the threshold concepts that one must face when teaching structural operational semantics and uses it to identify the requirements for a tool that uses techniques from program analysis to assist in the teaching of structural operational semantics.

5.5.8 Tools

UPPAAL UPPAAL is an integrated tool environment for modeling, validation, and construction of real-time systems modeled as networks of extended timed automata, i.e., interacting finite-state machines extended with real-valued clocks and discrete variable over (user-defined) types with bounded domains. The first version of the tool was released in 1995 and in 2013 the tool received the prestigious CAV Award as 'the foremost tool for the verification of real-time systems'.

UPPAAL consists of several branches that support the analysis of various extensions of timed automata ranging from verification (classic), optimization (CORA), performance analysis (SMC), synthesis (TIGA), testing (TRON) and learning (STRATEGO). A major effort completed during the period has been the integration of TIGA and STRATEGO reinforcement learning engines with SMC and classical model checking in the **UPPAAL 5.0** released in June 2023.

Improvements in UPPAAL **engines** have been made, including a highly efficient randomized reachability engine to find (counter)example traces (STTT'2022), improved Q and M learning algorithms (AISoLA'2024) in STRATEGO with the ability to export and import strategies. The use of the Runge-Kutta ODE integration algorithm in SMC has replaced that of Euler providing increased stability and better error control. The **editor** has been significantly modernized with local and global Find and Replace functions, automatic text tabulation, autocompletion language being aware of user-defined names (types, variables, etc.), and much more. The **simulator** has been extended with trajectory plotting and strategy simulation capabilities, trace saving and loading of the concrete simulator using JSON format, and heatmap coverage visualization. Finally, the underlying engine can now be configured and changed in the GUI, enabling remote connections to more powerful computers, exploiting GPU and multi-core CPU accelerated engines developed also during the period (Festschrift'2025).

Two major releases of branches of UPPAAL have been made recently: In (CONCUR'2025) the symbolic engine of TIGA is extended to support synthesis for multi-agent timed automata with respect to TATL specification. In (RP'2025) STRATEGO is extended to support the automatic synthesis of safety shields for hybrid Markov Decision Processes.

Over 5 years of downloads of UPPAAL come from more than 1600 user domains – some represent individuals while others entire classes. Courses using UPPAAL are offered at universities such as UPenn, Hamburg, Reykjavik, Twente, Oldenburg, Shanghai, Lorraine, Muenster, Swansea, Darmstadt, Szeged, DTU, AAU, Toulouse, Dortmund, Sorbonne, Berlin, Lübeck, Nantes, Graz, Rouen, Vanderbilt, Leuven,

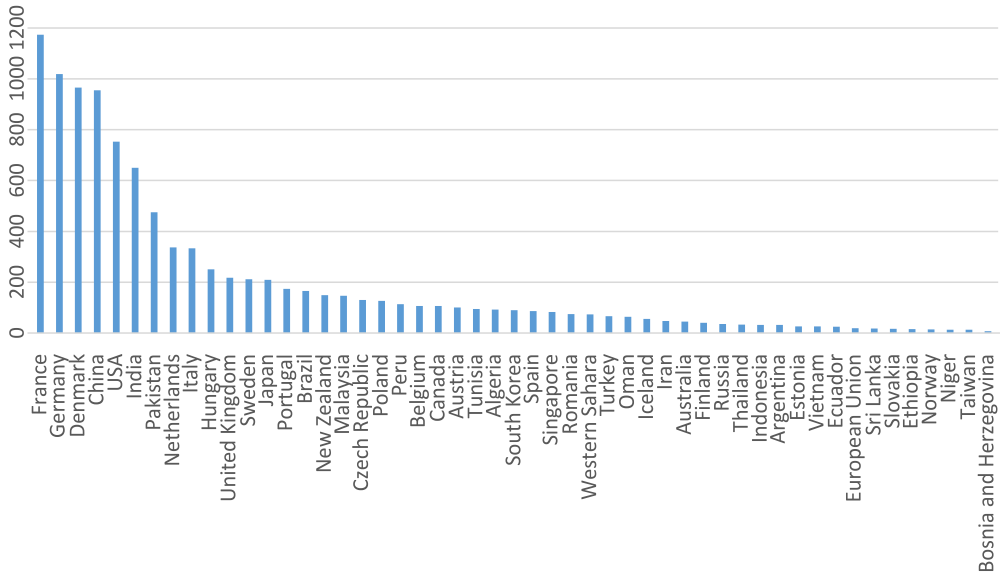


Figure 5.2: UPPAAL users per country (France=1174).

Lille, and many more. Fig 5.2 shows the top 50 counties. Furthermore, members of DEIS have given extensive (1-2-4 days) lectures at numerous PhD schools both at Aalborg University (multiple times) as well as at VERIMAG, Grenoble, France (2021), Udine (2023), Leipzig (WATA 2023), Huawei, Grenoble, France (2024), Beijing (SETSS 2025) and Marocco (ICTAC 2025).

Commercially, UPPAAL is available from the companies VERIAAL (veriaal.dk), UP4ALL (uppaal.com). In addition, STRATEGO has provided the basis for the spin-out companies IntelliGo (advanced traffic control, intelli-go.dk) and CEDAR (intelligent heat-pumps, cedar-heat.dk).

The industrial applications of UPPAAL are numerous with the recent survey "A Systematic overview on the Applications of UPPAAL" [1] providing an extensive account. Applications made by DEIS members themselves include Covid-19, smart batteries (IECON'2023), water management (ECC'2024, Journ. Logical and Algebraic Methods in Programming'2024, FSEN'2024) (the latter receiving best paper award), as well as autonomous systems (ICAPS'2022, IsoLA'2025), smart transport and energy systems.

[1] https://doi.org/10.3390/s25113484

TAPAAL Over the past five years, the development of the TAPAAL tool—a platform-independent verifier for colored timed-arc Petri nets and games—has focused on enhancing its core verification engines for efficiency and scalability in state-space exploration. Key advancements include the development of explicit model-checking techniques tailored for colored Petri nets, bypassing costly unfolding processes through optimized binding generation and linear programming approximations (ICTAC'2025). Complementary work introduced token elimination strategies (TACAS'2025), enabling dynamic and static reductions in Petri net markings to preserve reachability properties while yielding up two orders of magnitude speedups on some models. Other contributions, such as the potency-based heuristic search with randomness were integrated into TAPAAL (SPIN'2023) and further improve reachability analysis by dynamically adjusting action priorities during exploration, outperforming standard heuristics on large Petri net benchmarks. These efforts underscore TAPAAL's evolution toward practical handling of complex and large models, with structural and on-the-fly optimizations mitigating the state-space explosion.

The most recent extensions have broadened TAPAAL's applicability to further advanced features. The 2025 release of TAPAAL 4.0 introduced GUI support for colored nets, aligning with new verification engines that now support a wide range of logics including CTL, LTL and HyperLTL (ATVA'2025). An important achievement was the introduction of statistical model checking (SMC) for a novel stochastic extension of timed-arc Petri nets (PETRI NETS'2025), a work that was recognized by the best paper award at the 46th International Conference on Application and Theory of Petri Nets and Concurrency. This work, alongside TAPAAL's defense of three gold medals at the annual Model Checking Contest 2025 and ongoing tool development, highlights its competitive edge in various real-world applications, ranging from the synthesis of efficient network updates (Formal Aspects of Computing'2023) to probabilistic system verification. Overall, these developments position TAPAAL as a robust, award-winning tool in the model-checking landscape.

Tools for network verification Researchers at DEIS have during the past 3 years developed a large collection of tools advancing verification and synthesis of computer networks. AllSynth (TASE'2022) uses BDDs to generate transiently correct network update sequences incorporating operator preferences expressed as LTL policies, outperforming the competing tools like NetSynth and FLIP on Topology Zoo benchmarks. Kaki (Formal Aspects of Computing'2023) employs Petri games implemented the model chekcer TAPAAL for concurrent update synthesis in software-defined networks, minimizing the number of batches in which routers are

updated while preserving regular update policies; to speed up the update synthesis problem several optimizations like topological decomposition are implemented in the tool. SyPer (INFOCOM'2024) and SyRep (DSN'2024) are recent tools that tackle the problem of fast re-routing in computer networks in case of link failers, aiming at synthetising local fail-over routing rules that achieve a theoretical optimality described by the notion of perfect resilience: as long as the source and target nodes in the network remain connected under any set of failed links, the routing must guarantee a successful packet delivery. Both tools rely on the BDD technology in order to store the large number of possible routings and implement numerous efficiency improvements in order to deal with up to mid-sized network topologies. Finally, ExpectAll (VMCAI'2025) is a light-spectrum allocation tool for scheduling flows in all-optical networks, applying also the BDD technology in order to provide fast failover protection in scenarios with multiple link failures.

This range of tools integrates symbolic methods for scalable and optimal verification and synthesis of network configurations, validated on benchmarks that demonstrate sub-second repairs of network configurations (SyRep) and minimal-batch synthesis guarantees for concurrent software updates (Kaki), aligning the theory and practice for software-defined and optical networks. Open-source prototype implementations and formal theoretical guarantees position these tools as benchmarks for future research in the quest for dependable networks.

Reachability analysis of pushdown automata In the evaluation period, we introduced a number of interconnected tools and libraries for the verification of (weighted) pushdown automata (PDA/WPDA), primarily targeting the reachability analysis in infinite-state systems with applications to MPLS network verification under failures. The work was initiated by the development of the tool P-REX (Trans. on Networking'2022), a model checker for unweighted PDA verification that can model MPLS dataplane behaviors (e.g., label stack operations) with queries described by regular expression over stack contents and paths. The implementation of the algorithms in P-REX was improved in PDAAAL (ATVA'2022), an open-source C++ library that enables weighted reachability analysis of WPDS over idempotent semirings, supporting shortest/longest witness traces via saturation algorithms (pre*, post*, dual*) with several optimizations suggested in (ATVA'2021). These reachability engines are made available in the user-friedly GUI provided by AalWiNes (`https://aalwines.cs.aau.dk/`) for quantitative analysis of MPLS/SR networks, leveraging PDAAAL for efficient analysis enabling comprehensive policy verification like waypointing and loop-freedom in recursive tunneling setups. It is worth mentioning that the core verification algorithms in PDAAAL where formally

proven correct in the proof-assitant Isabelle HOL (FMCAD'2022, Arch. Formal Proofs.'2023) and the actual implementations verified by using differential testing against a provably correct oracle generated by Isabelle HOL.

Reachability analysis of dynamical systems At DEIS, we have significantly extended our framework JuliaReach for the formal analysis of dynamical systems, with a focus on continuous dynamics. The main development in this reporting period was the extension to AI controllers, in particular neural networks (AAAI'2022, NFM'2023, AISoLA'2024) and decision trees (NeurIPS'2023). We also developed a new reachability method for nonlinear dynamics based on recent error bounds for Carleman linearization (RP'2021), and a method that integrates probability bounds analysis to yield quantitative answers in cases where the initial states are given as probability distributions (ESREL'2022, Journal on Approx. Reason.'2024). Moreover, we wrote a survey about the different approaches to discretize a linear continuous system (IFM'2022), a class of systems which is a key strength of JuliaReach (Information and Computation'2022). In terms of core development, we published tool papers about the library for set computation (JuliaCon'2021) and about a new library for range enclosures (JuliaCon'2024), which we developed together with a Google Summer of Code student. Over the years, we regularly participated in the annual ARCH-COMP competition in the categories on linear dynamics (Int. Workshop on Appl. Veri. Contin. Hybr. Syst.'2024), nonlinear dynamics (Int. Workshop on Appl. Veri. Contin. Hybr. Syst.'2024) and neural-network control systems (Int. Workshop on Appl. Veri. Contin. Hybr. Syst.'2024).

5.5.9 Applications and Impact

Energy The research on using STRATEGO for an efficient synthesis of optimal and safe controllers in energy-demanding applications, with a strong emphasis on heat pump-based domestic heating, contains the following key contributions. End-to-end control frameworks that integrate continuous-time stochastic modeling via CTSM-R with STRATEGO for Q-learning-based synthesis on domestic heating models, achieving up to 30% cost savings over traditional bang-bang controllers while preserving the thermal comfort (TASE'2022, Journ. Building Engineering'2021). Extensions of the approach model hot water buffer tanks and allows us to exploit also mixing loops (FMICS'2023) for scalability in domestic-heating systems. The techniques are evaluated via simulations on an experimental house, revealing trade-offs in cost versus comfort based on tank size. A dedicated toolchain (SCP'2023) automates this process for a refined control of heat pumps, outperforming industry-

standard strategies, while model-driven approaches adapt to multi-story buildings for enhanced flexibility amid fluctuating electricity prices (Journ. Building Perform. Simulation.'2025). The success of this approach is documented by the spin-off company CEDAR established by Peter G. Jensen (still employed as a part-time associate professor at DEIS) that commercializes our academic research achieved on control of heat-pumps and demonstrates between 20-50% energy savings on real family houses across Denmark.

Water Within the Water domain, DEIS has participated in several funded project and worked on safe and optimal control using STRATEGO for a a variety of systems, including storm-water detention ponds, wastewater systems and coastal protection. (CCTA'2023, IFAC'2021, Journ. Hydroinformatics.'2023). The paper (FSEN'2024) received Best Paper award.

Complementary works broaden the scope to hybrid stochastic systems beyond heating by introducing the STOMPC framework (ATVA'2022) enabling stochastic model-predictive control by co-simulating with Uppaal Stratego and external tools, facilitating safe strategy synthesis across various different domains related to urban infrastructure. Underpinning these is a decidable synthesis method for robust energy-aware controllers via energy timed automata, accommodating timing constraints, variable rates, and uncertainty for infinite-run energy constraints (Formal Aspects of Computing'2021).

Covid During 2020-2022, several members of DEIS were very active in advising the Danish government on the spread of Covid-19, by weekly evaluation of suggested lock-down measure, opening scenarios, vaccination plans, etc. The basis for the advice was based on statistical model checking using UPPAAL SMC of an extremely large model (consisting of more than 1 million interacting stochastic timed automata, 2 citizen of Northern Jutland). During the $1\frac{1}{2}$ years the DEIS group became members of the Modeling Expert Group of The National Serum Institute.

5.5.10 Project and Funding

During the evaluation period DEIS has had a total of 38 new funded projects with a total amount of $79\,271\,581$ DKK. Table 5.1 lists the funded projects grouped by starting year, reporting for each group the count of projects as well as the total amount of funding. As can be seen, the number of projects and amount of funding vary considerable from year to year. In the previous period DEIS had 39 newly funded projects with a total amount of $72\,000\,000$ DKK.

Year	DKK	No.Projects
2021	33 472 162 DKK	10
2022	3 619 896 DKK	8
2023	4 425 445 DKK	6
2024	18 954 574 DKK	8
2025	18 799 504 DKK	6
Sum	79 271 581 DKK	38

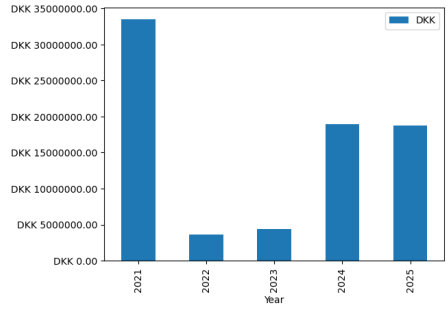


Table 5.1: Acquired funding in the evaluation period.

Below we briefly describe all the projects that have been active in the evaluation period.

Compositional Verification of Real-time Independent Research Council, 1 890 704 DKK, 2017-2021
The objective of the research was to exploit compositional analysis techniques to analyse the safety of multicore-systems.

LASSO ERC Advanced Grant, 18 578 477 DKK, 2015-2022
The LASSO project (Learning, Analysis, SynthesiS and Optimization of Cyber-Physical Systems) aims at developing a new generation of scalable tools for cyber-physical systems through combining advanced model-checking techniques with machine learning.

S4OS Scalable analysis of Safe, Small and Secure Strategies for Cyber-Physical Systems Villum Investigator Grant, 30 000 000 DKK, 2021-2028
Cyber-Physical Systems (CPS) are rapidly emerging across society—from transport and energy to cities and healthcare. Machine-learning techniques improve their performance and usability, but many CPSs are safety-critical, making rigorous verification against accidents and security attacks essential.

S4OS aims to develop mathematically founded, scalable methods and tools that integrate machine learning with symbolic verification techniques in a unified framework, enabling the construction of optimal CPSs that provably meet key safety and security requirements

ConAn: Contrastive Analysis for State-Space Exploration, Sapere Aude Independent Research Council, 6 192 000 DKK, 2024-2028
This project focuses on sequential decision making within Artificial Intelligence, on situations where agents need to find a plan or a strategy in order to achieve their goal. The Conan project introduces a new concept to guide search in AI Planning: Contrastive Analysis. The key idea is to develop methods and algorithms that automatically analyze the advantages and disadvantages of each alternative during search, and explores how they can be used to make better decisions and do it faster. The central hypothesis that the project aims to test is that understanding advantages/disadvantages is a fundamental skill for decision making and could change the way current AI systems make decisions and plans.

Cosyne: Safe Control Systems with Neural Networks, Sapere Aude Independent Research Council, 6 192 000 DKK, 2024-2028
This project addresses the fundamental question of how to trust a neural network that controls a dynamical system. Since neural networks are large black boxes, the research focuses on automatic methods to analyze such systems and human-interpretable certificates of the analysis results.

CLASSIQUE: Center for Classical Communication in the Quantum Era Danish National Research Foundation, 10 622 785 DKK, 2025-2031

The overarching objective of this Basic Research Center is to make fundamental contributions to the new evolution branch within classical communications, defined by the intersection of applications constrained by digital timing and quantum resources constrained by quantum timing. The research hypothesis of the center is: "The classical communication networks and protocols need to evolve to enable reliable and timely operation in distributed systems that process both classical and quantum data." Member of DEIS are co-PI of the center and leads its activities on "Reliability and Trustworthiness". The total funding by DNRF is 60.000.000DKK.

DIREC: Learning Technology for Improving Teaching , 124 000 DKK, 2021-2023
This project explored how we could use digital tools to improve teaching large classes while teaching resources are diminishing at universities.

DIREC: Supporting Diversity via Inclusive Teaching , 145 000 DKK, 2021-2023
The goal of the project was to increase the diversity of students in the educational programmes by establishing learning and teaching activities that supported diversity.

SEDIH EU, Erhvervshus Syd, 1 226 031 DKK, 2023-2026
Co-founded by the EU and Erhvershus Syd. The SEDIH (The Smart Energy Digital Innovation Hub) is an European Digital Innovation Hub to increase the digital maturity of companies in the energy domain. It supports tiny to small train-the-trainer, knowledge-bridge, test-before-invest assessments for industry-requested collaboration activities.

Digital Energy Hub Industriens Fond, 1 347 710 DKK, 2022-2025

New requirements for energy optimization and CO2 footprint challenge Denmark's strengths in digitization and energy and environmental technology. The Digital Energy Hub will create an open data-driven innovation environment to promote the development of intelligent energy systems.

FED Flexible Energy Denmark Innovation Fund Denmark, 3 356 031 DKK, 2019-2023
By use of digitalization and flexibility, this project attempts to balance energy consumption with the production of sustainable green energy. The project brought together Denmark's foremost researchers, organizations, supply companies, software companies and a number of living labs.

RACE - Realtid AI Computing i Energisektoren Energistyrelsen, 1 989 360 DKK, 2023-2026
The goal of the RACE (Real-time AI Computing in the Energy-Sector) project is to reduce energy consumption in district heating networks through improved IoT instrumentation, data analysis/visualization, and optimising machine learning based control to reduce differential outlet pressure and temperature while satisfying service level agreements.

FEVER EU H2020, 1 652 000 DKK, 2020-2024

In FEVER (Flexible Energy Production, Demand and Storage-based Virtual Power Plants for Electricity Markets and Resilient DSO Operation) DEIS focused on building energy modelling and model-predictive control of flexible energy systems.

DOMOS EU H2020, 1 725 000 DKK, 2020-2024
DOMOS (domestic Operating System) is to improve the energy performance of domestic buildings through new smart energy services deployed on an open, secure, multi-service Internet of Things (IoT) ecosystem for smart buildings, that facilitate interoperability af data and services. DEIS developed and demonstrated the "domOS-Arrowhead" instance.

CEDAR Cost Efficient heat pumps using predictive DigitAI twins and Reinforcement learning Innovation Fond Denmark, 1 500 000 DKK, 2023-2023
CEDAR aims to significantly reduce the cost of domestic heating by improving the control of air-to-water and geothermal heat pumps with their innovative technology.

CLAIRE - ControLing wAter In an uRban Enviroment Villum Foundation Synergy Project, 1 583 911 DKK, 2020-2023
This project pursues a digital approach that enables to measure, control and regulate water intelligently using active strategies. In this way, water can be managed to cause much less flooding and instead be used for the benefit of nature and humans.

DONUT Grand Solution, Innovation Fond Denmark, 173 619 DKK, 2018-2021
The project take a novel approach, utilising a network of simple, low-cost and low-energy sensors, combined with software sensors and machine learning to obtain a holistic overview of the water cycle, which can then be used across administrative boundaries to ensure a consistent basis for decisions on e.g., future investment. Partners of the project included Department of Built Environment, AAU, Aarhus Municipality and Aarhus Vand. A partial result of the project was the spin-out

company DRYP[2].

