Maastricht University

Self-Evaluation on Research 2015-2020

Department of Data Science and Knowledge Engineering

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Faculty of Science and Engineering
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PREFACE

This self-evaluation report on research was written as background information for the assessment, by an independent external review panel of peers, of the quality, relevance, and viability of research, as well as the PhD program, integrity and diversity policies at the Department of Data Science and Knowledge Engineering (DKE) of Maastricht University. It describes and evaluates all these aspects of the scientific research at DKE over the period 2015-2020 as well as the underlying strategies of DKE in achieving its goals. It follows and complies with the guidelines of the Strategy Evaluation Protocol (SEP 2021-2027) of the VSNU, KNAW, and NWO.

This report was composed by an ad hoc committee of senior researchers, management, and support staff of DKE. It was discussed and approved by the management team of DKE, by the Board of the Faculty of Science and Engineering, and by the Executive Board (CvB) of Maastricht University.

DKE would like to thank and acknowledge all who contributed to the assembly of the necessary information displayed in this report, and all who supported in organizing and tabulating the material.

Maastricht, October 2021

Dr. Rico Möckel

Director of Research of DKE

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1 INTRODUCTION

The Department of Data Science and Knowledge Engineering (DKE) is the largest of 13 departments and institutes within the Faculty of Science and Engineering (FSE) of Maastricht University (UM). With 33 tenured and tenure-track scientific staff members and in total 21 PhD candidates, researchers, and postdocs (in December 2020), DKE provides high-impact research in various areas of computer science, artificial intelligence, data science, robotics, and their mathematical foundations. Research at DKE is organized in eight research areas. These research areas span a variety of topics including (1) affective computing, computer vision, and natural language processing, (2) algorithms, complexity, and optimization, (3) cognitive robotics and complex self-organising systems (DKE SwarmLab), (4) game theory and dynamical systems, (5) explainable and reliable artificial intelligence, (6) game AI and search, (7) machine learning as well as (8) complex systems, signal and image processing. Furthermore, DKE researchers are part of the quantum and high-performance computing research area, a joint initiative with the FSE Department of Gravitational Waves and Fundamental Physics. DKE is also a core department of the Mathematics Centre Maastricht and a steering member of the Field Lab Robotics in Roermond.

DKE has three ordinary chairs:

- Mathematical Aspects of Knowledge Engineering (Prof.dr.ir. R.L.M. Peeters, since 2008)
- Computer Science/Artificial Intelligence (Prof.dr. G.B. Weiss, since 2009)
- Strategic Optimization and Data Science (Prof.dr. F. Thuijsman, since 2016)

three chairs with specialised remit:

- Machine Reasoning (Prof.dr. M. Winands, since 2019)
- Data Fusion and Intelligent Interaction (Prof.dr. A. Wilbik, since 2020)
- Explainable Artificial Intelligence (Prof.dr. N. Tintarev, since 2020)

and one endowed chair:

- Text Mining (Prof.dr.ir. J.C. Scholtes, since 2008)

DKE's expertise plays a relevant role to build up and amplify interdisciplinary research themes. DKE engages in joint research in various areas and with all faculties of Maastricht University, especially in the Science and Life Science context, in the biomedical and healthcare domain, in neuro-robotics and neuromorphic machine learning, in physics, at the intersection of AI, technology, and law, on robots and AI for children and elderly as well as on the responsible use of AI (see case study 6 in appendix B for examples of successful collaborations).

DKE research staff is strongly involved in research and education. The department is responsible for several continuously growing study programmes: both DKE's Bachelor's programme and DKE's Master's programmes are consistently ranking high in the annual Dutch Keuzegids[1], with all programmes frequently taking first place in their categories. In addition, DKE researchers provide service education at other faculties.

Despite high teaching load and several challenges (COVID-19, relocation of department, cyber-attack at UM) during the evaluation period 2015 – 2020, DKE researchers successfully published in high-ranked journals and conference proceedings, received various awards, and attracted ERC, Horizon 2020, and NWO grants (section 3).

During the evaluation period DKE responded actively to a changing environment:

- To respond to developments in science and society, where the visibility and impact of Data Science became more important, the name of DKE was changed in October 2015 into the Department of Data Science and Knowledge Engineering to reflect DKE's contributions to this field.

[1] https://www.keuzegids.org/ol/gidsen/uni17/opleidingen?wat1=i&wat2=i04&waar1=&submitter=wat2

- Following DKE's previous research evaluation, in 2018 DKE organised itself into the aforementioned eight research areas.
- In 2018 DKE joined the newly founded Faculty of Science and Engineering (FSE). Before DKE was part of its predecessor, the Faculty of Humanities and Sciences (FHS).

2 MISSION AND STRATEGY DURING THE ASSESSMENT PERIOD

This section discusses various aspects of the goals (Sections 2.1) and strategy (Section 2.2) of DKE. We also respond to the recommendations of the previous assessment published in 2017, which evaluates research performance and policies during the years 2010 – 2015.

2.1 Mission and strategic aims

The research mission and the strategic goal of DKE to **be a leading research unit** in the areas of **artificial intelligence** and **computer science** in the Netherlands have five dimensions:

Open Science: DKE aims to excel in providing high-impact, highly visible, FAIR (findable, accessible, interoperable, reusable) research output with strong societal impact. For this, DKE develops new methodologies and explores and develops application domains through multi- and interdisciplinary research cooperations with other scientific disciplines, as well as with stakeholders and end users from public and private sectors.

PhD Policy and Training: DKE is committed to the talent development of PhD students through high-quality training and aims to train the next generation of researchers for the job markets in computer science, artificial intelligence, data science, robotics, and mathematics.

Academic Culture: DKE aims to foster an inclusive, open academic community and to provide a safe work environment for all of its members including DKE researchers, support staff, students, and visitors. All DKE members are committed to conduct research according to the highest standards of research integrity as formulated in the Netherlands Code of Conduct for Research Integrity.

Human Resources Policy: DKE embraces diversity and aims to generate an attractive work environment where colleagues with a diversity of talents and backgrounds can grow their talents, progress in their career, contribute to our community, and get rewarded for their work and commitment.

Viability: DKE aims to remain financially viable and to continue its successful growth process by increasing and strengthening its research portfolio as well as its educational programmes. DKE is committed to being a strong and reliable partner for our staff members, our faculty, and our university, as well as for our Dutch and international partners.

2.2 Strategy

2.2.1 Research areas and foci

During the evaluation period 2015-2020, DKE performed high-impact research in a variety of promising research areas within **computer science, artificial intelligence, data science, robotics, and their mathematical foundations**. To keep focus, DKE carefully identified and selected eight research areas that we would invest in. The selection process was organized together with all DKE researchers and approved by the DKE management team. Feedback from DKE's previous research evaluation in 2017 was taken into account, as it encouraged DKE to distribute managerial workload over more senior colleagues and to restructure itself internally to remain manageable while growing. Knowing our strengths, five research areas were selected, wherein DKE had already gathered strong expertise:

- algorithms, complexity, and optimization (ALGOPT),
- game theory and dynamic systems (DGT),

- game AI and search (GAIS),
- machine learning (ML), and
- signal processing, complex systems, and images (SCSI).

By carefully evaluating opportunities, DKE chose three additional promising research areas with well-established initial expertise that we would expand upon and explore further:

- affective and visual computing and natural language processing (AVCL),
- cognitive robotics and complex self-organising systems (SwarmLab), and
- explainable and reliable artificial intelligence (ERAI).

This relatively wide area of topics (in relation to the available research FTE at DKE) was also chosen to make DKE research robust regarding changes in funding schemes and topics, to be able to react to a variety of needs of our research partners, and because historically, DKE researchers cover a wide area of topics to meet the requirements of our high-quality educational programmes. The investment into these areas showed success as all of them contribute to the research quality and impact of DKE (see section 3). The three additional research areas allowed DKE to expand its research to new high-impact domains and to increase its research income substantially (see case studies 1, 4, and 5 in appendix B).

In 2020, DKE also started investing into building expertise on quantum and high-performance computing with one DKE focus on quantum machine learning (see case study 2 in appendix B). The QC@UM project was founded as a collaboration between DKE and the Department of Gravitational Waves & Fundamental Physics. Additional focus to strategically important research fields was given through newly implemented chairs at DKE in Machine Reasoning (Prof.dr. M. Winands, since 2019), Data Fusion and Intelligent Interaction (Prof.dr. A. Wilbik, since 2020), and Explainable Artificial Intelligence (Prof.dr. N. Tintarev, since 2020), the latter two due to the successful implementation of the Computer Science sector plan in 2020 (see case study 1 in appendix B).