STORM_SAFE: Software reliability for critical infrastructures Interreg North Sea Region, 1 582 380 DKK, 2024-2027
In this collaborative project, several universities advise organizations responsible for coastal infrastructure in the North Sea region, such as Kystdirektoratet in Denmark, about model-based engineering for the development of the next generation of operating control software.

MAST - Managing Sustainbability Tradeoffs ITEA, 2 227 500 DKK, 2025-2027
Funding (2,227,500 dkk) from InnovationFund Denmark (IFD) for ITEA project MAST: Managing Sustainability Tradeoffs. Software-intensive systems are required to be more and more sustainable, regarding both the ease of making changes to the code, as well as their power consumption and associated carbon emissions. Often these aspects conflict with each other. MAST will deal with the complex trade-offs between these two aspects of sustainability by developing tools and methods.

Greencode ITEA, 2 227 500 DKK, 2025-2027
Funding from InnovationFund Denmark (IFD) for ITEA project GreenCode: Generative Review and Efficiency Enhancement, Networking Code Optimisation, Decarbonisation and Economics

Data Science meets Microbial Dark Matter Villum Fonden, 2 999 714 DKK, 2021-2023

In the DarkMatter project the aim is to improve the rate of recovery of microbial genomes based on sequenced DNA fragments representing diverse microbial communities. This interdisciplinary project bridges DNA sequencing and probabilistic graph-based representation learning for downstream binning/clustering of DNA fragments.

DarkScience: Illuminating microbial dark matter through data science Villum Fonden, 7 487 808 DKK, 2022-2026

[2]https://www.drypdata.com/

The DarkScience project is a continuation of the DarkMatter project. The project aims to develop probabilistic machine leaning models and methods for DNA sequence representation learning as well as enable model-based integration of heterogeneous external data to enable (uncertainty-aware) reasoning about the hidden links between microbial genome diversity and environmental data.

BEO-Covid Poul Due Jensen Fond, 1 205 233 DKK, 2020-2021
This project was carried out during the COVID crisis. The purpose was to utilize the Statistical Model Checking Engine of UPPAAL to make agent-based models of the population of Northern-Jutland (and Denmark) in order to advice the National Serum Institute of Denmark with respect to opening and reoping part of the society. The effort was coordinated by SSI and carried out in collaboration with a sister-initiative funded by Novo Nordisk.

CS **Support and Control for Regional Busses** Collaboration with Several Companies, 229 000 DKK, 2020-2022

The project lets an AI-based optimization unit control the bus's movement so the driver mainly supervises. The aim is to deliver rail-like passenger comfort

Model-Based Software Development Huawei Technologies, 587 000 DKK, 2020-2023

Collaboration to explore the use of models and formal methods for design, development, and (co-)verification of low-level high-assurance industrial hardware and software.

Mathematical Modelling of COVID19 Statens Serum Institut, 288 000 DKK, 2021-2023
The agent-based model of Northern Jutland/Denmark developed in the BEO-Covid project lead to members of DEIS to become members of the modeling expert group of SSI.

BEHAPI EU, H2020, Marie Sklodowska-Curie, 167 000 DKK, 2018-2023

A project involving universities and companies across the European Union aimed at developing the theory and applications of behavioural types (such as binary and multiparty session types) for reasoning about APIs (Application Program Interfaces). The funds were used for secondments between partners.

WHATIF Fast and Quantitative What-if Analysis WWTF, 945 315 DKK, 2020-2024
The WHATIF project aimed to enhance the reliability and performance of communication networks by automating the verification and maintenance of critical properties. It developed fast, provably correct tools for "what-if" analysis that ensure qualitative policies (e.g., reachability, loop-freedom, waypoint enforcement) and quantitative aspects (e.g., latency, bandwidth) hold under multiple failures.

Forbedret kapacitetsudnyttelse i Region Nordjylland Region Nordjylland, 350 000 DKK, 2020-2024

The project investigates how existing hospital data can be used to predict future patient activity to improve capacity planning and reduce bottlenecks. A key component focuses on modeling event data from the Emergency Department to predict patient flow and admission duration.

Quantitative Analysis and Synthesis of Networks , 2 782 551 DKK, 2019-2024
This project advanced automated analysis and synthesis of communication networks, enabling highly dependable operations with minimal human intervention. By combining formal methods like model checking, partial order reduction and BDDs we constructed correct and optimal network configurations.

Grant from Poul Due Jensen Fond Poul Due Jensen Fond, 8 500 000 DKK, 2018-2025

The grant is to strengthen and consolidate the research group in DEIS. Specifically, the grant covers the Associate Professorship of Max Tschaikowski

during a five-year period.

Verifiable and Robust AI, DIREC Explore Project Innovation Fond Denmark, 73 440 DKK, 2021-2025
The success of AI is accompanied by an increasing need for methods that explain the decisions of machine learning models, make their performance more robust under changing conditions, and can provide firm guarantees for their behavior with regard to aspects like safety, privacy preservation, and non-discrimination. In a dedicated DIREC workshop this challenge has been addressed.

Verifiable and safe AI, DIREC Bridge Project Innovation Fond Denmark, 2 009 022 DKK, 2021-2025
Together with industrial partners, this project aims to develop methods and tools that will enable industry to automatically synthesize correct-by-construction and near-optimal controllers for safety critical systems within a variety of domains.

SIOT Secure Internet of Things, DIREC Bridge Project Innovation Fond Denmark, 1 569 600 DKK, 2022–2025
In collaboration with industrial partners, the project aims to develop a modeling method for systematically describing relevant aspects of IoT systems/services with a focus on security, interaction, performance, and cost.

Teaching AI Green Coding Villum Experiment, 2 400 000 DKK, 2024-2027
Green coding practices are not in widespread use since they are not well understood, and they are cumbersome and time consuming to apply. In recent years Generative AI has emerged as a powerful tool in code development. The key question in this project is: Can generative AI be taught to develop green code?

Forensic age assessment of porcine granulation tissue Independent Research Council, 176 000 DKK, 2023-2027
The overall goal of this project is to develop new and objective methods and models to obtain accurate forensic age assessment of porcine granulation tissues. The developed methods are based on probabilistic graphical models for also reliably quantifying the uncertainty associated with the assessments.

EQuaL: Equivalence Checking of Quantum Circuits via Tensor Decision Diagrams and Machine Learning Danish e-Infrastructure Consortium, 2 381 587 DKK, 2024-2027
Equivalence of quantum circuits is a fundamental challenge that arises as part of compiling a quantum algorithm onto a physical quantum computer. We develop algorithms for equivalence checking based on tensor networks, decision diagrams, and reinforcement learning.

PROACTIVE: Flexible AI Planning for Proactive Agents in Scenarios with Multiple Possible Goals JPMorgan Faculty Awards, 322 000 DKK, 2025-2026

This project introduces a new class of multi-goal planning problems that generalizes existing formulations and provides the flexibility to reason over multiple possible goals. We will also develop an open-source tool to solve such problems efficiently, bridging theory and practice and enabling impact across both research and industry applications.

Foundations of secure resource sharing Independent Research Council, 57 600 DKK, 2025–2028
One of the long standing principles and best practices of building secure systems is to avoid resource sharing, which is in stark contrast to the fundamental tenets of the green transition to increase sharing of resources. This project will bridge that gap between security and increased resource sharing. To tackle the challenge of ensuring that the shared mechanisms are indeed secure, we will use a principled approach where we will prove that our mechanism are secure by design.

Full-Stack Cybersecurity for Danish Defense NFC, 83 760 DKK, 2025–2027
The goal of this project is to raise the level of cybersecurity in the Danish Defense through a pilot study into the use of formal methods in the full technology stack. The project will develop a prototype, e.g., at the OS or hypervisor level, exploring the current state of the art and advancing it.

EMBARQ Novo Nordisk Foundation, 3 476 909 DKK,

The EMBARQ project aims to address the need for improved risk assessment of

novel biological agents in agriculture and environmental management. A key component is the development of probabilistic machine learning models that can combine accurate predictions with well-calibrated uncertainty estimates for the assessments.

Future Projects

SWIM Grundfos, $4\,520\,000$ DKK, 2026-2031

Backed by a record-breaking grant from the Grundfos Foundation – a total of 60.000.000DKK – SWiM aims to tackle a pressing climate challenge: the energy-intensive cooling of buildings in megacities in Asia and Africa. The project has 10 partners from AAU, AU and Singapore. DEIS will lead work on Operation: Control, Optimization and Interoperability with focus on Multi-Agent Reinforcement Learning.

RACE2 Energystyrelsen, $1\,446\,000$ DKK, 2026-2030
The project significantly expands the AI component introduced in RACE. The AI model will integrate real-time building energy consumption data alongside production and distribution data. For demonstration we introduce two new application areas 1) building-level heat load management and 2) grid-sector flow control

ODAQC Innovation Fund Denmark, $5\,065\,834$ DKK, 2026-2030
. ODAQS will bridge the gap between high-level quantum algorithms and physical quantum platforms by design-automation technology, supporting optimal quantum software synthesis, compilation, simulation and verification. Collaborative project with Aarhus University. Total budget 17.500.000DKK.

5.6 Own Evaluation

5.6.1 Research Goals

We first evaluate with respect to the Research Goals set by the previous Research Evaluation:

Foundational Theories As promised in the last research evaluation, we introduced on-the-fly (LICS'2021) and optimality-preserving behavioral equivalences (IEEE Trans. Automatic Control'2025, IEEE Trans. Automatic Control'2024), with applications in computational biology and network theory. Likewise, as promised, we have studied approximate notions of behavioural equivalences which led to publications in computational biology and data mining (IEEE Trans. Automatic Control'2023, ICDM'2024, CMSB'2024). On algebraic and logical foundations of behavioral distances, we published (CALCO'2021, LMCS'2024, MFPS'2023), where (CALCO'2021) was awarded the Best Paper at CALCO 2021. Last but not least, we have introduced behavioral notions for quantum algorithms (TACAS'2024) which complement behavioral notions for quantum process algebra.

Programming Technology In the previous research evaluation we expected to pursue research in energy aware software development and ICT Infrastructure. This line of research was mainly followed by researchers from the programming technology subgroup. A number of external projects were established with some impact on Danish software practices and some papers were published in the area. However, during the reporting period one core member retired, one left for a position in industry and the remaining two had high teaching and administration loads. During the latter part of the reporting period a fruitful collaboration with researchers focused on distributed systems was established, and a number of externally funded projects made it possible to hire three Postdocs and a research assistant. With the newly established research group on Distributed Sustainable Software and Systems we expect to increase the research outcome of this area.

Security The stated goals for this evaluation period was twofold: to expand substantially (both staff and research output) and to involve and engage new staff members to expand the (formal methods) competencies in the security area, most notably in interactive and automated theorem proving. The latter goal has been reached which is especially noticeable with the recent formation of the Formal Methods for Security and Privacy research group, which has been joined by several new staff members with formal methods expertise. The goal of expanding staff and

research output has not been met: there have been no security-specific staff hires and core members still provide a significant amount of teaching on security related educations. However, we will seek to leverage the new research group structure to improve the balance and collaboration in a wider forum.

Artificial Intelligence and Machine Learning The group has maintained its strong research profile in Artificial intelligence and machine learning, where the additions of Álvaro Torralba, Andres Masegosa and Daniel Fišer have contributed with competences within planning and foundational theories and methods for probabilistic models. Attempts to attract further highly qualified researchers in AI/ML have been hindered by the very competitive job market in this field.

As envisioned in the report for the 2016–2020 evaluation period, the group has broadened its research activities with additional focus on verifiable and explainable AI, planning, and reinforcement learning. Furthermore, the group has engaged with and increased its collaborations with the other research groups at the department as well as other departments at AAU in interdisciplinary research projects. This has enabled the application and demonstration of the group's research activities across a broad range of domains.

Network Modelling and Verification The group maintained a strong research profile in verification and modelling of network protocols even after Stefan Schmid moved to Vienna and later on to Berlin. This was achieved by a continued joint collaboration on WHATIF project, mutual co-supervision of PhD students as well as local funding for these activities (QASNET project funded by DFF). The collaboration was strengthened by mutual visits and organized workshops, e.g. NetVAS meeting at Bertinoro in 2022. Such meetings created new collaborations with Remi Badonnel (CNRS, Inria Loria, FR), Damien Saucez (Université Cote d'Azur, Sophia Antipolis, FR), Ingmar Poese (BENOCS GmbH, GE) and Hideki Tode (Osaka University, JP).

Tools and Model Checking In the evaluation period DEIS have substantially improved the usability of the award-winning tool UPPAAL marked by the launch of UPPAAL 5.0. During the period, the combination of symbolic model checking and machine learning been used in several new domains, and by domain experts. This includes Water management, Smart Batteries, Autonomous Vechiles, as well as energy-Aware buildings. In the latter case, resulting in the spin-out company CEDAR. Also the TAPAAL tool has enhanced its core verification engines substan-

tially in terms of efficiency and scalability. In particular TAPAAL has successfully defended it standing in the Model Checking Contest, e.g. winning three gold medals in 2025. Most recently, TAPAAL has been extended with a statical model checking engine, work that was awarded with best paper award at PETRINET 2025.

The work on UPPAAL and TAPAAL as well as other tools developed in DEiS is highly relying on the availability of computing facilities. The DEIS Model Checking Cluster has been upgraded and extended during the period. In the next period, DEIS will benefit from the sizeable Villum Infrastructure grant of 15MDKK to establish a state-of-the-art AI cluster featuring the newest generation Nvidia GPU Blackwell DGX B200. The grant was given to Remus Teodorescu (AAU, Energy Technology), Petar Popovski and Zheng Hua Tan (AAU, Electronic Systems) and Kim Guldstrand Larsen (AAU, Computer Science).

Research Management and Staff During the period, we were fortunate to recruit five new associate professors, significantly strengthening our research profile in the areas of Validation and Verification, Planning, Machine Learning, and Quantum Systems. At the same time, we lost five associate professors, two of whom were key contributors to Programming Technology. We observe that the systematic use of search committees has increased both the number and quality of applicants, while also improving the diversity of candidates aligned with the DEIS profile.

The ambition to expand the staff of the DEIS Tool Laboratory was not realized; on the contrary, four members left during the period. This development is partly explained by the successful pursuit of business opportunities in the energy sector based on Reinforcement Learning, as two former laboratory members are now employed by the start-up company CEDAR. At the same time, this highlights the importance of establishing permanent laboratory positions—an objective that was not achieved during the period.

5.6.2 Scientific Output and Impact

The DEIS group has in the evaluation period published a total of 466 papers split into: 135 journal papers and 331 conference/workshop papers. In Table 5.2 we report the number of publications ranked according to a system consistent with the evaluation system used in previous evaluations. The ranking system is consistent with the International CORE ranking system[3] and can be found at the link[4]

[3] https://www.core.edu.au/icore-portal
[4] https://homes.cs.aau.dk/ bc37lv/researcheval/

Type	A	B	C	Total
Journals	58	52	25	135
	38	33	10	81
Conferences	106	133	92	331
	72	63	34	169

Table 5.2: Ranked papers published in the previous (gray numbers) and current evaluation period

We observe that the group, consistent with general trends in computer science, favours publishing at conferences rather than in journals. For both journal publications and conference publications we note that the group publishes at high-ranking outlets: 43% of journal papers were published at A-ranked journal, while 32% of conference papers were published at A-ranked conferences.

Comparison with previous evaluation period In Table 5.2 we observe that the group has significantly increased its general paper production, in fact by 86%. The group has increased its number of publications at both A-, B- and C-ranked conferences and journals. It is noteworthy that the size of the group has remained stable throughout the evaluation period while the group has increased its paper production, especially because the increase occurs across all ranks (A,B and C) and for both conference and journals.

5.6.3 Scientific Services and Recognition

Members of the DEIS group have provided substantial services (see Table 5.3 Table 5.4) to the scientific community by serving on several steering committees served as steering committee members of leading conferences (e.g. CONCUR and TACAS,), chairing conferences and workshops (e.g. TACAS – twice – SPIN), and serving on the editorial boards of journals. Furthermore, the group has served on many program committees (numerous times at TACAS, CAV, CONCUR), organized summer schools, and (co-)organised workshops (e.g. MOVEP 2022. We note that DEIS will be organizer of ETAPS (International Joint Conference On Theory and Practice of Software) 2027.

In terms of recognition, Kim Guldstrand Larsen and Jiří Srba are included on Stan-

Conference	Workshops	School Organisation
ETAPS 2027	NetVas Workshop on Verifiable and Robust AI Workshop on Verified Systems FMQC: Formal Methods in quantum computing ISola:Formal Methods Meet Machine Learning AISOLA: Verification Meets Learning and Statistics EXPRESS/SOS CoPLaWS	ProbAI MOVEP

Table 5.3: Events organised by DEIS

PC chair	Sterring Commitee	Misc. Boards	Editor
EXPRESS/SOS GandALF Logic Mentoring Workshop TACAS SPIN	CONCUR NordSec Panhellenic Logic Symposium TACAS MOVEP AAU Quantum Hub	ERC Panel Member (consolidator grant) Digital Wiseman of Academy of Technical Sciences Member of The Royal Danish Academy of Sciences and Letters Chair of the Computer and Information Sciences and Informatics Evaluation Panel for FCT Silicon Austrial Laboratory (SAL) member of Scientific Advisory Board-	COPLAS JAIR

Table 5.4: Scientific Services by DEIS

ford University's list[5]of the world's most highly cited researchers. Jiří Srba is recognized in the 2024 edition, while Kim Guldstrand Larsen is recognized both in the 2024 list and in the career-long impact category, placing them among the top 2% of scientists worldwide. Moreover Kim Guldstrand Larsen has been awarded the "Concur Test of Time" and been named the "Most Central Concurrency Researcher"[6] showing widespread recognition of the DEIS-leadership.

Also, members of the group have received several Best Paper Awards, received Outstanding PC Member awards , and won first prizes at competitions (see Table 5.5).

[5]https://elsevier.digitalcommonsdata.com/datasets/btchxktzyw/7

[6]Luca Aceto: CONCUR through time. EATCS Bulletin, number 138, October 2022.

Best Paper	Special Awards	Competition Place
FSEN'2024 ECAI'2025 SoCS'2022 CALCO'2021 PETRI NETS'2025 NeurIPS'2023 Formal Aspects of Computing'2021 EI2'2024	Concur Test of Time Most Central Concurrency Theory Researcher	1st Place Learning Track IPC 1st Place Agile Track IPC

Table 5.5: Awards Received by DEIS

5.6.4 Projects and Funding

During the evaluation period, DEIS has secured a broad portfolio of externally funded projects spanning multiple categories, ranging from industrial dissemination projects and strategic, application- and mission-driven initiatives to basic research and excellence-oriented grants. As can be seen from Table 5.1 DEIS has had a total of 38 newly funded projects for total amount of $79\,271\,581$ DKK. While this is a modest increase compared to the previous period, the number of staff that has successfully taken home funding – including several excellence grants – has spread to more people. On top of the 38 projects, three additional projects with a total funding of 10.000.000DKK has been granted at the very end of 2025 .

A particularly strong outcome of the period is the acquisition of several highly prestigious excellence grants, including an ERC Advanced Grant (LASSO; Kim G Larsen), a Villum Investigator Grant (S4OS; Kim G Larsen), and two Sapere Aude grants (ConAN; Alvaro Torralba. Cosyne; Christian Schilling). In addition, two research projects—MULTI-CORE Safety (Ulrik Nyman) and QASNET (Jiri Srba)—were funded by the Independent Research Fund Denmark. Taken together, these achievements clearly demonstrate the high scientific quality and international competitiveness of research conducted within DEIS.

Beyond the Villum Investigator Grant S4OS, DEIS has been highly successful in attracting funding from the Villum Foundation, including Villum Synergy Grants (CLAIRE, Data Science Meets Microbial Dark Matter) as well as Villum Experiment Grant (Teaching AI Green Coding).

Substantial funding has also been obtained within the area of quantum systems. Most notably, the Basic Research Center CLASSIQUE (Communication in the Quantum Era), funded by the Danish National Research Foundation, was established in collaboration with colleagues from Aalborg University's Departments of Electronic Systems, Mathematics, and Physics. More recently, starting in 2026, the ODAQS project—focusing on design automation for quantum computing—has been funded by Innovation Fund Denmark in collaboration with Aarhus University.

At the national level, DEIS plays a central role in the Digital Research Centre Denmark (DIREC), a partnership involving all Danish universities and the Alexandra Institute. DEIS members were among the founders of DIREC and currently serve as Workshop Stream Leaders. In addition, DEIS has been a key contributor to several DIREC bridge and explore projects (SIOT, Verifiable and Safe AI, VRAI), as well as to associated teaching and innovation activities.

Across several strategic application domains, DEIS has both acquired and actively contributed to a wide range of projects. Within the Energy-Aware Society domain,

funded activities span regional (SEDIH), national (Digital Energy Hub, FED), and European projects (FEVER, DOMOS), alongside direct industrial collaborations (RACE, RACE2) and spin-out companies (CEDAR). Most recently, the SWIM project—funded by the Grundfos Foundation—addresses energy-intensive cooling challenges in megacities in Asia and Africa. Many of these projects involve close collaboration with colleagues from the Database research group, and DEIS is also actively engaged in the AAU Energy Mission.

In the Water domain, DEIS has participated in several funded projects covering monitoring (DONUT), control of storm-water detention ponds (CLAIRE, DIREC), wastewater systems (DIREC), and coastal protection (STORM_SAFE). These efforts are characterized by strong collaboration with colleagues from Civil Engineering. DEIS is also represented on the steering group of the AAU Water Mission Platform.

Finally, DEIS addresses the growing energy consumption and carbon footprint associated with ICT, particularly in light of the rapid adoption of generative AI. In several recently awarded projects (MAST, GreenCode), sustainable and energy-efficient ICT is a central research focus.

5.7 Committee Evaluation

DEIS is the largest research group within the department and comprises a well established group of researchers and a portfolio covering a broad range of topics spanning foundational theory, verification and validation tools, security, AI and machine learning, distributed systems, programming language technology and quantum systems.

Commended

The DEIS group performed very strongly over the review period. Output in terms of publications was impressive: the total volume almost doubled compared to the previous period and, more importantly, the group achieved substantial representation at top tier publications venues for this area.

Similarly, with respect to research funding, the group performed very well, with close to 40 new funded projects over the period totalling almost DKK 80M, comparable to the previous review period. Included within this were several prestigious individual awards (ERC Advanced Grant, Villum Investigator Grant, two Sapere Aude grants). It was noted that, generally, research income has started to be spread more widely

across the members of the group.

Group members are leading and well represented in their research communities, e.g. witnessed by the research leader being identified as the "Most Central Concurrency Research" in the EATCS Bulletin and with multiple people engaging in leadership/organisational roles such as steering committees and organisation committees for major events. High research impact is furthermore witnessed by two professors being included in Stanford University list of 2% most highly cited researchers.

As observed at the departmental level, the group successfully balances research interests across the theory-to-practice spectrum. On the practical side, an important area of contribution continues to be the development and provision of research software tools, notably UPPAAL and TAPAAL, which yielded both academic impact and industrial uptake.

The group is large and covers a broad range of research areas. The successful development of a quantum computing strand, linked to the formal methods expertise of the group and backed by several new funded projects – including a prestigious new DNRF center CLASSIQUE – is a promising direction of evolution for the group. It was also noted that DEIS has maintained a strong, cohesive group identity despite its size and diversity.

Challenges noted

As raised by members during discussions, sustainability of tool development, which is an important part of the group's profile, is a potential area of concern. This follows the loss of dedicated developers, contributing strongly to UPPAAL, TAPAAL, and other tools. Possible mitigation strategies are discussed in the department-level analysis.

During discussion, the panel queried the staff profile of the group, notably the large number of Associate Professors, and whether this would potentially lead to issues distributing resources or opportunities to supervise PhD students. Largely this appeared to be an artifact of the typical Danish university career-structure context and was not a major cause for concern. Related to this, the group are keen to further develop research income for the group, particularly as some of the large personal grants currently held come to an end.

6 Human-Centered Computing

6.1 Executive Summary

The Human-Centered Computing (HCC) group researches the design, development, and evaluation of interactive computing technologies. The research is empirical and solution-oriented, and relates to the research communities of Human-Computer Interaction, Systems Development, and Software Engineering.

Research output from the HCC group has increased over prior periods, with 106 journal and 122 conference papers published. A total of 116 articles were published among the top venues in our respective fields. A total of twelve Ph.D. degrees have been awarded, three Ph.D. theses are currently under review, and another seven Ph.D. studies are in progress. HCC researchers are actively involved in service roles in their scientific community.

Over the past period, the group has placed greater emphasis on securing external funding. This has resulted in DKK 40 million in funding secured across 20 projects, 15 of which involve industry collaborations. Funding was obtained from a variety of sources, but primarily involved Danish foundations, the Digital Research Centre Denmark (DIREC), and the Independent Research Fund Denmark (DFF).

HCC has delivered teaching and provided supervision to students at the Department across the following areas of study: Bachelor of IT, Computer Science, Digitalisation and Application Development, Interaction Design, and Software.

The group has continued its expansion of staff across all levels, including both in Aalborg and in contributing to the Department's expansion into Copenhagen. The group attracted new colleagues primarily at the Assistant Professor level.

6.2 Profile

The HCC research group has a strong tradition of empirical, solution-oriented research on digital technology as used by both individuals and in organizational settings. The focus on individuals who create or interact with digital systems is reflected in the research themes cognitive support, emotion and well-being, and multimodal interaction. The research on organizations concerns the creation and use of digital systems, explored through the themes design and development processes, social computing, and digital transformation.

6.2.1 Cognitive support

This research theme investigates how digital technology shapes human cognitive capabilities and how systems can be designed to support them. We study various dimensions of cognitive processes, such as perception, attention, and decision-making, examining both how technology affects these processes and how it can augment them. Intelligent systems can help reduce cognitive load to minimize the risk of errors or, conversely, introduce cognitive friction to preserve users' cognitive autonomy. We also explore adaptive interfaces that tailor content to individual needs, whether in learning contexts or to promote self-reflection and metacognition. By understanding and augmenting cognitive processes, this research aims to empower users to make better and more thoughtful decisions in both professional and personal contexts.

6.2.2 Emotion and well-being

Digital technologies are an integral part of everyday life, allowing us to connect with other people while simultaneously acting as a major source of stress and anxiety. Work in this theme seeks to understand how technology affects emotional experience and well-being, and to design systems that promote healthier outcomes. This includes studying the emotional impact of digital environments as well as developing tools for tracking emotions, enabling users to gain insights into their emotional patterns and triggers through reflective practices. We also explore how technology can actively support emotion regulation, and how design choices shape users' emotional responses and habits. Ultimately, this research theme aims to create technology that not only addresses the challenges of digital life but also enhances well-being, empowering individuals to thrive.

6.2.3 Multimodal interaction

Our multimodal interaction research explores the design of prototypes and products, both digital and physical, that support how humans communicate and carry out activities in everyday and working lives. This research theme integrates emerging interactive technologies, often relying on more than one modality for human experience. We design and implement functional prototypes of interactive systems for specific use contexts, driven by advancements in input and output technologies for human-computer interaction. This theme also addresses interactions between people and physical systems, focusing on prototyping techniques for physical interactions, interactions through movement, and methods that engage domain stakeholders in the design of interactive systems in non-standard shapes and forms.

6.2.4 Design and development processes

This research theme investigates how organizations design, develop, and adopt software-based systems, and how these processes can be improved. The research involves empirical investigations of organizational processes for agility, user experience, security, software engineering, and user participation. Our research efforts are engaged in processes within teams, communities, projects, and companies, utilizing proactive research methods such as case studies, design research, and action research. Closely related to the empirical work, the research also studies the creation of new methods and techniques for supporting design and development processes.

6.2.5 Social computing

This research theme approaches the term 'social' from two perspectives. First, we understand it as the exploration of how technology impacts social interactions, and we evaluate how to design systems that better support collaboration and connection among users. In this context, we investigate collaborative practices not only among humans but also in interactions with digital agents and within mixed human-agent group constellations in relation to social issues. In this context, we investigate how technology can contribute tackling societal challenges such as sustainability, privacy and resilience. By exploring the complexities of social and collaborative computing, our goal is to create technology that enhances human relationships while supporting broader societal goals.

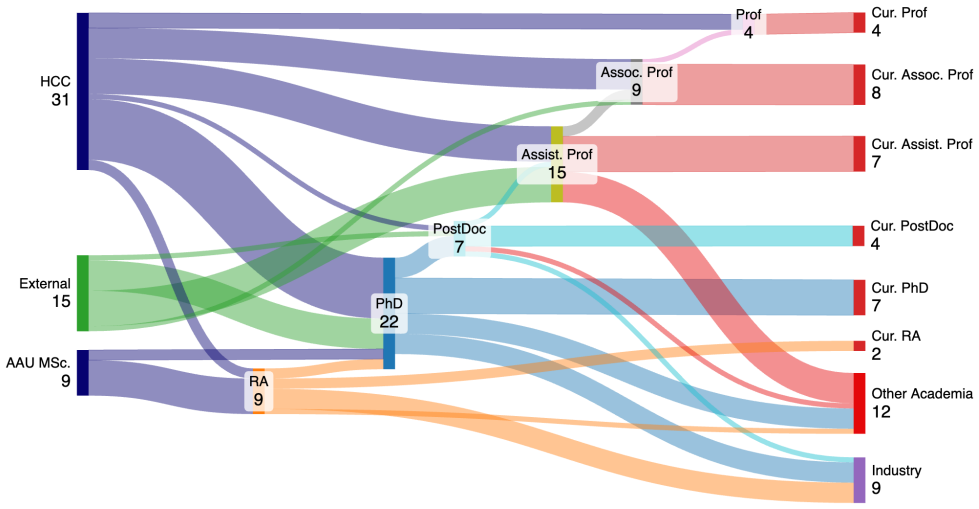


Figure 6.1: Staff sources and career development paths

6.2.6 Digital transformation

Many organizations are digitally transforming their products, services, and internal processes to meet the expectations of society in the digital era. These digital transformations often need to span the cultural and structural boundaries within and across organizations. Under this research theme, we study the boundary-spanning information systems and processes that help organizations create value from their digitalisation efforts. We conduct engaged research with private and/or public organizations to make combined contributions to research and practice. In doing so, we theorize and develop methodological support for key challenges in realizing value from data analytics, roadmapping interorganizational digitalization, digital infrastructuring of energy consumption, and reconciling divergent processes in sustainability initiatives.

6.3 Staff

This section provides an overview of the staff by the end of 2025.

6.3.1 Current staff

Professors (4): Niels van Berkel, Mikael B. Skov (20%), Peter Axel Nielsen (10%), Jesper Kjeldskov (10%)

Associate Professors (8): Anders Rysholt Bruun, Daniel Russo, Dimitrios Raptis, Florian Echtler, Ilhan Aslan, Ivan Aaen, John Stouby Persson, Timothy Robert Merritt

Assistant Professors (6): Alisa Ananjeva, Carla Florencia Griggio, Henning Pohl, Jeanette Falk, Nicolai Brodersen Hansen, Stine Schmieg Johansen

Post-doctoral researcher (4): Ashna Mahmood Zada, Maria-Theresa Bahodi, Rune Møberg Jacobsen, Samuel Rhys Cox

Ph.D. fellow (7): David Kinnberg Hein, Helena Bøjer Djernæs, Jade Martin-Lise, Shagen Djanian, Stina Olsson, Theocharis Tavantzis, Xinyuan Liu

Research Assistants (2): Phuong Thao Nguyen, Samir Memic

6.3.2 Staff development

Throughout the period we saw extensive development in HCC staff, covering external hires, internal promotions, and departures. At the Professor level, several senior HCC members took on administrative leadership positions at AAU (Head of Department, Vice Dean for Research) or abroad (Monash University), consequently reducing their commitment to HCC to part-time positions. We hired one new Professor through internal promotion.

During the evaluation period, we hired seven Assistant Professors and one Associate Professor. Five had no prior employment at AAU, indicating our ability to attract new talent. New academic staff span the whole range of topics covered by HCC. We hired three colleagues to AAU Copenhagen, aligning with our departmental strategy in Copenhagen and representing HCC expertise at AAU CPH.

Six Assistant Professors left during the evaluation period, primarily for academic positions elsewhere (Denmark, Norway, USA) or industry. Reasons for departure varied between individuals.

We employed six postdoctoral researchers during this period, one of whom transitioned into an Assistant Professor role early in the evaluation period. All but one of the six postdoctoral researchers are our own recent Ph.D. graduates. This number is partially distorted because roughly half of the postdoctoral researchers held short-term positions (under one year) that served as transition periods. Beyond the transition into an internal Assistant Professor role, two postdoctoral researchers

left HCC: one moved to industry and another secured a postdoctoral position in Norway.

HCC was home to 22 Ph.D. fellows throughout the evaluation period. We graduated a record number of ten candidates during this period. Several additional Ph.D. fellows will submit and defend their theses in the near future. Graduated Ph.D. fellows secured postdoctoral positions at HCC (currently two), at other universities (Copenhagen University, University of Nottingham, Norwegian University of Science and Technology, and Queensland University of Technology), or in industry. Among the 22 Ph.D. fellows, twelve have an educational background from AAU, and seven were hired internationally.

We employed nine Research Assistants throughout the period. Three of our Ph.D. candidates held prior Research Assistant positions in HCC, underscoring the importance of growing research capacity within the group. Of the five Research Assistants who did not continue with HCC, one currently holds a Ph.D. position at Aarhus University and one remains connected to HCC as a guest lecturer.

Regarding gender diversity, HCC lacks female senior staff. All Professors and Associate Professors are male. During the 2021-2025 period, however, gender representation has become more balanced at the Assistant Professor (four of seven are women), Postdoctoral researcher (1/3), and Ph.D. graduate (5/10) levels.

Reflecting the group's international orientation, 13 of 19 full-time research staff at postdoctoral level or above have prior academic employment at institutions outside Denmark.

6.4 Goals for 2021–2025

The detailed plan for the evaluation period 2021–2025 is described in the report from the previous research evaluation. In brief, for 2021–2025 HCC set out to strengthen its internal organization, increase research activity, professionalize the funding application process, and develop recruitment and staffing to support the group's long-term ambitions. These goals were to be pursued while advancing a set of strategic research themes across the department.

Increased research activity. The group sought to increase its overall research activity, measured in terms of the quality and breadth of publications, the number of submitted funding applications, and the volume and diversity of funded projects. An explicit ambition was to ensure that HCC contributed strongly to the department's research profile through visible, high-impact outputs in key venues and strategic collaborations.

In terms of research content, HCC planned to pursue and strengthen work across a set of strategic themes: Sustainability and the UN Sustainable Development Goals (SDGs), Human–AI Interaction, Digitalization, Empirical Software Engineering, Smart Homes, Mobility, Tangible Interfaces, and Critical Computing. These themes were chosen to align the group's research with departmental priorities and broader societal challenges, while providing a coherent framework for collaboration and project development in the 2021–2025 period.

Funding application process. HCC planned to make the funding application process more systematic and structured. This included improving how research problems were formulated, how relevant funding schemes were identified and matched to ideas, and how internal feedback on application drafts was organized. The intention was to raise both the quality and the success rate of applications, and to reduce dependence on ad hoc or individualized approaches.

Recruitment and staffing. The group's staffing goals focused on maintaining a healthy ratio of Ph.D. fellows to permanent staff and increasing the number of postdoctoral researchers, which was previously low compared to other staff categories. The aim was to ensure a sustainable pipeline of early-career researchers, support a vibrant research environment, and build capacity for both ongoing and emerging research themes.

Group organization and strategy. HCC aimed to develop a clearer and more robust group organization and strategy, covering both first-order research activities (such as paper writing and funding application writing) and second-order research activities (such as onboarding, internal communication, and research culture). The goal was to establish shared structures and practices that would support collaboration, mentoring, and long-term strategic planning.

6.5 Activities and Results

In this Section, we provide an overview of our activities by research topic, followed by a review of research performed in specific application domains.

6.5.1 Cognitive support

The research group has significantly contributed to understanding and enhancing cognitive processes through digital augmentations. This research seeks to empower users' mental abilities, whether for personal reflection or professional activities, and spans a variety of use contexts. Here, a central focus has been on modulating cog-

nitive attention in decision-making scenarios. For example, we have investigated how AI-generated suggestions, explanations, or visual augmentations (CHI'2025) can reduce cognitive load or introduce productive friction to support users' cognitive autonomy. Several studies have explored how interventions can enhance human-AI interactions and mitigate common challenges in contemporary AI systems (CSCW'2025). In parallel, we have explored how digital tools can support creative processes. Across this body of work, a shared emphasis lies in developing intelligent interfaces that balance user support and control to empower human cognition.

A second stream of work focused on technology for learning, particularly in complex domains such as healthcare or education (DIS'2025). Here, various studies sought to address the limitations of contemporary learning approaches or better understand the needs of diverse users (CHI'2025). These efforts aimed to address the limitations of conventional training approaches by introducing systems that adapt to users' needs. We have designed and evaluated interactive learning technologies in collaboration with domain experts and stakeholders. Examples include interactive systems that assist medical trainees in acquiring complex skills, conversational agents that prompt reflective thinking, and analyses of how researchers engage with neurodivergent users (CHI'2025).

Two Ph.D. dissertations were produced.

6.5.2 Emotion and well-being

Over the past five years, the research group has deepened our understanding of how digital technologies influence, support, and challenge emotional well-being. A central focus has been on emotional self-tracking and the design of tools that foster reflection on users' emotional states. This includes studies that leverage passive sensing (e.g., smartphone or wearable data), self-report methods, and hybrid approaches to help users recognize emotional patterns, gain insight into their triggers, and better regulate their emotions (TOCHI'2021).

Building on this, and following the rising availability of large language models, we have increasingly studied how conversational agents may support emotional reflection. These studies include interventions aimed at stress reduction, fostering emotional self-disclosure (CUI'2025), promoting healthier digital habits, and facilitating moments of pause or recovery during emotionally demanding situations. Other technologies investigated in this theme include smartphones, robots, custom physical artefacts, and creativity support tools (C&C'2025).

Finally, we have examined how the design of everyday interactive systems can shape

emotional experience and improve sleep quality. This includes investigating how notifications, feedback mechanisms, and interface design influence users' sense of control, emotional resilience, and overall well-being. Studies have investigated productivity technologies' unintended consequences and potential benefits, and how the framing and timing of system responses can either alleviate or intensify emotional strain as well as intervene through sleep stage classification.

One Ph.D. dissertation was produced.

6.5.3 Multimodal interaction

The group's research advances multimodal interaction within human-centered computing, with a significant focus on modalities that extend beyond traditional screens. This work explores how to embed computation into the physical environment through tangible and embodied interaction. Projects include the development of personalized sound zones (CHI'2023), which allow multiple individuals in a shared space to experience distinct audio simultaneously—a technology with applications in socializing and healthcare to support patient recovery. This research contributed novel interaction techniques, including shape-changing (CHI'2022) and graphical (CHI'2022) visualizations. Other research investigates interactions with tabletops and large surfaces (PACM ISS'2023, TEI'2024), tools for designing novel tangible interfaces (TEI'2021, TEI'2022, TEI'2024), and shape-changing interfaces integrated into transportation and built environments, thereby further blending the digital and physical worlds.

There has been an increasing focus on human interaction with autonomous systems, such as drones and robotic swarms (Interact'2025). The research addresses the unique challenges of coordinating multiple agents in complex, dynamic environments across domains like search and rescue (TAS'2024), security, and precision agriculture (HERD'2021). To address the challenge of intuitive control in these scenarios, the group has secured funding from the Independent Research Fund Denmark to investigate the integration of natural language with robotic systems for search and rescue (NAMUR'2024). This approach combines the reasoning capabilities of large language models (LLMs) with traditional mission planning algorithms, enabling users to issue high-level commands. This effectively translates human intent into executable robotic plans, creating more adaptive and collaborative systems. Funding from DIREC enables the investigation of multi-drone systems for supporting critical infrastructure (PERSIST'2025). This human-centered project examines coordination, long-term planning, and human–drone interaction supported by large language model–assisted interfaces. Four Ph.D. dissertations were produced.

6.5.4 Design and development processes

The HCC group's research on design and development processes contributes empirical insights into software development practices. In particular, the adoption of generative AI in software engineering, design and user research methods has been a central focus (CHI'2025, e-Business Management'2024, CHI'2025). This research has been formative in setting the research agenda and articulating a manifesto, which states a set of values and principles designed to guide the ethical and human-centric use of generative AI in software engineering. The research group has led three research projects in collaboration with nine software development organizations to explore how they can select and use various AI tools (AI Tool Integration'2023, AI Tools'2024, SAIR'2025). These projects were funded by DigitalLead, which allowed us to hire three full-time research assistants.

Other research activities on design and development processes are a continuation of the group's longtime focus on agility (IST'2022, TSEM'2023). These activities address the overall concerns of scaling approaches, team effectiveness, promoting quality, technical debt, integrating user experience design, and psychological safety (TSE'2024). They employ qualitative, quantitative, and mixed-methods research approaches to enhance the validity, reliability, and relevance of theories on agile development processes.

The research group has also participated in a project on security in software development, funded by Industriens Fond, which has enabled us to hire a PhD student, who is expected to submit the thesis in 2026. This line of research builds on and extends the HCC group's research on risk management (SJIS'2025), focusing on socio-technical attention shaping and the causal mapping of security risks associated with the adoption of AI.

In relation to design processes, the research group has also focused on how to design with/for provocation (TEI'2022), an example is the design and development of a game which allow the player to experience "jailbreaking" of large language models, thereby experiencing first-hand how this technology has different vulnerabilities and limitations and with the goal of prompting reflection on the technology (DIS'2024). Another example on prompting reflection on the technology used in design and development processes, including for example *research*-through-design processes, are studies which explored the carbon footprint of generative AI in research activities (CHI'2025) as well developed a tool for helping researchers calculate this carbon footprint during research activities (AAR'2025).

Finally, a large collaboration with Latin American researchers looked at how local cultural values shape and often clash with research and design methods often

adopted from Global North academic traditions, calling for greater reflexivity in participatory design projects with communities from the Global South (CSCW'2024).

6.5.5 Social computing

Over the past five years, and in relation to social interactions, the group has investigated online communication platforms by studying social and cognitive awareness, trust and credibility, by identifying how platform siloing impacts everyday users, and by exploring the effect of various input mechanisms (e.g. keyboards and emojis) on communication (CSCW'2024). Finally, the effects of various attributes (e.g., physical space, pace) on collaboration quality were investigated in the context of hackathons. In relation to social issues, the group focused primarily on environmental sustainability and privacy. Sustainable interactions were studied and/or designed in relation to food, heating and electricity consumption, primarily in home settings. Furthermore, a PhD project focused on designing data interactions to support sustainable consumption (DIS'2021). In relation to privacy, the group mainly engaged with the research area through another PhD project that dealt with designing artifacts that shape positive privacy experiences for individuals and householders for a variety of smart devices (MobileHCI1'2021, MUM'2022, DIS'2024, NordiCHI4'2024).