Organization of research at DKE follows several key strategies:

- DKE focusses **research on novel methods** as our goal is to produce widely applicable research.
- To successfully demonstrate novel methods, DKE targets **high-impact applications in close collaboration with domain experts and stakeholders**. Targeted application domains include healthcare (such as cardiology, research on diseases, well-being and assistive living, decision support systems), business (such as logistics, agriculture, Industry 4.0, decision support systems for businesses), and society (such as responsible use of data science and AI).
- DKE researchers choose their areas of research and targeted funding instruments freely. To **promote independent thinking in researchers** and to encourage all DKE researchers to take responsibility for their research and the organization of DKE, we do not implement a classic P.I. structure. Instead, we organize ourselves into the research areas mentioned above. Researchers are supported by senior researchers and fellow colleagues in their choices but ultimately decide for themselves which research they focus on. This gives room for everyone's talent while providing guidance and support.
- DKE embeds research on the **mathematical foundations of data science and artificial intelligence,** as we consider it to be a strength to have experts on computer science and applied mathematics working closely together e.g. in the areas of reliable and explainable AI.
- The interconnections between DKE research area groups are strong on purpose. Although we implemented research area groups to facilitate professional managerial processes within the department, **we embrace DKE as a single non-dividable unit** where colleagues strongly support each other.
- **DKE consists of team players**. In the past years, DKE actively supported the development of, and collaborated with, several inter-faculty organizations including the Mathematics Centre Maastricht (MCM, founded in 2019), the Institute of Data Science (IDS, founded in 2017), the Brightlands Institute

for Smart Society (BISS), and the Maastricht Centre for Systems Biology (MaCSBio, founded in 2015). DKE researchers are active in various national and international committees (see section 3).

As a result of these strategies, DKE researchers target a variety of funding instruments (national and international, public and private funding) typically in cooperation with national and international partners.

2.2.2 DKE's team approach to management and policy development

DKE embraces a strong team aspect that is reflected its organization, policy development, and HR procedures.

DKE's internal organization: DKE is led by a management team currently composed of senior researchers Prof.dr. M. Winands (Chair of DKE since 2021), Prof.dr. G.B. Weiss (Chair of DKE 2010- 2020), Prof.dr.ir. R.L.M. Peeters (Director of Research 2013-2020), Prof.dr. F. Thuijsman, Prof.dr. A. Wilbik, Prof.dr. N. Tintarev, dr. R. Möckel (Director of Research since Dec. 2020), and our managing director Ms. E. Narinx. For management including policy and guideline developments, the management team is supported by a team of DKE associate professors including the DKE research area coordinators. The area coordinators support the research chairs in the organization of the research area groups. Regular meetings of these teams (management team, management team plus associate professors, research area groups) as well as regular meetings with all DKE staff members help us implement effective communication channels and procedures to generate awareness for challenges and policies, and to properly involve DKE staff members in the decision and management processes. The open academic culture at DKE is further supported by annual retreats focused on research and education, as well as an open-door policy that allows all staff members to approach members of the management team at any time. We seek to create an open atmosphere where colleagues from all career levels feel encouraged to step forward to discuss issues and to propose solutions (see section 5).

Close collaboration with faculty and university: Where possible DKE builds required structures and policies through a team-based approach and in collaboration with our faculty and university, rather than just at the department level. DKE aims to comply with the strategic programme of Maastricht University. DKE gets actively involved and seeks to take a proactive approach in communicating needs and providing support, or adopts policies that were developed by our university. Many of the strategies and policies described in this self-evaluation report (e.g., research integrity, open science, PhD programs, HR/recognition and rewards, diversity, academic culture) are a result of this team-based process where we collaborate with others.

As part of the team-based approach, DKE is involved in a variety of organizations and committees within our university that take part in policy building. Prof.dr. R.L.M. Peeters serves as portfolio holder/Vice-Dean of Research of our faculty. Various DKE members serve and actively contribute to decision processes and in building policies and support structures as members of the Faculty Council, Maastricht Young Academy, Ethics Review Committee Inner City faculties (ERCIC), IT infrastructure committees, and other committees of our university and faculty.

One result of jointly building policies and structures with our university and faculty: as our last research evaluation also encouraged, DKE invests into a graduate school for PhD candidates. For this, DKE supports the implementation of a STEM Graduate school with tools for managing and monitoring the progress of PhD students at our faculty, rather than just at the department level. Prof.dr. R.L.M. Peeters serves as Director of the FSE STEM Graduate school.