Four Ph.D. dissertations were produced.

6.5.6 Digital transformation

The HCC group has been involved in researching the digital transformation of key infrastructures in our society, with a focus on contributing to the achievement of the Sustainable Development Goals. Between 2021 and 2025, we have been involved in the digital transformation of district heating consumption and environmental impact assessments. Our research on district heating was a collaborative project with researchers in energy planning and sustainable architecture, funded by the technical faculty of IT and Design. HCC employed a PhD student and a postdoc in this project. Key results include postphenomenological theorizing of the digitally mediated experiences of energy consumers and providers (NordiCHI'2022), as well as an examination of the infrastructuring work undertaken by various actors in large-scale digitalisation (ECIS'2021). The resulting PhD thesis provided insights into reconciling competing processes in a digital transformation towards sustainability.

Our research on digitally transforming environmental impact assessments was conducted as part of a project funded by the Danish Innovation Foundation, involving

researchers from computer science and planning. These assessments, which are mandatory in the EU, require balancing ecological, social, and economic concerns for large-scale infrastructure projects, such as a new highway. The resulting PhD thesis investigated roadmapping practices to support the multi-organizational venture in digitally transforming environmental assessments and proposes a practically useful roadmapping framework (IFIP'2022, ICSOB'2022).

We have also conducted research on boundary-spanning digitalization within organizations as part of an industrial PhD project on value creation from big data analytics. Through collaborative practice research at a large Wind turbine manufacturer, the thesis proposes and evaluates approaches to realizing benefits from big data analytics projects based on systems thinking, which pertains to dependencies, boundary judgments, and the measurement of benefits (IS&e-BM'2023, Computer'2023). Three PhD dissertations were produced.

6.5.7 Projects and Funding

Overview of significant externally funded projects during the evaluation period.

HCC Delprojekt Plustur og Hovednettet, 2018-2021, North Denmark Region (strategic funds), DKK 540.000, HCC Share: DKK 270.000. Qualitative and quantitative studies of mobility and flexible rides in Northern Jutland. One PhD candidate partially worked on this project.

Energy Synchronization (ENERGYSYNC'2019), 2019-2021, Technical Faculty of IT and Design (TECH) at Aalborg University, DKK 3,267,750, HCC Share: DKK 1,424,206. A strategic interdisciplinary project on the digitalization of district heating. One postdoctoral researcher and one PhD candidate worked on this project.

Bus Comfort Control, 2020-2022, private funding (companies), DKK 700.000, HCC Share: DKK 168.000. Pilot study on designing feedback systems for bus drivers for achieving better driving comfort. One PhD candidate and one research assistant partially worked on this project.

Interactive Sound Zones for Better Living (ISOBEL'2019), 2019-2022, Innovation Fund Denmark, DKK 28,100,000, HCC Share: DKK 4,000,000. The ISOBEL project aims to develop a dynamic and interactive sound zone system

that adapts to the surroundings. Two PhD candidates worked on this project.

DeUCoE (DFG'2018), 2018-2024, German Research Foundation, DKK 3,500,000, HCC Share: DKK 2,000,000. The project "Decentralized Ubiquitous Computing in Everyday Environments" analyzed how centralized cloud platforms as the foundation of our daily computing environments could be replaced by decentralized services, e.g. in the contexts of smart homes or instrumented environments. Two PhD candidates worked on this project.

FEVER HCI, 2020-2023, Horizon Europe, DKK 74,000,000, HCC Share: DKK 290,000. This project studied flexible energy consumption and production across Europe, HCC's role focused on eliciting user requirements for UI and subsequently design UIs for prototypes. One research assistant worked on this project.

Digitally supported Environmental Assessment for Sustainable Development Goals (DREAMS'2020), 2020-2023, Innovation Fund Denmark, DKK 27,500,000, HCC Share: DKK 648,000. Digitally transforming the way society accesses and communicates information about environmental impacts of projects and plans in order to enable the best decisions towards green transition in a transparent and inclusive democratic process. One PhD candidate worked on this project.

Security by Design (Sb3D'2020), 2020-2023, Danish Industry Foundation, DKK 10,500,000, HCC Share: DKK 2,032,750. This project integrates security and data protection considerations throughout all phases of software development, offering a organization-wide alternative to the common but costly practice of treating security as an afterthought. One PhD candidate worked on this project.

Improving Sleep Quality Using Sound Intervention (SLEEP'2021), 2021-2026, Innovation Fund Denmark and SoundFocus, DKK 2,200,000, HCC Share: DKK 360,000. This industrial PhD project studies the use of interactive AI based sound interventions to improve sleep quality in noisy home environment. One PhD candidate worked on this project.

EXPLAIN-ME: Learning to Collaborate via Explainable AI in Medical Education (EXPLAIN-ME'2021), 2021-2025, DIREC, DKK 29,193,570, HCC

Share: 3,455,069. This project investigates how AI systems can support clinical education for healthcare professionals and patients seeking health information. One PhD candidate and one research assistant worked on this project.

HERD: Human-AI Collaboration - Engaging and Controlling Swarms of Robots and Drones (HERD'2021), 2021-2025, DIREC, DKK 17,165,547, HCC Share: DKK 3,195,867. This project deals with interaction techniques and control algorithms that let end-users engage and direct coordinated swarms of agriculture robots as well as search and rescue drones, enabling faster, lower-cost execution of complex tasks through real-time collaboration and adaptation. One PhD candidate worked on this project.

Algorithmic Explainability for Everyday Citizens (F21-0159'2022), 2021-2026, Carlsberg Foundation, DKK 5,200,000. This project examines how to enable public participation in evaluating and designing AI systems that increasingly shape daily decision-making and interaction. Two PhD candidates and two postdoctoral researchers worked on this project.

AI-powered tools in software development and UX practices (AI Tool Integration'2023), 2023-2024, DigitalLead, DKK 596,000. This project investigates the usefulness of AI tools in software development organizations through action research. One research assistant worked on this project.

mAIa: A Framework for Selecting AI Tools to Address Software Development Challenges (AI Tools'2024), 2024, DigitalLead, DKK 594,000. This project creates and tests a framework for selecting appropriate AI tools according to organizational contexts. One research assistant worked on this project.

Strategic Artificial Intelligence in Logistics: Enhancing Human-Machine Interactions for Port Digitalization (SAIL'2025), 2024-2026, Villum Foundation, DKK 3,994,037, HCC Share: DKK 2,021,502. This project deals with theoretical and empirical questions about the integration of AI-based decision support systems in critical, real-time, physical contexts. One postdoctoral researcher worked on this project.

NAMUR: Natural-language Assisted Human-Multirobot Interaction and Planning (NAMUR'2024), 2024-2029, Independent Research Fund Den-

mark (DFF), DKK 6,744,699, HCC Share: DKK 3,372,350. This project develops LLM-enhanced planning algorithms and operator interfaces enabling natural-language and low-level control of multi-drone search and rescue missions with closed-loop reasoning, robust situational awareness, and adaptive error handling. One postdoctoral researcher worked on this project.

Support platform for AI Risk Management in Danish SMEs (SAIR'2025), 2025-2026, DigitalLead, DKK 600,000. This project designs a platform for assessing risks associated with AI integration in small and medium sized enterprises (SMEs) developing software. One research assistant worked on this project.

PERSIST: Persistent Drone Operations at Critical Infrastructure (PERSIST'2025), 2025-2027, DIREC, DKK 4,484,271, HCC Share: DKK 2,167,311. This project develops AI autonomy and operator interfaces to enable continuous, multi-drone operations (patrol, inspection, fire-risk monitoring) at critical infrastructure, such as power plants, improving safety, efficiency, and resilience. One postdoctoral researcher worked on this project.

AI:MIND (AI:MIND'2025), 2025-2028, Aalborg University, DKK 7,600,000, HCC Share: DKK 3,800,000. This project combines psychology and computer science to address mental health issues in young people through conversational AI, designed to strengthen identity through guided and personalized reflection and reduce psychopathological symptoms. Two PhD candidates worked on this project.

mInt: Human-centered design principles for effective management of social boundaries in interoperable text messaging platforms (mInt'2025), 2025-2028, Independent Research Fund Denmark (DFF) and AAU TECH, DKK 3,668,000. Generation of human-centered design principles for messaging interoperability to promote freedom of app choice, grounded in social psychology and user studies of novel user-interface prototypes. Two PhD candidates and a postdoctoral researcher worked on this project.

AI4SE1DK: Human-centered Adoption of Artificial Intelligence for Software Engineering in Denmark, 2025-2029, Innovation Fund Denmark (Grand Solutions), DKK 30,428,213, HCC Share: DKK 3,548,804. This project advances the adoption of human-centered AI for software engineering in Denmark, addressing knowledge gaps, technical adaptability, and trust in

AI-generated software. It combines empirical, constructive, and action research methods in collaboration with a consortium of Danish software companies, research institutions, and technology transfer organizations to develop tailored AI-driven methods and tools aligned with Scandinavian values and sustainability goals. One PhD candidate worked on this project.

6.6 Own Evaluation

6.6.1 Increased research activity

In terms of research content, we observe a clear difference between the research themes planned in 2020 and the six themes that best describe our research from 2021 to 2025. Historically, the HCC group has often strayed from its planned themes, and one explanation for this pattern lies in its applied, problem-oriented profile. The previous research evaluation committee identified this orientation as a potential challenge, noting that the group risked "letting a thousand flowers bloom" without a sufficiently coherent research strategy.

However, such drifting must also be understood in light of the exceptional external conditions shaping the period 2021 to 2025. This has been a time marked by rapid technological paradigm shifts in AI, IoT, and robotics, the societal and organizational transformations triggered by the COVID-19 pandemic, and geopolitical instability with attendant macroeconomic pressures shaping, e.g. funding policies. These changes jointly formed a "perfect storm" of shifting conditions for digitalisation research. Against this backdrop, the evolution of the HCC group's research themes can be seen not as a lack of direction, but as an adaptive response to a dramatically changing landscape. The group has repeatedly had to recalibrate its focus to remain relevant, fundable, and aligned with emerging societal needs. Here, the emergence of large language models and generative AI from late 2022 reshaped both public expectations and funding priorities. This provided new opportunities and research questions for HCC on the topic of human-AI collaboration.

Next, we analyze the productivity of our research group in terms of publishing.

Publications

In total, the HCC group published 106 journal [1] and 122 conference papers during the reporting period 2021-25, in contrast to 38 journal/103 conference papers in the previous reporting period. The journal venues have been ranked into A/B/C categories according to SCImago Journal & Country Rank [2], while the conference venues were ranked according to the iCORE Rankings [3].

Conference publications were roughly 40% each in A and B categories, with the remaining 20% in C-level venues. Journal publications, on the other hand, were about 65% in A-level, 25% in B-level, and 10% in C-level venues. These numbers indicate a consistently high quality level of our publications, with C-level venues mostly being selected for regional proximity or a particular topic fit.

Regarding other types of publications, the HCC group published 11 PhD theses for 2021–2025, an almost threefold increase over the 2016-2020 period with 4 PhD theses. Moreover, HCC members published 11 book chapters, 37 demos & Work-in-Progress papers, and co-organized 16 workshops. These latter contributions are usually summed up as non-archival publications.

Table 6.1: Publication Output

(a) Conference Publications

Year	A	B	C	Total
2021	11	10	3	24
2022	9	15	2	26
2023	7	8	5	20
2024	9	6	10	25
2025	14	6	7	27
Sum	50	45	27	122

(b) Journal Publications

Year	A	B	C	Total
2021	8	2	4	14
2022	18	10	2	30
2023	15	5	2	22
2024	18	4	2	24
2025	7	8	1	16
Sum	66	29	11	106

Reflection. Looking back on the reporting period in terms of publications, there was a drop in the number of conference papers in 2023, which can possibly be attributed to post-pandemic effects (e.g. less options for live studies in the previous two years). In contrast, the number of journal papers spiked in 2022, which may also be related to the COVID-19 pandemic.

[1] 14 papers are in new ACM journals (e.g., PACMHCI) based on conferences such as MobileHCI and CSCW.

[2] $Q1 \rightarrow A, Q2 \rightarrow B, Q3/Q4 \rightarrow C$

[3] categories A* and A were merged

Overall, however, the HCC group has shown a consistent level of research output in high-quality venues, matching the group's growing size and resources in relation to the previous reporting period.

6.6.2 Funding application process

The group has increased its internal coordination through bi-monthly funding meetings, resulting in a rise in submitted and granted applications. Nevertheless, application success rates remain low.

As presented in Section 6.5.7, HCC has attracted significant external funding across a number of projects. Several additional projects have been granted and are set to launch in the coming year. Topically, these often built on the topics investigated during this research evaluation period, suggesting that the group has gained traction on a few key topics. Noteworthy about HCC's funding achievements is not only the increased funding success but also the broader representation of HCC's academic staff in these activities compared to previous evaluation periods.

6.6.3 Recruitment and staffing

On an organizational level, the previous research evaluation committee recommended that the HCC group address compensating for the loss of a top researcher, providing leadership support, developing a recruitment strategy, and promoting diversity and inclusion.

Over the evaluation period, two professors moved into University management positions, and only one new professor has been appointed at the end of 2024. Nevertheless, the group's dynamic capability to navigate multiple demands across research, teaching, and administration has ensured a strong publication output and an even stronger emphasis on funding, albeit across varied thematic areas. Notably, one theme, Human-AI, has become a clear anchor point for both publications and funding among several members of the group.

Leadership support has improved through targeted coaching and leadership-development activities for emerging research leaders. The recruitment strategy has been strengthened through the establishment of departmental search committees.

With regard to diversity and inclusion, the group maintain a strong outward-facing hiring profile: five of the seven assistant professors hired in the period obtained their PhD outside AAU, and four of them are female.

6.6.4 Group organization and strategy

In addition to the aforementioned activities, the group sought to have a positive impact on its peers, students, industry, and society. We next reflect on these aspects in relation to awards and organizational roles, teaching, and society and industry.

Awards and Organizational Roles

Across the HCC group, members collectively held more than 40 organizational roles in international scientific communities between 2020 and 2025, demonstrating strong and sustained engagement in shaping the field. These include:

- Editorial responsibilities: Members have served on the editorial boards of six international journals, including Empirical Software Engineering, International Journal of Human–Computer Studies, Behaviour & Information Technology, Biotechnology Design Journal, and the Journal of Visualization and Interaction (co-founded by an HCC member in 2023). In addition, several have acted as guest editors for special issues in leading venues.

- Conference leadership and reviewing roles: HCC scholars have served as Associate Chairs (AC), Technical Program Chairs (TPC), and Subcommittee Chairs (SC) at premier ACM and IEEE conferences including CHASE, ICSE, EASE, ICIS, MSR, CHI, CSCW, DIS, UIST, MobileHCI, TEI, NordiCHI, ISMAR, and IEEE VR. Across these venues, HCC members have collectively contributed to over 25 program and organizing committees, and chaired or co-chaired at least 10 major tracks.

- Scientific community and board memberships: HCC researchers hold positions on five international committees and working groups, including the COST Action on Digital Mental Health for Young People (Management Committee and Working Group Leader), the SIGPRAG Board, and the SIGCHI Operations and Latin American Committees.

- Awards and recognition: The group's contributions have been acknowledged through multiple best paper and service recognitions, including paper awards at CHI, DIS, HRI, MobileHCI, TEI, highlighting both scholarly and organizational excellence.

Reflection

The Human-Centered Computing group at AAU has established itself as a core contributor to the international HCI and Systems Development research communities. Members' leadership in editorial boards and program committees ensures close involvement and understanding of emerging themes central to human-centered computing. Equally, the group's coordination of community events such as the Danish HCI Day and participation in COST Actions and SIGCHI committees have strengthened long-term research collaborations and funding opportunities and contributed to both the Nordic and European research ecosystems.

Teaching

PhD courses: The HCC group has offered seven PhD courses in the report period, covering topics such as crowdsourcing human insights, robots and sustainability, research transparency in science, structural equation modeling, human-centered artificial intelligence, and drones in research and industry.

Four courses involved collaboration with international partners, including Simo Hosio (Oulu University), Haiyi Zhu (Carnegie Mellon University), Anke Brock (ENAC - National School of Civil Aviation), Lonni Besancon (Linköping University), Maximilian Häussler (UCSC), Chatchavan Wacharamanotham (University of Zurich), and Jessica Cauchard (TU Wien).

The courses have evolved over time, with more recent ones addressing AI and emerging technologies.

Papers with our students: We have been successful in publishing research based on student problem-based learning projects, thereby tightly aligning our research and educational activities. About 12% of HCC conference papers have emerged from teaching activities and include contributions from students. 2024 was the year with the highest number (seven) of conference papers published with students. NordiCHI stands out as a venue for papers published together with students. In addition, five journal papers were published with students during the reporting period.

Further, the group has engaged in IT-Vest-funded projects on digitalizing teaching, enabling the hiring of postdocs for this purpose.

Society and Industry

During the reporting period, the HCC group strengthened its role as a trusted partner for industry, public-sector stakeholders, and cultural institutions. We ap-

ply human-centered computing research to concrete societal challenges, particularly sustainability and other SDG-related priorities, by co-developing and piloting solutions in real-world settings, leading to joint projects, industrial PhDs, publications, and demonstrators across domains such as mobility, health, critical infrastructure, and public engagement with AI and data.

Engagement with society and industry is embedded in our research and education through consortium grants, contract research, advisory roles, and partner-driven student projects. Recent examples include a large-scale hackathon at the National Museum "Kongernes Jelling" (Jelling'2025), the GIRAF multiproject (GIRAF'2025), and cross-disciplinary consortia for major national grants on resilient critical infrastructures (PERSIST'2025) and human-centered AI for emergency services (NAMUR'2024).

6.7 Committee Evaluation

HCC researchers share an overall approach of empirical solution-oriented research from a human centred perspective. The specific domains, themes and approaches to this are very diverse across the group, e.g., from individual cognition to organisational perspectives. This is both a strength in its diversity and a challenge for creating synergies and intra-group collaborations. However the articulation of their diverse research into their six themes makes good sense.

Over the evaluation period, HCC has grown significantly, albeit with new hires at relatively junior levels. The HCC members have also been very successful in maturing their approach to funding acquisition and external collaborations with good results (see below). The group has a good international profile and a strong publication profile in key venues for their topic areas (see below).

Commended

The publication profile has significantly improved over this period compared to the previous period, both in numbers of publications and the diversity of venues. The consistent publication pattern is particularly to be commended given that the group has been growing over that time. The almost threefold increase in PhD theses is also noted as well as the many best paper awards which reinforce the quality of the research.

HCC has very strong engagement with local/national stakeholders, and a broad and growing portfolio of industry and public-sector collaborations across mobility,

health, energy, critical infrastructure, sustainability. Several collaborations have led to industrial PhD projects which is to be commended especially at this time when external funding is increasingly difficult to acquire.

HCC has good cross-campus connections while retaining HCC's distinct focus. The AAU robotics platform participation is a good example of this.

HCC members have good international visibility and play many leadership roles in their peer communities, e.g., editorial board members, conference leadership, and so on. HCC also has good collaborative networks and strong international links as evidenced by e.g., invitations to Dagstuhl, workshop co-organisation, COST Actions/SIGCHI involvement, and partnership in several EU Horizon consortia

The increased focus and effort towards acquiring external funding has resulted in a diverse and growing funding portfolio: DKK 40M across 20 projects (15 with industry), despite no EU funding won as lead. This demonstrates the success of a more structured approach to supporting funding applications, albeit with challenges beyond their direct control (like getting accepted).

There was also a broader representation of HCC staff in the funding activity compared to previous periods which is to be commended.

What was particularly evident in the interactions with the group during the site visit was the strong social/collegial culture. Activities such as weekly informational meetings, Friday Bread, and mentoring support from the senior professor were generally highly valued by members.

Challenges noted

As also noted in the report, the application success rate was low. However this is a challenge that is shared by researchers across Denmark and Europe as funding becomes increasingly competitive.

While HCC were able to contribute their HCC-expertise strongly to external collaborations, it seemed like there were missed opportunities for sharing of perspectives and collaborations across groups within the Department.

As with all the groups with members across Aalborg and Copenhagen campuses, it is an ongoing challenge to ensure cross-campus visibility and to promote quality interactions. The group is very aware of this and put in place measures to address this.

With only one full-time full professor there is a significant structural imbalance, especially given this person's combined research and section leadership load. There is a risk of overload concentrated on this one senior figure as funding and leadership

demands continue to grow.

Part II

Vision and Strategy

7 Vision and Strategy

7.1 Introduction

The department was reorganized during 2025 into four sections, each with a head of section. The new sections are based on the previous research groups, where the major change is that Copenhagen became a section on its own, and DESS and DKW were joined into one section. After the reorganization the sections are as follows:

- Copenhagen Section, CPH, head of section Johannes Bjerva
- Data Section, DATA, head of section Christian S. Jensen
- Distributed, Embedded, and Intelligent Systems Section, DEIS, head of section Kim G. Larsen
- Human-Centered Computing Section, HCC, head of section Niels van Berkel

The sections are where the scientific staff is affiliated, the daily life occurs, where teaching and other tasks are discussed and allocated, and where the immediate management and coordination resides. The sections are managed by the heads of sections.