2.2.3 Viable growth of research and education at DKE

DKE targets a sustainable, financially healthy, employee-friendly growth by growing its research and education capacities simultaneously. This strategy is based on the following needs and observations:

- Through its bachelor's and master's programmes DKE trains early-career researchers who qualify for academic positions at DKE and elsewhere. Some have been hired at DKE. Our in-house education is vitally important considering the lack of qualified personnel and intense employer competition on the job

market, which threatens the expansion of computer science research in the Netherlands (see threats in section 6.1).

- DKE sees a viable way to offer attractive working conditions, such as permanent positions and promotions for talented researchers, by driving a sustainable parallel growth of research positions and educational programmes. DKE strongly supports the efforts of the Association of Universities in the Netherlands (VSNU) to increase the number of permanent contracts at Dutch universities also for early and mid-career researchers (see e.g. the most recent Collective Labour Agreement of Dutch Universities (CAO-VSNU) valid from 1 January 2021). With research funding alone, which typically only generates short-term positions, we cannot offer such permanent positions.
- DKE, its researchers, and its research partners strongly benefit from DKE students supporting state-of-the-art research. At the same time, DKE students benefit from DKE research projects as they receive early exposure to state-of-the-art research during their studies.

Between 2015 and 2020, DKE successfully followed the strategy to grow its research and education capacities simultaneously. During the evaluation period, DKE's scientific staff (assistant, associate, and full professors) grew from 21 to 33 people, corresponding to an increase in research FTE from 9.7 to 13.5 (Table A.2). By securing and increasing the amount of research and education funding, the total number of postdocs, researchers, and PhD students at DKE also increased from 16 to 21 persons corresponding to an increase in research FTE from 14.4 to 16.9. Table A.5 provides an overview of DKE's annual incomes and expenditures. By acquiring research grants and by securing direct funding, DKE continuously grew its research funding between 2015 and 2020 to a total amount of about €1.28Mio per year in 2020, corresponding to a growth of 150% in comparison to 2015. On average, DKE attracted about €60K of contract funding (partially booked in Table A.5 as "other funding") annually. DKE's total annual income (including research and education funding) grew by about 90% from about €3.88Mio in 2015 to €7.27Mio in 2020. During the evaluation period, DKE was able to mostly maintain its reserves. Only in 2019, DKE invested some of its reserves with approval of our faculty management. This strategic investment into more staff was vital in view of correctly anticipated growing student numbers and due to developments in artificial intelligence and data science. The investment helped unload already overburdened DKE staff including when teaching loads grew even more due to the COVID-19 pandemic.

3 QUALITY AND RELEVANCE

Research output indicators deemed important and relevant for DKE's research are summarized in Table A.1 in Appendix A and discussed in the following sections.

3.1 Demonstrable Research Products

Research products that best reflect DKE's research quality and relevance to society are DKE's peer-reviewed journal and conference publications as well as published accessible datasets, software, and open-source robotic hardware that we make available for the scientific community and end users.

Peer-reviewed articles in journals and conference proceedings

Research quality

To demonstrate DKE's research output quantity and quality, we counted the numbers of publications in various categories for the period 2015-2020. The results can be found in Table A.7 in Appendix A. A full publication list is provided in the supplementary material. DKE focusses on high-quality peer-reviewed articles in scientific journals and conference proceedings. When compared over the evaluation period, the number of published refereed journal and conference articles increased between 2015 and 2020, from 29 to 44 refereed journal articles and from 26 to 42 conference articles annually. The increase in high-quality

publications is particularly visible during the years 2018 to 2020. This increase is partially to be expected from the increase in research FTE at DKE over the years. However, especially during the years 2019 and 2020 also the relative number of publications per research FTE increased, showing the positive effects of DKE's strategies implemented to provide DKE researchers with more quality research time (to the extent that was possible).

Overall, we see an increase of conference publications since 2018. Only in 2020 there was a small decrease in conference articles (from 47 in 2019 to 42 in 2020) that can be explained by the COVID-19 pandemic, during which several DKE target conferences were postponed or cancelled.

Most important scientific publications

The peer-reviewed publications that DKE considers most important for this evaluation include about 30 articles in journals with a quartile score of Q1. Table 1 lists a selection of DKE's top Q1 journal publications. Each publication represents one of DKE's main research areas. Citation numbers given next to the publications were obtained from Google Scholar (Oct. 2021). Quartile scores are taken from the Scimago Journal and Country Rank database. Citation numbers can vary due to the different years of publication.