The department's management group consists of the daily management group and the heads of the four sections; see Figure 7.1 and sizes in Figure 7.2.

Research within and across the sections is organised into new, small research groups as follows (the profiles of the research groups are presented in the following):

- Automated System Verification and Validation, lead Jiri Srba
- Data Engineering, Science, and Systems, lead Kristian Torp
- Distributed Sustainable Software and Systems, lead Bent Thomsen

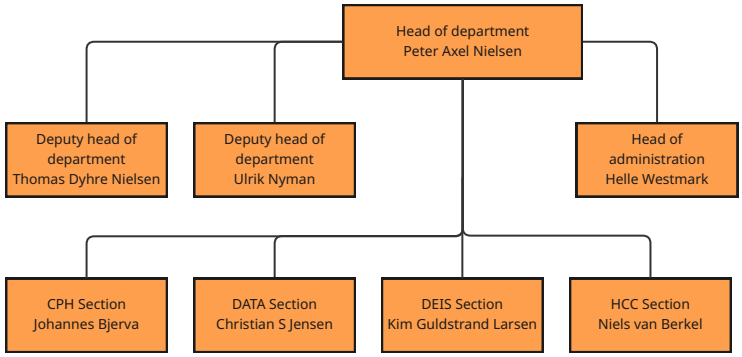


Figure 7.1: Management structure

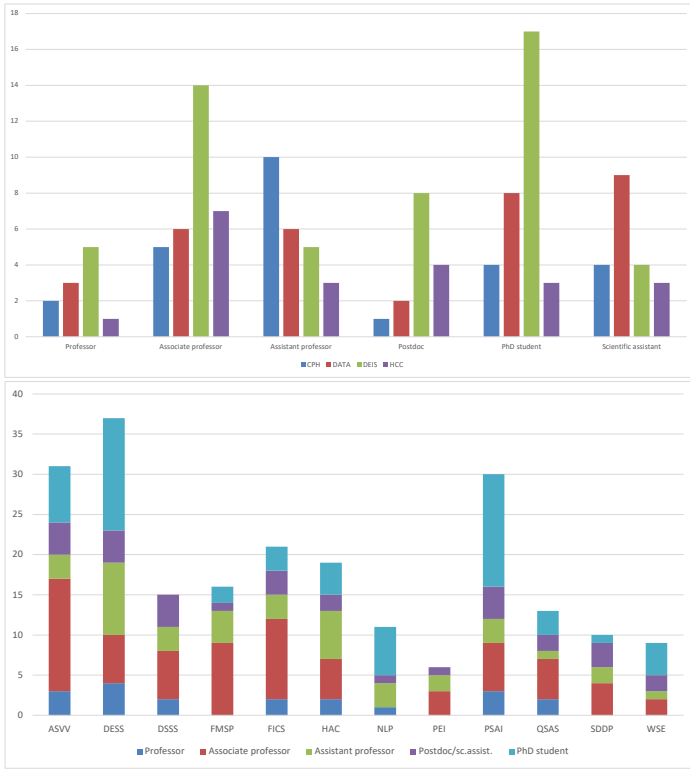


Figure 7.2: The size of the new sections (top), and the size of the new research groups (bottom)

- Formal Methods for Security and Privacy, lead Rene Rydhof Hansen
- Foundations for Interacting and Computing Systems, lead Kim G. Larsen
- Human Augmentation and Collaboration, lead Niels van Berkel
- Natural Language Processing , lead Johannes Bjerva
- Physical and Embodied Interaction, lead Timothy Merritt
- Probabilistic and Symbolic AI, leads Alvaro Torralba & Thomas Dyhre Nielsen
- Quantum Computing, leads Christian Schilling & Kim G. Larsen
- Systems Design and Development Practice, lead John Stouby Persson
- Web Science and Engineering, lead Peter Dolog

The research groups are each anchored in a section, but can have staff members from other sections. Members of the scientific staff can belong to one or more research groups, but only one section. The research groups are the primary structure of the department's research in the future. The ambitions and goals for the department's research are structured according to the research groups.

7.2 Department of Computer Science: Vision and Strategy

In the department, vision and strategy follow the same four dimensions as in the previous research evaluation. For each dimension, there are 1-2 specific goals to be reached during 2026–2028, see Table 7.1. The department's strategic goals are aligned with the university strategy, Knowledge for the World 2026-2028 , as well as the TECH Faculty Strategy. The department's strategy will be revised by the end of 2028 at the same time as the next university strategy.

External funding The department will pursue externally funded research by supporting the staff application process (administratively and research-wise), as well as through support for project administration. The department will continue increasing on past success (2025) and venture into EU funding, both ERC and collaborative research, in addition to private foundations and national research councils. The department will play a key role in the national research center DIREC.

Strategy	Goals 2026–2028
Research	External funding Research expansion
Education	Modernizing educations
Workplace	Diversity and inclusion
Engagement with society	Missions and platform Innovation

Table 7.1: The department's strategic goals for 2026-2028.

Research expansion The department will expand and contribute to key strategic research issues supported by the university and the TECH Faculty. This will include opening thematic efforts in collaboration with the other TECH departments and an international opening for a professor position at the department.

Modernizing educations The department will take an active and clear responsibility for AI in educations. The department's educations, both BSc and MSc, will be revised to take into account AI (incl. LLMs) as key content and instrument, e.g., in programming and group work. This will involve pedagogical elaboration on the use of AI. Master's educations will be extended to offer tracks allowing students to be simultaneously employed in a software company while undertaking their studies as part of the ministry's education reform.

Diversity and inclusion The department emphasizes the importance of diversity and inclusion at the workplace. The department will strengthen its support for and focus on gender diversity, recognizing it as a challenge throughout the field of computer science and within computer science educations. The department will also work explicitly on psychological safety and cultural inclusion, in particular as more than half the scientific staff are of international origin. This will also apply to the recruitment processes.

Missions and platforms Aalborg University is mission-driven at the strategic level. The department will take a key role in contributing to the university missions within energy, health, and well-being, and in other mission-oriented endeavors. The department will also be a key partner in university platforms within water, robotics, and AI for the People. Backing groups will be established for the department's involvement in these initiatives to further facilitate

and support a broad engagement of the scientific staff.

Innovation Innovation has increasing national attention, and the department will establish a visible presence in selected innovation activities and a strong connection with AAU Innovation. Within the department, innovation will provide merit to staff for career advancement.

The sections below present the goals and visions for the research groups together with a profile description and a staff overview.

7.3 Automated Systems Verification and Validation

7.3.1 Profile

The ASVV research group focuses on advancing the theory and practice of automated verification and validation of complex systems. The core work revolves around model checking—including statistical, symbolic, parallel, and distributed methods—and the development of efficient algorithms for analysis and synthesis of a wide range of quantitative models, such as timed automata, probabilistic and hybrid systems, Petri nets, and pushdown automata.

Key areas of research include:

- Model Checking: Investigating various forms—statistical, symbolic, parallel, and distributed—to verify system properties efficiently.
- Algorithm Design: Creating efficient algorithms for string solving as well as model checking and bisimulation checking across quantitative models such as timed automata, probabilistic systems, hybrid systems, Petri nets and pushdown automata.
- State-Space Exploration: Applying techniques like model reductions, partial order methods, and heuristic search to manage complexity.
- Verification Data Structures and Technologies: Leveraging technology such as binary decision diagrams (BDD), satisfiability modulo theory (SMT), difference bound matrices (DBM), dependency graphs, and quantifier elimination to improve scalability and reliability of system analysis.
- Strategy Synthesis: Designing efficient methods for strategy generation and representation in games and multi-agent systems, including a synergy with machine learning techniques.

- Static Analysis and Theorem Proving: Employing both automatic and interactive approaches for verifying system correctness.
- Applications of Formal Methods: Addressing real-world challenges in cyber-physical systems (CPS), network verification, and system monitoring.
- Tool Development and Validation: Constructing and deploying verification tools, integrating with domain-specific platforms through co-simulation, and validating approaches through case studies and experiments.

The group emphasizes practical impact through the development and deployment of verification tools, often integrated with domain-specific environments for co-simulation and validation. Highlighted tools developed within the research group include UPPAAL, TAPAAL, AALWINES, CAAL, Mata, Z3-Noodler, JuliaReach, and TimeRex.

7.3.2 Staff

Members of the ASVV research group are listed below with the head of the research group being underlined.

- Professors: Kim G. Larsen, Thomas D. Nielsen, Jiri Srba
- Associate professors: Michele Albano, Rene R. Hansen, Giovanni Bacci, Lukas Holik, Manfred Jaeger, Marius Mikučionis, Marco A. Muñiz, Brian Nielsen, Ulrik Nyman, Danny B. Poulsen, Christian Schilling, Anders Schlichtkrull, Arne Skou, Martin Zimmermann
- Assistant professors: Elli Anastasiadi, Jonas K. Hinrichsen, Morten K. Schou
- Postdocs/research assistants: Xinyu Ge, Martin Kristjansen, Andreas H. Høeg-Petersen, Daniele Toller
- PhD students: Suhaib Al-Rousan, Giacomo Bais, Oliver S. Bak, Asger H. Brorholt, Nicolaj Ø. Jensen, Michal Sedy, Fouzi Tabouri

7.3.3 Research & funding

The research group is committed to maintaining its excellence in the area of system verification and synthesis, with a strong focus on further developing high-impact

tools, publishing at leading conferences, and applying formal methods across disciplines. The members of the group are visible as organizers, PC chairs or members of the steering committees of top international conferences and among others, we will in 2027 organize ETAPS and chair the TACAS conference. Our strategy emphasizes the ability to rapidly adapt to emerging challenges and hot research topics, while grounding our work in solid, technically sound and tool-supported methodologies. The group contributed to the well-known Handbook of Model Checking[1] that will soon obtain an updated revision. We actively integrate our tools into real-world case studies, ensuring that our research remains relevant and impactful beyond the theoretical domain. A key component needed for our success is the dedication to long-term tool maintenance and usability, supported by a virtual lab environment designed for software development and experimental validation.

To sustain and grow our research capabilities, we invest in cutting-edge computing infrastructure, including the recent acquisition of five Genoa compute nodes to support large-scale experiments. Looking ahead, we aim to expand into automatic learning of models and explainable AI, seeking tighter integration of formal methods with machine learning to develop systems that are not only correct but also transparent and trustworthy. We encourage researchers to pursue excellence grants and other prestigious funding opportunities as well as other funding sources for applied interdisciplinary research both at the national as well as international level. The members of the group obtained substantial funding during the past five years (e.g. an Villum Investigator Grant of 30 MDKK); it will be a challenge for the group to match this success during the next five years. We recently secured a new large project on district cooling in collaboration with GRUNDFOS, but in the future, we will aim for several senior researchers to actively work on attracting additional funding in order to maintain the momentum in the high research output of the group.

7.3.4 Engagement with society

Our research group is deeply committed to creating real-world impact through active engagement with society. We pursue this by translating advanced formal methods into practical solutions for pressing societal challenges, particularly in the areas of energy-aware optimization and transport infrastructure. A recent example is the spin-off company CEDAR, which applies our research in formal verification and controller synthesis to the intelligent control of heat pumps in domestic heating systems, contributing to more energy-efficient and climate-friendly homes. This

[1] https://link.springer.com/book/10.1007/978-3-319-10575-8

demonstrates our ability to move research beyond the lab and into everyday life, where it can directly benefit citizens and the environment.

Similar examples include the transfer of our general control methods for optimal water detention ponds, helping to mitigate flooding risks and optimize urban water management. In the area of intelligent traffic control, we initiated research on intelligent control of traffic lights, an area where another spin-off company ATS (Advanced Traffic Systems), works with municipalities and stakeholders to develop smarter, more adaptive systems that improve traffic flow and reduce emissions. These collaborations not only validate our research in operational settings but also ensure that our innovations address concrete societal needs.

Both CEDAR and ATS started as academic projects that are the focus of the research group and relied on the combination of strategy synthesis and machine learning with early prototypes being run in UPPAAL Stratego. We identified further industry potential in the water domain, where intelligent control of the urban water infrastructure is lacking; the group has been active in this domain as well. By continuing to foster partnerships with the public and private sectors, we aim to be a leading force in bringing verified and intelligent technologies into the future infrastructure.

7.4 Data Engineering, Science and Systems

7.4.1 Profile

DESS encompasses up-and-coming scientists as well as experienced scientists, all with strong records of excellence and contributions in data engineering, data science, and data systems spanning more than three decades. Embracing the opportunities enabled by the ongoing, sweeping digitalization of societal, industrial, and scientific processes, we collaborate with our partners to conduct research that aims to advance value creation from data. In doing so, our research covers spatio-temporal, multidimensional, time series, sensor, and graph data, with applications in areas such as intelligent mobility, digital and renewable energy, smart buildings, and greenhouse gas emissions reduction.

Specifically, the research in DESS concerns:

- The invention of purposeful artifacts, such as frameworks, algorithms, data structures, indexes, languages, and methods and techniques, as well as tools, systems, and solutions based on such components.
- The construction of prototype software, typically either for proof-of-concept or

for the purpose of conducting studies of the properties of the artifacts.

The research focuses on spatio-temporal, multidimensional, time series, and sensor data, but also encompasses graph and IoT data. In terms of topics, the research concerns data management and analytics, including query processing, data mining, and machine learning. Examples include:

- Data management: data integration and data lakes, data warehousing, data compression and storage, and indexing.
- Analytics: prediction and forecasting, pattern and outlier detection, similarity search, advanced routing, and transfer learning.

Further, the research spans foundational topics as well as advanced applications and aims to take advantage of opportunities for cross-fertilization between foundational and applied research activities. The research also embraces a data science approach, where solutions to specific domain challenges are invented.

While key applications are in the general areas of intelligent transportation and digital energy, the group covers a wider range of data-intensive applications. Example applications include:

- Digital energy that enables the ongoing transformation of the electricity grid and society-wide electrification.
- Smart services for energy-efficient buildings.
- Greenhouse gas emission estimation.
- IoT data-based diagnostics and prediction in the renewable energy sector.
- Adaptability and failure prediction in power electronics.
- Learning of travel times and travel-time-based routing in dynamic road networks.
- Advanced data-driven services in transportation, including infrastructure maintenance and fuel consumption estimation.
- Maritime analytics, including trajectory imputation and sea-depth inference.

At the same time, we recognize opportunities for growth, including strong momentum in AI/ML, increased interdisciplinary interest, and rising funding opportunities such as the NNF Grand AI Challenge. We also acknowledge areas for improvement, such as expanding application areas (e.g., scientific data management, medical data, and digital humanities) and strengthening lab-tech support for prototyping. In addition, we remain attentive to external challenges such as increasing competition in data management, strong demand for AI talent across sectors, and an increasingly competitive funding landscape.

7.4.2 Staff

The head of the group is Professor Kristian Torp. An overview of the group's staff is provided below. The staff in each category are sorted alphabetically. "S" is used to identify members who have chosen DESS as their secondary group. The counts per staff category do not include secondary members.

Professors (4): Christian S. Jensen, Hua Lu, Torben Bach Pedersen, Kristian Torp

Associate Professors (4): Daniele Dell'Aglio, Peter Dolog (S), Tianyi Li, Tomer Sagi (S), Simonas Šaltenis, Christian Thomsen

Assistant Professors (7): Søren Kejser Jensen (tenure track), Tung Kieu (tenure track), Yushuai Li (tenure track), Yan Lin, Tiantian Liu, Juan Manuel Rodriguez (S), Yumeng Song, Suman Sourav (S), Sean Bin Yang (tenure track)

Post-docs (3): Liwei Deng, Hengyu Liu, Chuangtao Ma

Part-time Faculty Members: Chenjuan Guo (Associate Professor, 5%), Jilin Hu (Associate Professor, 5%), Arijit Khan (Associate Professor, 5%), Wolfgang Lehner (Professor, 20%), Bin Yang (Professor, 5%), Yan Zhao (Associate Professor, 10%)

Ph.D. Students (14.42): Abduvoris Abduvakhobov, Jonas Brusokas, Sriom Chakrabarti, Zhen Chen, Carlos E. Muniz Cuza, Sarah Hasan, Subina Khanal, Mohammad Hadi Mehdizavareh, Ehsan Bonabi Mobaraki, Martin Moesmann, Ibraheem Taha, Frederik Marinus Trudslev, Sigmundur Vang (42%), Jiachen Xu, Yu Zhang

Research Assistant (0.8): Christian Schmidt Godiksen (80%)

Academic Technical Staff (AC-TAP) (1.05): Kasper Fromm Pedersen, Laurynas Siksnys (5%)

7.4.3 Research and funding

Research. In the next five years, the group will continue working on important topics within its current research strongholds and will embrace new topics that have become increasingly relevant.

Spatial, temporal, and spatiotemporal data have been a focus area of the group since it was founded more than three decades ago. This will remain a focus area. We will continue to innovate and apply AI/ML techniques in this area, and we will actively seek interdisciplinary opportunities that integrate this and other areas. The growing digitalization across sectors generates increasing amounts of data, offering opportunities to broaden impact across data-intensive applications.

Our current stronghold in end-to-end time series management for IoT/sensor data,

spanning data capture, compression, storage, quality improvement, indexing, querying, and downstream analytics, will continue to be a central theme for the group. On the application side, our current stronghold of digital energy, intelligent mobility, and smart transportation will be more important than ever, given the urgent need to accelerate the Green Transition.

Some say that AI is 75% data and (only) 25% ML: certainly, the importance of data management in the broad sense is more important than ever in an age where AI is everywhere. Specifically, the (efficient and effective) integration of data and AI workflows/pipelines, e.g., the efficient integration of data compression and ML model training or the efficient use of ML model predicates in database queries, will be topics of investigation. While our efforts on digital energy can in some sense be seen as AI for energy, the reverse topic, energy for AI, the exploding and increasingly non-sustainable energy needs for AI data centers, is becoming central for computing overall. So-called sustainable computing is becoming a key topic for computer science in general, as witnessed by a 2025 Special Section of CACM. Specifically, sustainable data management, in terms of the resources consumed both for operations and production of hardware, will be an upcoming theme for the group. This also aligns with our emerging research direction in sustainable computing, which opens new opportunities for collaboration with other research groups.

Funding. The group will build on its current approach of maintaining a balanced portfolio of grants across excellence-pillar and challenge-driven funding sources and individual- and consortium-level schemes. For the excellence pillar, the group will pursue individual schemes such as ERC, DFF Sapere Aude, and Villum/NNF Investigator grants, as well as consortium schemes such as MCSA. For the challenge pillar, the group will pursue consortium schemes such as Horizon Europe Pillar II, e.g., Clusters 4 and 5, IFD Grand Solutions, as well as private schemes such as the NNF Data Science Collaborative Research Programme. We also aim to ensure that all faculty contribute to the execution of projects and are given opportunities to apply for their own grants.

To increase the success in obtaining funding, the group will make efforts to encourage greater participation in funding activities, especially by young faculty members. We will offer training in proposal writing, involve junior colleagues in writing large joint proposals, and mentor them to strengthen their profiles for prestigious career grants. We will also enhance internal knowledge sharing on what to apply for, how to apply, etc.

Moreover, we will pay particular attention to cultivating more opportunities for interdisciplinary collaborations that may lead to joint grants. With the group's

strengths in data and AI/ML, such collaborations can be established with application domains such as energy, transportation, and the maritime sector, as well as scientific disciplines such as natural sciences, medicine, and the humanities and social sciences. Example relevant funding opportunities include the Villum Synergy Programme and the NNF General Interdisciplinary Collaboration Programmes. We will also explore new opportunities arising from small facility-focused grants and emerging industry programmes (e.g., Amazon and Google).

7.4.4 Engagement with society

The group will continue its significant efforts to support sustainability and the green transition. Specifically, the work on digital energy, e.g., the further development, application, and standardization of FlexOffers, will continue, preferably in large consortia with potential for massive impact. A key example of such activities is the project "Sustainable Water-based cooling in megacities (SWiM)," which was awarded 60 million DKK from the private Poul Due Jensen (Grundfos) Foundation and will run in 2026–2030 with a multidisciplinary consortium across AAU, Aarhus University, and Nanyang Technological University. Here, FlexOffer technology will be extended to utilize energy flexibility for cross-sector optimization and trading between electricity and (district) cooling.

Next, the group will further consolidate its long established research on smart transportation through closer collaboration with industrial partners and other relevant players in relevant sectors. With such collaborations, the group aims to create value for its collaborators and society. For example, it aims to make notable contributions to reducing CO_2 emissions from transport on land, at sea, and in the air. The group also recognizes opportunities to further expand societal outreach, for example, by conducting practitioner workshops that demonstrate our tools with real data and by presenting our research in more accessible ways to the public. At the same time, we aim to improve support for non-Danish colleagues in initiating external collaborations and to increase the visibility and popularization of our research.

Furthermore, the group will study the energy consumption of SQL queries over the databases underlying IT systems. The research will involve the software company Software Improvement Group. As it has more than 400 international clients, the research has the potential to catalyze green digitalization. The group will also explore opportunities offered by strengthened support from AAU management to open doors to new external partners.

7.5 Distributed Sustainable Software and Systems

7.5.1 Profile

Researchers in the DSSS group analyse, design, implement, test and deploy open distributed computer systems with a focus on sustainability.

Our research spans computer architecture, compilers, program analysis, program transformation, program generation, generative AI, operating systems, distributed computing, local and distributed networking.

We work on

- sustainability with software, which refers to using software to achieve broader sustainability goals, like reducing carbon emissions, improving resource efficiency, and promoting social good.
- sustainability of software, where we focus on making the software itself more environmentally friendly, energy-efficient, and maintainable.

In our research we build software tools and applications based on theoretical foundations through model based, static and agentic analysis, as well as constructive, experimental and imperative approaches based on testing and performance analysis.

Keywords: computer systems, distributed systems, networking, IOT, sustainable systems, energy efficiency, compilers, generative AI, agentic systems

7.5.2 Staff

Members of the DSSS research group are listed below with the head of the research group being underlined.

- Professor: Hua Lu, Bent Thomsen (MSO)
- Associate professors: Michele Albano, Brian Nielsen, Arne Skou, Lone Leth Thomsen, Marius Mikučionis
- Assistant professors: Søren Kejser Jensen, Levs Gondelmans, Suman Sourav
- Postdocs/research assistants: Antheas Kapenekakis, Dragos Ionescu, Esther Hahyeon Kim, Jonas Hansen

7.5.3 Research & funding

The DSSS research group was formed in August 2025. The founding members came from the subgroups in DEIS focussed on programming technology and distributed systems. However, after an open consultation the group now has members from three sections; DEIS, DATA and CPH. It is the goal of the group to establish itself as a leading research group in the field of distributed sustainable systems and software. The group currently has three funded projects - two of which are industry driven in the context of the ITEA research programme. We have several tools in the pipeline which will be applied to industrial use cases. The research is often experimental, but we are seeking connections with theory via smart contract languages, theorem proving, cost semantics and models which can be subjected to analysis via tools like UPPAAL. We plan to seek funding for more industrial collaboration and funding for PhD students. We seek to expand university collaboration. Due to the multifaceted characteristics of sustainable systems research the publication landscape is scattered, thus we will publish in the most suitable venues striving for the most prestigious outlets.

7.5.4 Engagement with society

Members of the group have advised the Danish ICT Industry Association (IT-Branchen), the ministry of digitalisation and many companies on issues relating to sustainable system development. The GreenCode project has as one of its goals to establish international standards in the field. Members of the group have also participated in various news articles, podcasts, social media posts and interviews to reach a broader audience. We expect such activities to continue. We will seek opportunities appropriate for each group member to engage in scientific services.

7.6 Formal Methods for Security and Privacy

7.6.1 Profile

The Formal Methods for Security and Privacy (FMS&P) research group works on developing and applying formal methods for analysing, developing, and verifying security and privacy of systems. The group's research spans automated and interactive theorem proving, model checking, program logics, type systems, static analysis, and differential privacy. Applications fall within a broad range: from hardware and low-level software, over IoT and distributed systems, to (security) protocols and

socio-technical systems.

7.6.2 Staff

Members of the FMS&P research group are listed below with the head of the research group being underlined.

- Associate professors: Michele Albano, Giogio Bacci, Daniele Dell'Aglio, René Rydhof Hansen, Hans Hüttel, Brian Nielsen, Danny B. Poulsen, Anders Schlichtkrull, Martin Zimmermann;
- Assistant proferssors: Elli Anastasiadi, Léon Gondelman, Jonas K. Hinrichsen, Suman Sourav;
- Postdocs/research assistants: Frederik M. Trudslev;
- PhD students: Andreas Kjeldgaard Brandhøj, Tobias Worm Bøgedal.

7.6.3 Research & funding

The group was recently formed by members interested mainly in formal aspects of program verification, security, and privacy. The group is currently involved in three funded projects focussing on rigorous and formal approaches to security in a variety of contexts, e.g., IoT and resource sharing "green" systems. While currently a relatively small group, it is the group's long term goal to become a leading research group and centre of expertise for developing and applying rigorous approaches to developing and verifying the security and privacy of systems. While the group's research is primarily of a theoretical nature, we frequently realise the theory in the implementation of prototypes and tools. We intend to support and strengthen this approach by seeking funding for, e.g., (student) programmers and research assistants.

The group will continue to pursue both traditional funding opportunities as well as explore more recent opportunities related specifically to cybersecurity, defense, and related areas. We also plan to continue and expand our current collaboration not only externally, but also to explore internal collaboration both departmental and university-wide. In the short term, we will survey currently ongoing security related research across groups and sections within the department and, in the longer term, extend it to also include other departments.

7.6.4 Engagement with society

In the current geopolitical climate and focus on digital sovereignty and cybersecurity, it is particularly important to share and disseminate the FMS&P groups knowledge and expertise into these matters. The research group actively pursues engagement with society through active collaboration and transfer of knowledge with relevant stakeholders, e.g., owners/controllers of critical infrastructure.

7.7 Foundations for Interacting and Computing Systems

7.7.1 Profile

The FICS research group focuses on the theoretical foundations for interacting and computing systems, using semantics, logic and automata to specify, reason about, and synthesize correct functional behaviors as well as constrained and optimal quantitative performance. The work spans from individual programs to communicating components and cyber-physical systems, addressing behavioral and logical equivalences, satisfiability, proof systems and synthesis. We explore the trade-offs between expressiveness, decidability, and complexity, aiming to establish rich mathematical frameworks that enable the sound specification, verification, and design of trustworthy computational systems.

Key areas of research include:

- Semantics: Develop mathematical semantics for programming-, process- and system-languages providing precise and unambiguous foundation for understanding, reasoning, refining and optimizing systems with respect to relevant behavioral properties,
- Logics: Study, exploit and design logical formalisms to specify functional correctness, non-functional performance as well as security properties enabling systematic reasoning about both correctness and performance.
- Automata Theory: Provide precise operational foundation of semantics and create the algorithmic backbone for connecting specification logics with verifiable system behavior. We design new automata models for efficient reasoning and succinct representation, e.g. as in model checking and pattern matching.
- Cyber Physical Systems: Face the challenge to achieve foundations that captures quantitative behavioral aspects covering real-time, continuous dynamics and stochasticity while settling decidability and complexity bounds.

- Concurrency Theory: Device process calculi that capture interaction, synchronization, and communication between processes as well as investigate their behavioral equivalences.

- Contracts: Support compositional specification theories through contracts and assume-guarantee reasoning, enabling modular specification and scalable verification of complex systems.

- Synthesis: Provide formal and algorithmic methods for automatically constructing correct and often optimal controllers or components of interacting and cyber-physical systems (CPS) from high-level logical specifications.

- Monitoring: Online observation and verification of an interacting system during run-time—rather than relying solely on offline verification—to achieve a complementary and practically crucial set of benefits, especially for complex and machine-learning enabled systems.

- Interactive Theorem Proving: Establish sound and (where possible) complete proof systems for higher-order logic, forming a foundation for trustworthy interactive verification of trustworthy software, system, and tool development.

7.7.2 Staff

Members of the FICS research group are listed below with the head of the research group being underlined.

- Professors: Kim G. Larsen, Jiri Srba

- Associate professors: Giovanni Bacci, Giorgio Bacci, René Rydhof Hansen, Lukas Holik, Hans Hüttel, Marco Antonio Muñiz Rodriguez, Anders Schlichtkrull, Arne Skou, Martin Zimmermann

- Assistant professors: Elli Anastasiadi, Jonas Kastberg Hinrichsen, Daniele Toller

- Postdocs/research assistants: Nicolaj Østerby Jensen, Thomas Møller Grosen, Jonas Hansen

- PhD students: Andreas Kjeldgaard Brandhøj, Sean Kristian Remond Harbo, Michal Šedý

7.7.3 Research & funding

The FICS research group pursues a long-term vision of establishing generic mathematical foundations for interacting, concurrent, and computing systems. These foundational frameworks constitute essential enablers for the rigorous specification, verification, optimization, and synthesis of dependable and secure systems. As such, they underpin and empower the research conducted in other DEIS research groups as well as in collaborations beyond DEIS. At the same time, the foundations developed within FICS are continuously refined and extended in response to emerging system behaviors, increased system complexity, and novel classes of properties arising from new application domains.

The group pursues a balanced funding strategy that targets both excellence-driven grants and application- and collaboration-oriented projects. Existing national collaborations, notably within the DIREC initiative, will be further strengthened and expanded.

For application-oriented projects, FICS will collaborate closely with other DEIS research groups and external partners, contributing the mathematical foundations that enable rigorous, scalable, and dependable solutions. Representative application areas include monitoring-based anomaly detection in cyber-physical systems, hyperlogics for security analysis, automata- and string-based methods for efficient test generation, and control synthesis for energy-aware systems.

Finally, we are confident that the group's members possess the scientific maturity, originality, and international recognition required to compete successfully for individual excellence grants such as ERC, Villum, and Sapere Aude.

7.7.4 Engagement with society

Engagement with, and impact on, society is pursued through close collaboration with other research groups within DEIS and with external partners, where FICS provides foundational insights that enable application-driven research, as outlined above.

Engagement with the international research community will be maintained and further strengthened through continued organizational involvement in major venues. This includes key roles in ETAPS, where DEIS members serve on the Steering Committee and TACAS Program Committees, and where DEIS will host ETAPS and chair TACAS in 2027. DEIS will also continue its long-standing service on the steering committees of CONCUR, GANDALF, and MOVEP, and plans to organize workshops on foundational theory, including SOS, EXPRESS, and MOVEP.

Finally, DEIS will intensify collaboration with leading international research groups in, among others, Edinburgh, Oxford, Paris, Saarbrücken, Trento, Reykjavik, Uppsala, Taipei, Dortmund, Pisa, Rome (Sapienza), Munich, and Braunschweig.

7.8 Human Augmentation and Collaboration

7.8.1 Profile

The Human Augmentation and Collaboration group designs and evaluates interactive and AI-augmented systems that extend human cognitive and collaborative capabilities in digital environments. Our research examines how digital technologies impact both individual experiences and practices as well as collaboration within and across teams.

The research group adopts an empirical approach rooted in real-world problems. We integrate multiple perspectives by understanding the problem context, developing prototypes, and conducting evaluations. This approach combines quantitative and qualitative methods to explore how people adapt to and adopt technologies across domains, including digital health, education, well-being, and work. Beyond domain-specific contributions, we look to develop research methods and theoretical contributions that advance the field of Human-Computer Interaction.

We work towards a future where digital systems extend human capabilities rather than diminish or replace them. Our work advances technologies that support human agency and decision-making across diverse contexts and populations. Some of this work focuses on systems that augment individual cognition, for example in creative work or information retrieval. Other work examines how technology can enhance human-to-human collaboration and communication, as well as collective problem-solving in digitally mediated environments. We aim to establish principles and methods for designing such augmentation systems in ways that are effective and human-centered.

This vision responds to current tensions in how technologies are designed and deployed. Many systems optimize for engagement or efficiency without adequate consideration of the agency and well-being of its users, including long-term effects on cognition and relationships. We seek to demonstrate alternative approaches where technology genuinely serves human needs and capabilities.

Our research contributes fundamental knowledge about how humans work with technology, and how they work with each other through technology. We examine how people integrate digital systems into their personal and professional lives and

how this reshapes their relationships and capabilities over time. This helps to inform the design of more human-centered digital systems and to develop theoretical frameworks that advance the field of human-computer interaction.

In addition to pursuing research excellence in the aforementioned areas, we aim to be a supportive research community that prioritizes inclusive participation and a development-driven culture.

7.8.2 Staff

The HAC group includes the following researchers:

- Head of research group: Niels van Berkel
- Professors: Mikael B. Skov
- Associate Professors: Anders Bruun, Daniel Russo, Dimitrios Raptis, Florian Echtler, Timothy Robert Merritt
- Assistant Professors: Carla Florencia Griggio, Jeanette Falk, Levs Gondelmans, Nicolai Brodersen Hansen, Stefano Lambiase, Stine Schmieg Johansen
- Postdocs: Rune Møberg Jacobsen, Samuel Rhys Cox
- PhD fellows: Helena Bøjer Djernæs, Jade Martin-Lise, Stina Olsson, Xinyuan Liu

7.8.3 Research & Funding

Our research is grounded in real-world problems with clear societal significance. We combine system design and prototyping with rigorous empirical evaluation, conducting studies in authentic settings where possible. Our research focuses on novel and emerging technologies, allowing us to shape their development early and to contribute knowledge about their impact on individuals and society.

The group unites expertise in qualitative and quantitative research approaches. We value both types of methods and apply this methodological breadth to address research questions from multiple angles. Interdisciplinary collaboration is central to our work. The real-world challenges we address require expertise from computer science, psychology, design, health sciences, and other fields. We actively seek partnerships that bring diverse domain perspectives and methods to our research questions.

We are ambitious in our research, targeting premier venues in human-computer interaction, whilst also engaging with specialised conferences to engage more closely with peers working on similar challenges. We take an active role in advancing the field through developing new methods, contributing theoretical frameworks, and engaging critically with methodological challenges. We contribute to the research community through organizational activities and service roles that shape the field's development.

We pursue funding opportunities that support both fundamental research and applied impact. Our interdisciplinary research focus positions us to access diverse funding streams through collaboration with domain experts. We recognize that advances in HCI require both theoretical development and real-world validation, and aim to balance our funding portfolio accordingly. We are committed to building research capacity through Ph.D. supervision, postdoctoral training, and early-career researcher development.

7.8.4 Engagement with Society

Our work aims to create value beyond academic publications. We engage directly with practitioners and communities to ensure our work addresses real needs and produces actionable knowledge. We work across a range of sectors, including healthcare, education, creative industries, and software development. This cross-sector approach allows us to address authentic challenges whilst developing knowledge that generalizes beyond single domains. To further the impact of our work, we seek to release our research data and methods as open source to the wider community and participate in dissemination activities at the national and European levels. These activities will further strengthen our funding approaches.

7.9 Natural Language Processing

7.9.1 Profile

The Natural Language Processing (NLP) group at Aalborg University conducts fundamental research on language technology, aiming to contribute to the broader research vision of Trustworthy Artificial Intelligence. The group's work spans the full spectrum from computational linguistics to large-scale neural language models, with a unifying focus on multilinguality and linguistically informed methods, with a particular interest in linguistic typology. Central research themes include NLP Security, Privacy, Safety, and Factuality – areas of growing societal importance

as large language models (LLMs) become integrated into critical applications. By combining theoretical insights from linguistics with machine learning and integration of knowledge graphs, the group aims to develop language technologies that are robust, interpretable, and socially responsible. The NLP group has evolved rapidly from its establishment within the Data, Knowledge, and Web Engineering (DKW) section and is now an independent research unit at the Copenhagen campus. The group's rapid expansion reflects a strong foundation of externally funded excellence grants, including awards from the Novo Nordisk Foundation (Ascending Data Science Investigator), the Independent Research Fund Denmark (Sapere Aude), the Carlsberg Foundation (Semper Ardens: Accelerate) – in addition to an AAU-internal AI:X Labs award. These grants, and others, provide a robust basis for consolidating a leading research environment in multilingual and trustworthy NLP over the next five-year period.

7.9.2 Staff

Professor Johannes Bjerva leads the group and currently includes Assistant Professors Russa Biswas and Heather Lent, with Tenure-Track Assistant Professor Dustin Wright joining in early 2026. The team further comprises one postdoctoral researcher and six PhD students, with funding secured for four additional postdocs and four new PhD positions starting in 2026.

7.9.3 Research & Funding

The overarching vision of the NLP group is to establish Aalborg University as a leading European center for research in Trustworthy NLP within a 5–10 year horizon. The group's research addresses core challenges of reliability, interpretability, and resilience in language technology. Methodologically, the group develops linguistically motivated approaches to model interpretability and multilingual generalization, drawing on linguistic typology in particular, while advancing the emerging field of NLP Security. Current projects investigate how malicious inputs, data poisoning, and adversarial prompts can be detected and mitigated by analyzing linguistic regularities in model behaviour. Complementary strands address privacy-preserving learning, knowledge graph-grounded factuality, and alignment between human and model reasoning. Multilinguality remains a defining principle across all activities: By studying underrepresented languages and typological diversity, the group improves both performance and robustness across languages. In the coming years, the group will expand into more fundamental machine-learning con-

tributions – targeting venues such as ICLR, NeurIPS, and ICML – and deepen its interdisciplinary collaboration with linguistics, cybersecurity, human–computer interaction, and techno-anthropology in particular. A particular strategic goal is to nurture early-career researchers toward independent funding success, thereby ensuring group scalability, continuity, and long-term excellence, including targets such as DFF: Sapere Aude, ERC:StG/CoG, Villum Young Investigator, as well as collaborative funding that aligns with our strategy (e.g. Villum Synergy, ERC:SyN, NNF: Collaborative Data Science).

7.9.4 Engagement with society

The group places strong emphasis on openness, outreach, and societal impact. All research outputs are released as open-source software and datasets whenever possible, reinforcing transparency and reproducibility. The group actively engages in public dissemination and policy dialogue on AI safety and security, including expert contributions to the European Scientific Advice Mechanism (via SAPEA) and invited talks at national and international venues such as V2 Security 2026. Industrial collaboration is an increasing priority, with ongoing partnerships exploring practical deployment of secure LLM technologies in real-world settings. Through these collaborations and its role in national and European research networks, the group aims to serve as a preferred partner in Horizon Europe projects on AI security. By combining scientific excellence with responsible innovation, the NLP group contributes to building language technologies that can be safely and securely integrated into society.

7.10 Physical and Embodied Interaction

7.10.1 Profile

The Physical and Embodied Interaction group (PEI'2025) investigates how people interact with and through interactive computing systems that take physical form — robots, drones, tangible objects, and spatial interfaces. Our vision is to advance understanding and design of interactive systems that act, communicate, and adapt within the material and spatial environments people inhabit. We explore how interaction unfolds through movement, form, and bodily engagement, and how digital technologies can extend human action, perception, and collaboration across diverse domains such as healthcare, critical infrastructure, and education.

Our work bridges interaction design, robotics, and AI to study and prototype embod-

ied and spatial interaction. We define interactive physical systems as technologies that sense, process, and act in the world — turning computation into expressive and adaptive physical behavior. Current research themes include:

- Human–Robot and Human–Drone Interaction – designing and evaluating embodied systems that coordinate motion, perception, and communication with people.
- Tangible and Spatial Interfaces – creating physical and virtual surfaces, artifacts, and environments that afford collaboration and embodied cognition.
- Emotion, Attention, and Context Awareness – enabling systems that respond to human states and environments in meaningful ways.
- Prototyping and Fabrication Methods – developing new tools and materials for rapid exploration of physical interaction.
- Our research draws on research-through-design, design ethnography, and iterative prototyping, integrating theory, technical innovation, and empirical study.

7.10.2 Staff

The head of the group is Associate Professor Timothy Merritt. An overview of the group's staff is provided below.

- Associate Professors (3): Florian Echtler, Ilhan Aslan, Timothy Merritt
- Assistant Professors (2): Henning Pohl, Stine S. Johansen
- Postdoctoral Researcher (1): Maria-Theresa Bahodi

7.10.3 Research & Funding

Our research aligns with Danish and European priorities in interactive technologies, robotics, and digital transformation. Funding opportunities include DFF, Innovation Fund Denmark (Grand Solutions, DIREC), Villum Fonden, Novo Nordisk Foundation, Carlsbergfondet, and Industriens Fond.

Over the next five years, the PEI research group will strengthen our position as a leading research group, advancing both theoretical understanding and applied

innovations that reimagine how intelligent physical systems participate in human life.

PEI collaborates closely with other groups within Aalborg University including the HRI Lab, Aalborg Robotics Challenge (ARC), and Robotics and Automation Group. We publish in leading venues including CHI, HRI, TEI, DIS, UIST, and journals such as TOCHI and THRI.

7.10.4 Engagement with Society

The group engages with industry, healthcare, and public organisations to translate physical and embodied interaction research into real-world applications. We contribute to:

- Safe and accessible interaction with intelligent physical systems in workplaces and public spaces.
- Collaboration and connectedness across distance through embodied and spatial interfaces.
- Responsible integration of robotics and drones in societal infrastructures (aligned with CER and NIS2 frameworks).
- Through participatory research and public engagement, we foster dialogue about how emerging physical technologies reshape human activity and space.

7.11 Probabilistic and Symbolic AI

7.11.1 Profile

The group works on a range of topics in the area of probabilistic and symbolic AI, with particular focus on probabilistic machine learning and graphical models, graph and relational learning, neuro-symbolic learning, and automated planning and (model-based) reinforcement learning. A common theme for the group's research in these areas is an emphasis on trustworthiness through models and solutions that are interpretable, explainable, safe, and robust. Our research spans foundational theories, methodological and algorithmic developments as well as applications in sustainability (e.g. water management and renewable energy) and bioinformatics.

Key areas of research include:

- Probabilistic Methods and Models: probabilistic graphical models; latent variable models; PAC-Bayes methods; (statistical) relational learning; relational Bayesian networks

- Decision Making and Automated Planning: heuristic and symbolic search; Markov decision processes; intelligent problem solving; model reasoning and reformulation

- Safe Reinforcement Learning: strategy representations; verification of learned strategies; shielded reinforcement learning; shielding and learning for multi-agent systems

The research in the group has led to the development of several software tools that are applicable across a wide range of domains. These tools include Conan, Cpddl, JuliaReach, Primula, and UPPAAL Stratego.

7.11.2 Staff

Members of the PSAI research group are listed below with heads of the research group being underlined.

- Professors: Anders Læsø Madsen (20%), Kim Guldstrand Larsen, Hua Lu, Thomas Dyhre Nielsen

- Associate professors: Andres Masegosa, Christian Schilling, Daniel Fišer, Manfred Jaeger, Peter Dolog, Álvaro Torralba

- Assistant professors: Abdulkadir Celikkanat, Sean Bin Yang, Tung Kieu (tenure track),

- Post docs: Antheas Kapenekakis, Mike Zhang, Xinyu Ge, Zeynep Gondugar

- PhD students: Asger Horn Brorholt, Fouzi Tabouri, Giacomo Bais, Heather Christine Lent, Maria Fernanda Salerno Garmendia, Martin Kristjansen Naja Kathrine Kollerup Als, Nicholas Herrmann, Raffaele Pojer, Ramus Grønkjær Tollund, Sriom Chakrabarti, Suhaib Al-Rousan, Thomas Heede, Shuangzhulong Li.

7.11.3 Research & funding

The newly established research group on probabilistic and symbolic AI gathers researchers from all four sections of the department, spanning both the Aalborg and Copenhagen campuses. The group aims to foster collaboration between researchers at the two sites and to encourage the sharing of regional networks and contacts. In doing so, we seek to broaden the outreach beyond each local area and strengthen the potential for new collaborations and funding opportunities. The group will continue its work within its key areas of research, while also emphasizing the flow of research from foundational theories to applications and back again. The two-way exchange of research is partly driven by the group's tool developments, which enables general algorithms and methodologies to be integrated and subsequently applied across domains.

The group aims to apply for both excellence and application/collaboration-oriented grants. With the group's research profile in AI and machine learning, there is a strong potential for interdisciplinary contributions in areas such as water management, bioinformatics, and energy systems - domains in which the group has already established collaborations. To strengthen the group's potential for joint collaborative grants, the group will expand its external network by selectively participating in strategic initiatives at the university level (e.g., missions, platforms), regionally, and beyond. Members representing the group at such networking events will promote the group's research agenda, enhance visibility, and help establish new connections.

In bringing together researchers with different AI and machine learning profiles, the group aims to strengthen collaborations within the group and to explore the intersection among its various areas of expertise. For example, we plan to further explore the integration of probabilistic models and methods within automated planning and shielded reinforcement learning. Similarly, there are recent efforts to bridge the gap between the automated planning and reinforcement learning communities.

7.11.4 Engagement with society

The research group will continue its active engagement with society through dissemination activities as well as practical applications and projects. The activities will promote ethical uses of AI under the broader theme of trustworthiness that also characterizes the group's research agenda.

There is a wide range of network events related to AI research both at the national and international level. The group will actively participate in such network activities to promote and disseminate the research and results of the group to a broader

audience beyond the research community. The group also aims at creating impact through more practically oriented projects addressing challenges in both industry and society at large. An example is SWiM (Sustainable Water-based Cooling in Megacities), which aims to develop a sustainable and cost-effective cooling system for hot, humid megacities in middle-income countries. Similarly, DK-Future (Probabilistic Geospatial Machine Learning for Predicting Future Danish Land Use under Compound Climate Impacts) will forecast future landscape transformations – and provide relevant stakeholders with data-driven and open-science compliant tools for sustainable planning. These projects not only illustrate the group's societal engagement, but also its involvement in applications within sustainability.

Active engagement and collaboration on industrial and societal challenges will not only help the group achieve impact beyond its immediate research communities, but it will also inspire and challenge the group's theoretical and methodological work within probabilistic and symbolic AI.

7.12 Quantum Systems Analysis and Synthesis

7.12.1 Profile

The QSAS research group was founded with the ambition to become a leading player in Denmark for advancing quantum computing and communication by providing foundational support through software engineering and analytical methodologies.

While we do not directly engage in building quantum computers, our work is pivotal in making quantum computing accessible. By focusing on the underlying principles and enabling technologies, we facilitate developers and engineers who work on building quantum solutions. Our expertise in fostering innovation within computing helps bridge the gap between theoretical exploration and practical implementation.

This section outlines the key research themes that we have identified based on our main competences. While we have already contributed to some of these areas in the recent past, we have a strong intention to expand our contributions to all the other areas in the next years. This expansion will also require growth in staff numbers, and hence we hope to attract more talents to our research group and extend our collaboration efforts with other emerging and established quantum research groups.

- Quantum Software: We emphasize software tools that streamline quantum programming and allow quantum users to implement quantum algorithms efficiently while leveraging quantum hardware effectively. Directions include developing high-level programming languages and frameworks.

- Automation: By developing automated workflows and tools, we enhance the efficiency of quantum development processes. This automation is crucial for managing the complexity of quantum systems, allowing developers to focus more on experimentation and innovation rather than on repetitive tasks.
- Compilation: Compilation is a critical aspect of optimizing quantum software for efficient execution on quantum hardware. We work on methods to convert high-level quantum programs into low-level instructions suited for various quantum processors while maximizing the performance.
- Simulation: Digital simulation techniques are central for modeling quantum systems and predicting their behavior under different conditions. We develop specialized simulation tools, to which we have already contributed with dimensionality reduction and tensor network contraction.
- Verification & Validation: Ensuring the correctness of quantum software is paramount. We actively work on methods to check that a quantum circuit adheres to a specification using an automata-theoretic framework, and we develop equivalence checks of quantum circuits before and after compilation.
- Synthesis: The concept of synthesis focuses on the integration of various quantum technologies and methodologies to create cohesive, functional systems. This involves the combination of different quantum components to produce configurations capable of addressing complex computational tasks.
- Quantum Protocols: Quantum protocols are critical for establishing secure communication and interaction in quantum networks. Equipped with a strong background in classical networks, we make key contributions to the basic research center CLASSIQUE on secure exchange in the quantum era.

7.12.2 Staff

Members of the QSAS research group are listed below with heads of the research group being underlined.

- Professors: Kim G. Larsen, Jiri Srba
- Associate professors: Giorgio Bacci, Lukas Holik, Marius Mikučionis, Marco Antonio Muñiz Rodriguez, Christian Schilling
- Assistant professors: Stefano Lambiase

- Postdocs/research assistants: Nicolaj Østerby Jensen, Loke Walsted
- PhD students: Suhaib Al-Rousan, Benjamin Clausen Bennetzen, Nikolaj Rossander Kristensen

7.12.3 Research & funding

Quantum is a recent research direction at our department. The current research focus of the QSAS research group is on the foundations of some key challenges in quantum computing. This is in part also a practical necessity, given the moderate size of the group and the fact that most members also have other research interests. Nevertheless, we have the ambition to become a leading research group in our focus areas. We have already laid some of the strategic grounds to achieving this goal by securing critical funding by the Danish government (distributed by DeiC) in the EQuAL project, and the basic research center CLASSIQUE (funded by DNRF). This helped to grow the QSAS group with several PhD students. As the next step, we hope to make the growth sustainable by also attracting senior researchers whose core research direction is focused on quantum.

Given the nature of funding in the area, our main focus is on collaborative project applications. There are ample funding opportunities, with even growing budgets at key funding agencies. We have a strong network in Denmark, and particularly good relations with the new quantum research group in Aarhus and the quantum center in Odense, as well as with collaborators outside Demark such as at TU Munich (Germany) and Academia Sinica (Taiwan). This network will be of strategic relevance for future project applications.

7.12.4 Engagement with society

In the recent past, we have been active in placing the department and AAU on the quantum map. Two QSAS members are in the AAU Quantum Hub steering group, including the chairman. Through the Quantum Hub, AAU is a member of the Danish Quantum Community (DQC), which is a quantum interest group with many major players in Denmark. QSAS members are also members of the quantum committee of the Danish Royal Society and the DQC's technical working group, which provides strategic advice to politicians. We have organized a workshop on Formal Methods in Quantum Computing (FMQC) together with a colleague from Aarhus in 2025, and will co-organize the second edition in 2026 as well. Further events we help co-organize in 2026 are DQC's annual Scientific Quantum Conference and the IEEE International Conference on Quantum Control, Computing and

Learning (qCCL), both of which will be hosted at AAU, and a workshop on Empirical Works on Quantum Software Development (E-QSE). We aim to keep up this engagement with the community in the future. Once we have laid the foundations, we will also increase our engagement with society. We gave a presentation at the Digital Tech Summit 2025, advocating for the development of a quantum software stack in Denmark. Also, we are currently starting a collaboration with Kvantify, a company advising businesses from the life sciences on the use of quantum technology. They face practical computing-related problems that we can help them with. This collaboration will also lead to interesting new research questions.

7.13 Systems Design and Development Practice

7.13.1 Profile

The **Systems Design & Development Practices (SDDP)** group studies how digital technologies are designed, developed, and applied in real-world contexts.

We care about:

- Real-world **practices** emerging from social structures and human agency in digitalization;
- Evolutionary **development** processes within and across organizations;
- Situated **design** of digital artifacts and interventions;
- Socio-technical **systems** understood through their practical consequences.

Our work bridges **human-centered design**, **information systems development**, **software engineering**, and **organizational studies** to address how diverse stakeholders experience and shape digital technologies.

We combine empirical richness with theoretical ambition through methodological pluralism. Our research focuses on the lived experience of digitalization, and the values, risks, and tensions that emerge with digital technologies. We seek to understand digitalization as situated, social, and evolving. Contributing with knowledge that supports reflective practice among designers, developers, and managers.

7.13.2 Staff

The head of the group is Associate Professor John Stouby Persson. An overview of the group's staff is provided below.

- Professors (1): Peter Axel Nielsen (10%)
- Associate Professors (4): Ivan Aaen (50%), Anders Rysholt Bruun, John Stouby Persson, Dimitrios Raptis
- Assistant Professors (2): Alisa Ananjeva, Nicolai Brodersen Hansen
- Postdoctoral Researchers (1): Ashna Mahmood Zada
- PhD Students (1): David Kinnberg Hein
- Research Assistants (2): Samir Memic, Phuong Thao Nguyen

7.13.3 Research & Funding

Our research and funding strategy is to organize our work around a coherent research agenda to:

1. understand digital transformation through real-world practices,
2. shape thoughtful and sustainable digital futures,
3. advance methodological innovation in socio-technical inquiry and human-centered design.

We support this agenda through a balanced and sustained funding portfolio that enables deep empirical engagement in organizations and long-term, practice-oriented research. Key funding sources include Innovation Fund Denmark, the EU Horizon Europe framework, private foundations, and Nordic collaborative programs.

Collaborative projects with industry, public-sector organizations, and NGOs are central to our research approach. These partnerships allow us to study technologies in situ, co-create design interventions, and examine development practices across organizational boundaries. They also support PhD and postdoctoral positions, talent development, and methodological experimentation.

Our ambition is to maintain a steady pipeline of research proposals, sustain cross-disciplinary collaborations, and ensure continuity in project-based funding. We aim to produce high-quality research with both academic impact and practical relevance while expanding the group's long-term research capacity.

7.13.4 Engagement with Society

SDDP researchers come from a strong tradition of engaging with societal stakeholders, which is a core element of our research identity. Our work contributes to society through three primary forms of engagement:

1. **Collaborative knowledge creation**

   We work closely with companies, public institutions, and community partners to design, evaluate, and improve digital solutions. These collaborations generate mutual value: partners gain actionable insights, and researchers gain access to rich empirical contexts for inquiry.

2. **Capacity building and reflective practice**

   Through workshops, design interventions, and teaching activities, we support practitioners in developing reflective and human-centered approaches to digital design and development. We help organizations understand socio-technical risks, improve development practices, and build capacities for digital innovation.

3. **Professional dialogue**

   We contribute to debates on digital transformation, responsible AI, and socio-technical design for the individual user, organization, and society at large. Our aim is to conduct useful research that helps people address their problems and supports empirically-informed decision-making.

Overall, our societal engagement reinforces our commitment to producing research that matters both academically and practically. By cultivating long-term relationships with external partners, we help shape sustainable digital futures.

7.14 Web Science and Engineering

7.14.1 Profile

The Web Science and Engineering group focuses on AI-based methods for improving the use, access, and evolution of the Web. The research includes methods for learning user preferences from explicit and implicit user data and from side information, as well as methods for recommending items and users for different tasks on the

Web. We are actively advancing the state of the art in Recommender Systems, Personalization, User Modeling, (Personalized) Information Retrieval, and Web social networks analytics.

Our work also contributes to realizing the vision of the Semantic Web, where data and knowledge are represented in a machine-interpretable way to enable intelligent automation and interoperability. We develop novel methods for ontology engineering by automating the construction of ontological fragments to fill conceptual or relational gaps using representative corpora of web data. Furthermore, we design tools for visualizing and supporting the AI-assisted construction and maintenance of ontologies by practitioners. By combining AI techniques with semantic technologies, we aim to make knowledge representation more adaptive, scalable, and integrated across domains.

7.14.2 Staff

The head of the group is Associate Professor Peter Dolog. In total, the research group comprises three Associate Professors (Peter Dolog, Josva Kleist (20%), and Tomer Sagi), one Assistant Professor (Juan Manuel Rodriguez), four Ph.D. students (Martin Pekár Christensen, Mads Corfixen, Theis Erik Jendal, Abiram Mohanaraj), and two research assistants (Dragos Ionescu and Jovana Dobreva).

7.14.3 Research & Funding

Recommender Systems. In the previous period, we have primarily focused on graph-based recommender systems. This is still an active area, and we would like to continue in this direction. We would like to see how we could better tackle data sparsity, also in the context of graphs in recommender systems.

Fairness in recommender systems is crucial because these systems shape what users see, experience, and believe. Traditional metrics focus on the average across users, but that might result in some groups receiving much better recommendations than minority groups. Providing a fair experience means ensuring that all users, regardless of background or behavior, receive equitable access to relevant, diverse, and representative content. At the same time, items and creators deserve fair exposure so that attention and opportunities are not monopolized by already popular or mainstream content. In this context, we aim to study how to increase the exposure of unpopular items while improving the quality of recommendations for niche users, i.e., users who prefer non-popular items. The main goal is to reduce the trade-off between fairness and traditional metrics by targeting users who are likely to receive

less relevant recommendations from traditional approaches.

There is a new trend in the recommender systems community, namely conversational recommendation systems, mostly motivated by the movement in large language models but also beyond. The key problem is the heterogeneity in representations when taking into account LLM as well as the traditional recommendation models. We would like to expand our research to that area and see how to better support such recommendation scenarios. The work may include supporting data, supporting machine learning models, as well as supporting learning representations.

We would also like to expand on the previous aspect of the work on personalization and user modeling, not only in a recommendation context. We would like to achieve that mostly in collaboration with other groups.

Ontology Engineering Based on our recent work on ontology learning and evaluation, we intend to continue our research in this promising field, where a data-driven approach to constructing and evaluating ontologies is yielding significantly more actionable results and greater domain coverage than previous manual and rule-based methods.

Our preliminary work on ontology visualization has been enthusiastically received by practitioners. We intend to continue this line of research by developing tools that combine the automated evaluation and construction of ontologies with visualization platforms.

Funding Based on our past successes, we will focus on acquiring funding at both the national and EU levels. Based on our existing network of collaborations in the medical, oceanographic, and humanities domains, we intend to apply for synergistic and application-oriented research funding. We further intend to continue applying for basic research funding in our core areas of ontology engineering, web semantics, and recommender systems.

7.14.4 Engagement with society

Our work on ontology visualization and evaluation is generating much interest in industry and academia. We intend to capitalize on this and work to create a user group around the tools to drive development and research. ODINI, our oceanographic data integration project, is part of the AAU Marine Blue initiative - a platform for engaging with industry and government bodies around marine research. We intend to continue this engagement by maintaining and adding open-source

packages and software tools, and by presenting them in workshops, demos, and poster sessions to expose our work to practitioners and elicit user feedback.

We are involved in the AAU Health mission by contributing solutions for health data integration. We intend to continue our engagement with health department officials via the OHDSI Denmark node to further the interoperability of Danish health data by adopting international semantic standards, such as the OMOP CDM and its vocabularies.

We intend to leverage our nascent "AI for the people" bridging project with the design department to deepen our involvement in consumer-facing technologies. The project goal is to use foundational AI models to analyze people's perceptions of everyday objects, including furniture, clothing, and consumer electronics, to understand the motivations for fixing and continuing to use these objects instead of just replacing them. The final goal is to better understand people's perceptions of objects to reduce waste, contributing to societal and UN climate goals.

We expect to maintain our impact on the computer science curriculum by providing courses and course modules on management and processing of web-information, learning from web data, as well as master's thesis topics in our research areas.

7.15 Comments and Recommendations

7.15.1 Department of Computer Science

The restructuring of the department into new groups and subgroups, which was in part triggered by advice from the previous research evaluation, featured heavily in the report and on-site discussions. Broadly speaking, the committee views this as a positive development. The new group structure already appears successful in increasing the prominence and delineation of research areas, and proved a useful and effective way to present the department's diverse research. It offers good coverage of the field of computer science, with no significant gaps.

The committee would like to commend the department on the collaborative and inclusive process that seems to have been used in the formation of the majority of research subgroups, which has led to a high degree of shared ownership of the new structure. It was also repeatedly reported how the groups enabled more focussed discussions and mutual support. Another positive aspect of the new structure is that it offers more opportunities for leadership and capacity development across the department, with more people taking on leadership roles in the groups.

Recommendations

- *Research funding:* Whilst the amount of research funding coming in to the department has increased in the last few years and seems to be on a positive trajectory, it should be noted that (i) the funding levels still fall below the target levels set by the university, and (ii) the current funding portfolio is somewhat dominated by a small number of large, prestigious grants. Both of these points were acknowledged by research groups during discussions, and there is clearly a collective appetite to pursue more grants and to diversify the funding portfolio. Many promising ideas for proposals and research agendas were on show during presentations, from researchers at all career stages, and the committee strongly encourages mechanisms at both group and department levels to promote the sharing of expertise from more experienced staff members to help develop these ideas into grant proposal submissions. Currently this relies on individual initiatives, some of which could serve as role models for expanding initiatives.

- *Research organisation:* The process of forming new research groupings has resulted in twelve groups, which will be discussed in more detail later in the document. While the resulting groups make sense in terms of organising the expertise in the department, the committee noticed that there is considerable diversity across groups in terms of size, level of seniority, and focus. We encourage the department to consider the relative advantages of groups that have a full professor (or more than one) versus those that don't in terms of access to strategic information, resources, visibility, power and influence, career stage impact, and mitigation strategies. This can have an impact on departmental strategy and hiring. The committee furthermore encourages the department to continually review their research groupings, and names, with a view to giving a clear external perspective of Aalborg's Computer Science research strengths.

- *AI research:* On a related note, the department is advised to ensure that they have a joined-up strategy around **AI**. It was noted that many groups have successfully embraced AI topics, and are publishing research in strong venues in this space. The cross-section AI theme should also help in this regard. The committee suggests that the department target a clear external presentation of the department's expertise in this area, and to tell a coherent story about its different contributions across the groups.

- *Sections and Research groups:* Despite the benefits of regrouping, some

unintended consequences are inevitable. Related to this, managing the split of the department across the Aalborg and Copenhagen sites remains a challenge, including around the cohesion and identity of research groups and subgroups, and a sense of belonging across campuses. The committee recommends regular reviews of the communication mechanisms that are now in place and, more generally, building in regular structured reflection points about what is working well, what is not working so well and what can be done differently.

Issues to be aware of include: (i) the integration challenges of Copenhagen-section staff in Aalborg-centric research groups, for example after the reorganisation of mailing lists and no longer having visibility into Aalborg section information; (ii) some loss of visibility as to what is happening at the departmental level, and decreased awareness of related research being done in separate groups; and (iii) needing more clarity about the roles of sections and research groups and what non-research specific activities are best supported at what level.

Department members at all levels should be encouraged to self-organise in this respect, and create opportunities for communication and discussion beyond section and group meetings and for different peer cohorts or themes. Several instances of good practice were seen in this regard, from "junior club" to breakfast seminars and weekly informal gatherings, which could be adopted in other sections. On a related note, the department should be commended for providing resources to travel between sites, but this would be used more often and more effectively if more cross-department events, social or otherwise, were organised. This may also help address issues raised by many people about wanting to know more about what other groups in the department are working on, helping to seed new internal collaborations.

- *Leadership development:* The research group reorganisation provides a great opportunity for more staff to develop leadership experience and to build the department's capacity in this regard. This should be accompanied with mentoring or coaching support for new group leaders. The department should also take care when distributing administrative tasks and roles to ensure that leaders who are early career researchers in particular, and those who are still building up their research agendas, are not adversely impacted in terms of their research development.

- *Career pathways:* The department, or university more generally, may wish to look at the use of research-adjacent career pathways, as used in some other

university and research funding set-ups.[2] In particular, this could include a "Research Software Engineer career" pathway, which is known to be of particular value and importance for several research sections. Note that CoARA (`https://www.coara.org/`) argues for "recognition and valorisation of diverse roles and careers in research, including: ... software engineer and data scientist roles, technical roles, ... to name a few."

On a related note, the committee heard comments during group meetings regarding both the benefits and challenges of research staff being involved in spin-out/start-up companies. We would encourage this activity, making use of University provisions for innovation, as a means to demonstrate the impact of the department's research.

- *Hiring:* As noted above, the department has been successful in hiring high quality researchers in the last period, suggesting that strategic actions such as the use of search committees have worked effectively. On the other hand, during discussions with research group members, staff often seemed unaware of some of these processes. The committee would recommend greater transparency in the area of staff hiring, and the involvement of a broader range of inputs from department members. Search committees also adopted a focus on gender diversity. There are positive signs at the more junior levels of staffing, but hopefully progress can be made in this regard to attract more female staff in more senior positions. With anticipated growth of the Copenhagen campus, the challenge around how to integrate new hires into the department and sections will need particular attention.

- *Research outputs and impact:* Recognising the many current crises facing academic publication, the committee invites the department to consider how they might value quality over quantity of peer-reviewed publications, an intention already expressed by some groups, as well as recognise diverse sorts of research outputs and impacts, such as policy, practice, standards, public communication efforts etc, which some groups already contribute. This can align well with AAU's commitment to CoARA and its role in the Danish Network.

[2] The following are examples that the committee are aware of: UK Science Council initiative: `https://sciencecouncil.org/our-work-with-employers/technician-commitment/`; UCL Research Software Engineers: `https://www.ucl.ac.uk/advanced-research-computing/research-software-engineers`; Uni of Warwick Technical Staff Career Pathway: `https://warwick.ac.uk/research/technicians/93663_-_uow_technician_commitment_brochure_web.pdf`

- *Research Evaluation Report:* The committee found the site visit very helpful in forming a complete picture of the department. The written self-evaluation report was also helpful but could have been more concise, relegating details to appendices. It was also noted that while the sections on future plans used a common template among research groups, there was much less of a common structure when the work since the previous review was described. The committee invites the department to consider how future reports might be structured to make it easier for evaluation panels to identify key achievements and plans.

7.15.2 Automated System Verification and Validation (ASVV)

Commended

This is a well established research area for the department, with group members consistently publishing in top venues. The development of research software remains an important theme within this group, providing good external visibility and opportunity for connections and collaborations between group/section members. Staff are also taking leadership roles within the research community, e.g., via steering committees and major event organisation. The group's work is well supported by external funding, including significant success in getting major hardware investment to support research.

Challenges

Software staff support. It was noted by the group that, particularly given their focus on developing publicly released research software, losing some long-running staff/resources to support this activity had been challenging.

Site split. Given that this is a large group and includes members based in Copenhagen, effective coordination and communication between group members is a potential challenge after migration to the new group structure.

Research funding. There are multiple large grants supporting this group, but some of these are nearing completion and there are a large number of staff in the group, so ongoing success in bringing in further research funding is key.

Suggestions

Communication. Consider alternative and/or informal ASVV-wide (or DEIS-wide) communication mechanisms to ensure that all group members, including those based in Copenhagen, are able to keep up-to-date on the section's activities.

Software resources and expertise. Even in the absence of new resources for software development staff, set up regular meetings and communication between staff and students working on tool development, to share and document best practices, e.g., on newer technologies such as AI-based coding and infrastructure.

7.15.3 Data Engineering, Science and Systems (DESS)

Commended

This is another well-established research area in the department which continues to be productive, publishing in high-quality venues. There is a strong sense of identity focusing on data-centric AI research, with SIGMOD being the core community for most group members. There is a clear research strategy that values publication quality over quantity, has good ideas about topical publication pipelines, aims to cover the full spectrum from theory to applied research, and has clear values with regard to group culture. The leadership have used their experiences in the last period, and reflected deeply on how they want things to work, and what is fair and sustainable.

Challenges

Site split. This is another large group with members both in Aalborg and Copenhagen – this was also raised as a challenge in the group's presentation. Associated challenges include the risk of losing coherence, making sure that new hires have a sense of belonging, and how to properly engage with decision making in the Copenhagen section, e.g., regarding hiring.

Visibility. It is important to translate the strong internal coherence into outside visibility, e.g. by developing a strong social media presence. In this respect the Daisy label (Data-Intensive Systems) might be more useful than the DESS name.

Strategy. The group strategy is strong on intentions and identifies some useful mechanisms such as transparent and early co-authorship agreements, but some goals are more aspirational (e.g. develop new collaborations) and need pairing with concrete instruments.

Suggestions

Leadership. The challenges create an opportunity for more capacity building and leadership mentoring, by involving non-professors in discussion how to answer some of these questions, and by sharing some of the leadership roles between senior and early-career colleagues.

Strategy development and delivery. It is recommended that the group spends time on how to more practically operationalise the intentions on aspects like quantity over quality (what will this mean for publication strategies), work life balance (how will this be promoted and supported in the group, what are the 'costs' of doing this and how will these be relatively weighted), saying no more often (against what clear criteria of what is important to say yes to). Progress on these issues could be monitored by building in reflection points.

7.15.4 Distributed Sustainable Software and Systems (DSSS)

Commended

There was considerable enthusiasm and positivity around the formation of this completely new research grouping, drawn from a wide range of the old research groups (and both physical sites). The topic of the theme is very well aligned with University, national funding and industrial priorities, and a number of promising directions for further research projects and collaborations have been identified.

Challenges

The key challenge, with such a broad and diverse group of researchers publishing in distinct research communities, is how best to establish a coherent group identity. Other challenges identified by the group were heavy teaching and administration load for some of the group's senior members.

Suggestions

If not already in place, regular research-focused meetings should be maintained, to ensure good communication and connections within the group, which will become more important as its identity and focus evolves over time. As noted, this timely research area has very strong potential for attracting research funding, which should be exploited in order to bring more resources and staff to the group. There is also

considerable experience amongst existing members in building groups and collaborations, including with external companies, knowledge which should be actively shared amongst the group.

7.15.5 Formal Methods for Security and Privacy (FMSP)

Commended

The creation of this group seems to have been a positive way to cluster and to externally promote the department's work on formal approaches to security. From the discussions observed, this seems to be a cohesive group who actively communicate and collaborate amongst themselves.

Challenges

Visibility. Despite the successful external presentation of the group's work, it remains a challenge to evolve into a research group that is more prominent in the area of computer security more broadly.

Split site. As with several other groups, as the group grows in size it may be challenging to maintain a cohesive group split across the Aalborg and Copenhagen sites.

Suggestions

Hiring and focus. Consider hiring further researchers who have a primary focus on computer security, whose specialisms go beyond the connections to formal methods and, if successful, think about a better (perhaps broader) name for the group to help with outside marketing.

Future directions. The proposed future research directions of linking formal security approaches with generative AI and critical infrastructure seem like promising ways to encourage new group members and connections and further grow the group; these are to be strongly encouraged. The group could further explore additional teaching links via PBL/Masters courses to bring in more students in these lines of research.

7.15.6 Foundations for Interacting and Computing Systems (FICS)

Commended

In line with the Automated System Verification and Validation (ASVV) group, which has overlapping membership with FICS, there is a well established group of researchers in this area, publishing high quality research in top venues and contributing to the area via leadership and organisation roles. Presentations from the group highlighted strong expertise in a wide range of foundational research topics, combined with promising ideas for their application to timely real-world problems.

Challenges

The group argued that convincing the University of the value of foundational research was an ongoing challenge but that the related challenge of bringing in more external research funding would further help make this argument.

Suggestions

The group is in a strong position to apply for research funding, including individual and excellence-based schemes, given that they have prior experience and track record of successfully executing theory-to-practice research, and a promising set of further ideas to continue in this space. More senior group members are strongly encouraged to find ways to systematically share knowledge and experience amongst the group to help all members secure more research funding, including both smaller stepping-stone projects and larger ones.

7.15.7 Human Augmentation and Collaboration (HAC)

Commended

Research identity. Members reported the new research group provides a clearer focus for them and their research, compared to the previous HCC group. Work is published in high quality venues. That said, there is still a huge diversity of topics, application areas, methods, cross-disciplinary connections and so on. This can be seen as both a strength and a challenge (see below).

Culture. There seems to be a very supportive collegial culture with open communication and monthly status meetings. There are also clear plans to develop shared

knowledge about successful grant applications and to extend the external funding portfolio.

External collaborations. HAC is very strong on research collaborations outside of the department, e.g., with industry partners and cross-faculty.

International profile. HAC is particularly well connected internationally as evidenced by numerous exchanges and visits to Aalborg. Members are also very active in activities such as co-organising workshops, participation at Dagstuhl workshops, and hosting an international conference. These will further enhance the visibility and reputation of the group.

Challenges

Unbalanced structure. The group is somewhat unbalanced with only one full-time professor, most people at early and mid career level, and not so many PhD students. This has the risk of overburdening the senior person with administration, especially when they are also section head, and impact their ability to focus on research. The lack of junior researchers also impacts the capacity available for research.

Group coherence and collaboration. Having group members across both Aalborg and Copenhagen campuses makes coherence a challenge. There is also a related challenge about how to seed expertise sharing and foster collaborations within the group, especially for newer people.

Internal collaborations. HAC is not so strong on internal collaborations within the department, despite many shared interests, for example around AI. This seems to be a missed opportunity as HAC can offer unique perspectives and expertise here.

Articulating the strength from the diversity. While the overall focus for the new group is clearer, the diversity of specific interests and application domains across the group is very broad. This makes it harder to position and 'sell' themselves especially with respect to the rest of the department.

Suggestions

Strengthen identity and how to articulate this. Build on the focus that the high-level HAC framing offers and develop more clarity about what specifically HAC does, how, and why. The discursive process of exploring the connections and themes across diverse research interests and projects could help with: the cohesion across campuses; the integration of new people to find their place in the group and identify who to collaborate with; and making clearer the value that HAC can offer

to other research groups in the department and beyond.

Clearer communication and increased visibility. Explore opportunities to more compellingly communicate the work of the group to diverse audiences, both internally and externally.

7.15.8 Natural Language Processing (NLP)

Commended

The NLP group was established and has grown to a significant size in a very short time, with a good funding profile. The report and the presentation articulated a well thought-out approach not just to developing the group's research focus but also for career growth of group members, social cohesion etc. Assistant Professors feel supported and are encouraged to develop their own research focus. Opportunities for interdisciplinary research (NLP+) are actively explored, e.g. with HCI group and through AI:x.

Challenges

Managing growth. Expansion over the summer may lead to a doubling of the group in size, which may have unintended side effects in terms of group culture, cohesion etc.

Location issues. The group being entirely located in Copenhagen has obvious advantages in terms of cohesion, but brings challenges in terms of having access to departmental services, e.g. research portfolio manager, which are located in Aalborg.

Suggestions

Group identity. Think about the kind of group you want to be, and adjust growth aspirations to that. Create opportunities for discussions about this.

Leadership. The group lead has significant responsibilities as both group and section head. As the Copenhagen section expands, there may be a need to consider a shared leadership model to protect the long-term sustainability of key people in both research and work-life balance.

7.15.9 Physical and Embodied Interaction (PEI)

Commended

Clear overall focus. PEI is a relatively small group that has an overall shared research focus on novel technologies and collaborative interactions in the physical world. They also have a clear idea of their main publication venues, where different specialised conferences such as TEI, HRI, and UIST reflect the different technologies the group are working with.

Collaborative group culture. As a new small group, members are actively working on getting to know what each other is working on, and developing a cohesive group strategy. This is facilitated by a monthly group meeting, with plans for a group retreat.

Group leadership. There are plans for a rotating leadership model. This seems like a good strategy to explore, especially for capacity building and for sharing the load so that no one mid-early researcher is too negatively impacted by the leadership demands.

International connections. The group has strong international networks and collaborations.

Challenges

Developing a clearer identity. While the overall shared focus is technology-driven, each of the members is working on quite different technologies and application domains. There is also some overlap with the research of HAC in terms of methods, domains, technologies etc.

Key questions are: How to further develop a group identity when they are all doing different work around this focus? How to support diverse streams while also drawing out the synergies across these? How to better differentiate the research of PEI and HAC?

Rotating leadership. While a potentially good idea in principle, it is not so clear exactly how rotating leadership might work in practice.

Suggestions

Group identity. Continue to work on the articulation of the group research focus to better differentiate it from other groups in the section, and also to identify complementary strengths and interests within the group. The planned group retreat

can be important for this work.

Develop the leadership model. Work through the details of how a rotating leadership model might practically work, e.g., capacity building, length of term, the hand-over process, and what it will be like to step down and hand-over the role. Lessons learnt from this could be useful for other groups in the department.

7.15.10 Probabilistic and Symbolic AI (PSAI)

Commended

This group and the broader AI theme have already improved internal visibility of AI research topics across the department. The group presents a clear research focus with concrete opportunities for collaboration. The extensive suite of developed software tools enhances the group's identity and can set it apart from other AI groups, particularly now initiatives have started to combine some of them (e.g. Primula with UPPAAL).

Challenges

Visibility. How to grow external visibility in a crowded field and attract top talent?

Site split. Like many other groups, there are challenges associated with being distributed over two sites.

Suggestions

Visibility. The group may want to think about a name that more clearly expresses the particular research focus of the group to the outside world. Just saying you combine probabilistic and symbolic AI is not enough – why should they be combined, what challenges can be solved this way? Perhaps safety/robustness is a better option?

Software tools. The group's experience and expertise in software tools is a key asset that could be leveraged to create new connections and collaborations in other areas of AI, but this needs a strategy and buy-in from across the group.

7.15.11 Quantum Systems Analysis and Synthesis (QSAS)

Commended

Direction and funding. There has been impressive progress on developing this new research direction, over a period of just a few years. Group members are producing publications in the top formal methods venues and taking on organisation/leadership roles within the community. The group has also secured significant collaborative research funding success to enable it to develop further.

Challenges

Expertise. Current staff members mostly sit at the intersection of formal methods and quantum computing. It would be beneficial, although challenging, to recruit new staff with a specific focus on quantum areas, e.g. to supervise the new PhDs and postdocs already being hired in this area through recent funding.

Suggestions

Local connections. Consider connecting to other local research groups, e.g. with a focus on security, to expand the scope of the quantum topics covered by the group.

Software. Exploit existing experience from within the DEIS section to develop stable/usable software tools to support research in this area.

7.15.12 Systems Design and Development Practice (SDDP)

Commended

Group focus. SDDP has a well considered and clearly defined research agenda that is built on deep empirical engagement, taking a long-term practice-oriented perspective, with a view to real impact on organisations.

Ethos. The group articulates strong underpinning values built on an ethos of care and meaningful research.

Pipeline strategy. There has been a very deliberate strategy of building up a project pipeline from "smaller" projects. This has enabled an evolving research focus and also helped with consortium building and relationship building with partners/collaborators etc. This seems an appropriate strategy given the applied and context-specific nature of the work. The group has a good idea of best suited

funding agencies for the type of research they want to do and have built up close partner collaborations for developing proposals.

Commitment to service. In line with the strong ethos of care, all members of the group are making significant departmental service contributions.

Challenges

Sustainability. Intensive long-term collaborations within organisations requires ongoing commitment and resourcing. The shadow side of a progressive pipeline strategy is, what happens to the research if a next funding application is not successful?

Bringing good care to all aspects. How to balance service, teaching and research in light of their strong care ethic? How to avoid burn-out as care cannot realistically be applied at the same level for all aspects of work?

Scaling. The ethos of care also plays out in members wanting to be close to the everyday practice of research. This creates a scaling challenge.

Suggestions

Valuing diverse contributions. The context-specific in-situ nature of the group's research, alongside its high service loads, should be taken into account in any research evaluation exercise.

Scaling. Consider what level of scale the group wants to aspire to, without running the risk of compromising their values. Consider other ways that scaling might play out beyond growing numbers of projects.

Considered application of a care ethos. Similarly, consider diverse ways in which care can be instantiated, prioritising when high quality versus 'good enough' care makes sense. This is about idealistic care versus realistic care so that the resources of the group can be managed in the long term.

7.15.13 Web Science and Engineering (WSE)

Commended

Group identity. There was a palpable energy and enthusiasm among the group members for the possibilities that the re-structure has offered in setting themselves up as a distinct research group and being able to build on their strong sense of identity with the web conference community, and on a long tradition of department research on this topic area since 2006.

Focussed research. The deliberate inclusion of 'engineering' (about the construction of systems) and 'science' (the web as the object of studies) in the name of the new group points to where they see their future contributions. Each of the members of the group articulated a clear research focus exploring new directions (around conversational recommender systems, ontology engineering, semantic data integration and open source ontologies) and talked about specific research funding and collaboration plans, with clear plans for a focus on synergistic funding sources, as well as ideas to apply for a Danish industry PhD.

Engagement of students. A particular strength is the engagement of undergraduate and masters students in WSE research, resulting in peer reviewed publications with student co-authors.

Challenges

Group structure. Despite the group being strengthened by one member moving from 20 to 100%, they are nonetheless still a relatively small group, without a Full Professor position, and with four of the current PhD students due to finish soon.

Sustainability. The challenge now is building up the long term sustainability of the group and how this can practically happen. The funding plans aim to address this but the risk remains.

Suggestions

There were a range of plans and strategies discussed at the meeting with WSE and these are collated here as suggestions:

- Consider strategies in parallel to writing research proposals that can progress research while waiting for funding success, e.g., continue to promote student engagement in research and publishing, put time and effort into developing external collaborations and connecting with existing networks for collaborations.

- Look at ways to get industry more involved, e.g., industry PhD, attending RecSys Danish Meet-up events, student internships, PBL and MSc projects in collaboration with industry partners.

7.15.14 Junior Staff

PhD Students

The evaluation committee met with 10 PhD students from different research groups, different stages of the PhD (some very early, some on their second extension) and different locations (4 Copenhagen, 6 Aalborg). One Copenhagen student was on an industry PhD.

Commended

Overall the students were reasonably to very happy and felt supported.

Training: Students were required to take a mix of mandatory and elective courses to a total of 30 ECTS credits. The elective courses offered a lot of flexibility, with some of them offered on demand within sections or research groups. There was a range of ways in which credits were awarded, from active attendance to exams. Courses could also be taken at other universities, or credits could be awarded by summer schools.

Teaching: The students were also required to do 750 hours of teaching over their 3 years. This was mostly done through PBL project supervision. This was seen as reasonable and a way to provide value to the department.

Challenges

Location: Some of the Copenhagen-based students felt a bit remote from their research group if it was primarily located at Aalborg.

Mandatory training: There were mixed opinions about the mandatory courses which were not subject-specific and not always perceived as useful.

Teaching: The project topics weren't always close to the students' expertise and there wasn't much in the way of teacher training, so students occasionally felt like "winging it".

Time concerns: There was a concern that courses, teaching and a mandatory research stay elsewhere took a lot of time away from research. The perception was that it was very hard to finish everything in 3 years and that extensions were necessary in order to complete.

Lack of onboarding.: The amount of information given to students at the start depended very much on their supervisor and research group. It wasn't always easy to find the information, e.g. about what courses would be available to them at other universities (apart from the fact that differences in semesters and timetabling

made this sometimes difficult).

Suggestions

Onboarding: There is a clear need for a better onboarding process and pointers to where information can be found.

Training: Look for opportunities to make the training programme more relevant, or at least justify the mandatory component better.

Time concerns: Doing a PhD in 3 years is challenging even if no time is spent on training, teaching and a research stay. While it may not be in the department's power to change this, at the very least there is a need to better manage any anxieties among students arising from this.

Postdocs and Assistant Professors

The committee met with twelve postdoctoral researchers and assistant professors.

Commended

Overall people experienced working in the department as being friendly, comfortable and supportive.

Teaching: They particularly appreciated the democratic approach to decision making around teaching as well as the mentoring scheme for new staff, though the quality of this varied by group. The PBL seminar was also useful for meeting people from other groups.

Work culture: The support for some autonomy and for work life balance was valued. People also reported good informal support in their groups, e.g., for research and paper writing, as well as the department support for meetings and travel.

Challenges

Precarity: In line with the sector-wide challenges, the main issue was the lack of job security and the associated uncertainty and stress. Many reported a lack of transparency about possible tenure track options, the pathways to career progression, and not knowing the criteria for how they would be assessed if they applied for a tenure track.

Career Development: People reported needing more than the once-per-year employee development conversation and were looking for more integrated feedback and input. Some also experienced a lack of autonomy in being able to advance

their own research.

Onboarding: This was especially an issue for people who were new to AAU.

Belonging: Some postdocs felt that they missed peer support, falling in-between PhD students and 'young scholars' who each had targeted meet-ups. Some also experienced feeling a disconnect between being told they are valued and then not having any outlook for a permanent position in the department.

Suggestions

Transparency: Provide more transparency at hiring about the role of non-tenure track positions, AAU career outlook, and the path to tenure track, and how decisions are made.

Mentoring: Offer individual and peer-group mentoring for career development, ideally with the freedom to choose who might be a good mentor as well as being able to change mentors, with a focus on how to make strategic choices (work, service, papers, grants, students, teaching etc) to best set themselves up for either a tenure track position at AAU or to apply for a position elsewhere.

Peer support: Create opportunities for peer support within and across research groups. This can include in-person meet-ups and events, both cohort-organised or departmental-sponsored, as well as creating online spaces for connection.

Research support: In an ideal world, small amounts of seed funding from the department could help people develop some autonomy in developing their own research agendas and help set them up for next career steps.

7.15.15 Conclusion

In closing, the committee thanks all members of the department for their enthusiastic engagement in the process, both in reflecting on their work over the last 5 years to produce the written report, and in the open discussions with the panel. Complementary to the impressive collective achievements articulated in the report, the meetings provided an opportunity to better understand the quality of the people and the culture through which these outputs were produced.

Departmental values around democratic inclusion, openness, fairness, collegiality and sustainable work-life practices were clearly evident and provide a sound basis for the next five years. We wish the department every success in this next period.