Table 1: DKE's most important journal publications per research topic

Q1 journal publication	Citations
Research topic: Machine learning [1] Mocanu, D. C., Ammar, H. B., Lowet, D., Driessens, K., Liotta, A., Weiss, G., & Tuyls, K. (**2015**). Factored four-way conditional restricted boltzmann machines for activity recognition. Pattern Recognition Letters, 66, 100-108.	43
[1] Mehrkanoon, S. (**2019**). Deep neural-kernel blocks. Neural Networks, 116, 46-55.	15
Research topic: Neuromorphic machine learning [2] Kroner, A., Senden, M., Driessens, K., & Goebel, R. (**2020**). Contextual encoder–decoder network for visual saliency prediction. Neural Networks, 129, 261-270.	50
Research topic: Computer vision, affective computing [3] Alvarez, F., Popa, M., Solachidis, V., Hernandez-Penaloza, G., Belmonte-Hernandez, A., Asteriadis, S., ... & Daras, P. (**2018**). Behavior analysis through multimodal sensing for care of Parkinson's and Alzheimer's patients. IEEE Multimedia, 25(1), 14-25.	29
Research topic: Algorithms [4] Kelk, S., & Linz, S. (**2019**). A tight kernel for computing the tree bisection and reconnection distance between two phylogenetic trees. SIAM Journal on Discrete Mathematics, 33(3), 1556-1574.	4
Research topic: Game AI [5] Bošanský, B., Lisý, V., Lanctot, M., Čermák, J., and Winands, M.H.M. (**2016**). Algorithms for Computing Strategies in Two-Player Simultaneous Move Games. Artificial Intelligence, Vol. 237, pp. 1-40.	37
Research topic: Brain-computer interfaces and cognitive robotics [6] Benitez-Andonegui, A., Burden, R., Benning, R., Möckel, R., Lührs, M., & Sorger, B. (**2020**). An augmented-reality fNIRS-based brain-computer interface: a proof-of-concept study. Frontiers in Neuroscience, 14, 346.	5
Research topic: Signal processing [7] Cluitmans, M. J., Bonizzi, P., Karel, J. M., Das, M., Kietselaer, B. L., de Jong, M. M., Prinzen, F.W., Peeters, R., Westra, P. & Volders, P. G. (**2017**). In vivo validation of electrocardiographic imaging. JACC: Clinical Electrophysiology, 3(3), 232-242.	67
Research topic: Game theory [8] Staňková, K., Brown, J. S., Dalton, W. S., & Gatenby, R. A. (**2019**). Optimizing cancer treatment using game theory: A review. JAMA oncology, 5(1), 96-103.	71

[8] Bayer, P., Herings, P. J. J., Peeters, R., & Thuijsman, F. (2019). Adaptive learning in weighted network games. Journal of Economic Dynamics and Control, 105, 250-264.	6

Relevance to society

Among the publications listed in Table 1 are articles from DKE's interdisciplinary research lines with high relevance to society. This includes applications in fields like medicine, healthcare, neuroscience:

- With colleagues from neuroscience, we develop novel artificial neural networks models that help us to better understand neural processing in the human brain [2].
- We develop novel methods in the areas of computer vision and affective computing for assistive living, used in caregiving for elderly suffering from dementia, but also to support children with disabilities [3].
- DKE's research on cognitive robotics and brain-robot interfaces helps create the next generation of assistive robots and interfaces for patients with motor impairments, so that they can gain more autonomy and quality of life [6].
- Research in signal processing is regularly applied to cardiology [7].
- New methods from game theory are used for modelling and treating diseases like cancer [8].

Datasets, software, and (robotic) hardware

Research quality and relevance to society

In addition to developing methods and publishing articles, DKE encourages its researchers to generate and publish datasets, software, and (robotic) hardware to be used by end users and the scientific community. DKE recognizes these efforts in the recognition and reward procedures (see personnel policies, section 5). DKE supports the FAIR (Findable, Accessible, Interoperable, Usable) use of data, software, and hardware to maximize the impact of DKE's work and to make it usable by a wide community. Examples that highlight the quality of research at DKE and its relevance to society, are:

- the Ludii general game system, which DKE uses to reconstruct and understand ancient games thus making major contributions to archaeology. This is the world's most advanced general game system and is available as open source.
- a photorealistic dataset for unsupervised event detection and other computer vision challenges.
- a dataset resulting from DKE's work on "Social Emotion Mining Techniques for Facebook Posts Reaction Prediction".
- a dataset for behavior understanding and personality recognition in a non-social context relevant e.g. for assistive living and elderly care.
- Singular Spectrum Decomposition, a method for data-driven and adaptive decomposition of nonlinear and nonstationary time series. Originally developed by DKE for the analysis of brain signals within a collaboration with the Faculty of Psychology and Neuroscience, the technique was later adopted by other fields thanks to its versatility.
- ARIADNE, a software that implements rigorous numerics and allows for "mathematics through computation" by overcoming the limitations of finite precision.
- MYOKIT, a software for the simulation of models of myocytes, which is indispensable for carrying out comparisons with published models in the cardiac electrophysiology literature.
- ALLEN, a GPU framework and reconstruction software for the first stage trigger of the LHCb detector at CERN's Large Hadron Collider. Allen will be used when the detector starts taking data as of 2022.
- the Educational Modular Robotic Platform (EDMO) for education in robotics, artificial intelligence, and computer science of children, university students, and the general public. All hardware components are available as open-source material.

3.2 Demonstrable Marks of Recognition

Research quality - Marks of recognition from peers

Individual and major collaborative research grants

DKE researchers regularly acquire research grants from highly competitive funding instruments. Due to their expert knowledge and experience in high-impact interdisciplinary research, they are welcomed partners in many projects. During the evaluation period, DKE supported Dr. C. Browne in order to receive a highly prestigious €2Mio ERC Consolidator grant for his Digital Ludeme Project, wherein he aims to reconstruct and inter-relate 1,000 ancient games using artificial intelligence. DKE also successfully participates and participated in four H2020 RIA/IA projects (ICT4Life, MaTHiSiS, PROCare4Life, CoRoSect) with major contributions by DKE researchers and three H2020 projects (MindSpaces, FourCModelling, Moore4Medical) with minor DKE contributions (DKE budget below €150K) adding up to a total of about €2.9Mio of funding for DKE. For the H2020 CoRoSect project with at total budget of €8.6Mio and 19 partners, DKE is coordinator. Furthermore, DKE is coordinating the H2020 ITN EvoGamesPlus project and participates in the ITN PersonalizeAF project. DKE participates in the large-scale NWO/Gravitation project "New Science of Mental Disorders" and in the "European Network for Game Theory" (COST Action CA16228). DKE is also involved in a medium size NWO-project (SWARMPORT, Total funding: €0.9Mio), and was coordinator of a Luik 3 project (Advanced Robot-Brain Interfaces, Total funding €0.8Mio).

Awards for scientific impact

A list of awards to DKE researchers can be found in the supplementary material. For their high research quality, DKE researchers won the prestigious NWO Stairway to Impact prize, an LHCb Early Career Scientist award from CERN, five best conference paper awards, and two best poster awards. In addition, DKE researchers and their students won three international competitions on game AI as well as a Best Interactive Session (Finalist) Award in social robotics.

Memberships in scientific committees and organizations, organization of major scientific events

DKE members chair and participate in major scientific committees and organizations. DKE contributes to the ICAI network and participates in the research committee of the Platform Wiskunde Nederland, in the ICT Research Platform Nederland, in the regional AI Hub UM/Zuid as well as in the national research group AI & Mathematics. Within the IEEE Computational Intelligence Society, Prof. A. Wilbik is the vice chair of the Fuzzy Systems Technical Committee and a member of Data Mining and Big Data Analytics Technical Committee where she is also chairing the taskforce on Explainable Machine Learning. Furthermore, DKE is represented in the management teams of three major Dutch research schools: SIKS, DISC, and LNMB.

DKE regularly organizes and chairs major scientific events. Some examples of scientific events that DKE attracted to Maastricht University include:

- The 5th World Congress of the Game Theory Society and the 17th ACM Conference on Economics and Computation in 2016 ran in parallel at Maastricht University with over 900 participants, including three Nobel prize laureates, and were jointly organized by DKE and the School of Business and Economics. Prof.dr. F. Thuijsman (DKE) served as general chair.
- the IEEE Conference on Computational Intelligence and Games took place in 2018 at Maastricht University with DKE members serving in various organizational roles including Prof.dr. M. Winands (DKE) as general chair.
- the 7th Symposium on Conformal & Probabilistic Prediction with Applications from June 11-13, 2018. Dr. E. Smirnov and Prof.dr. R.L.M. Peeters (both DKE) served as general chairs.
- the 20th European Agent Systems Summer School as well as the 12th Maastricht Summer School on Data Science.

More scientific events organized and chaired by DKE members can be found in the supplementary material.

During the evaluation period, DKE researchers were invited to co-supervise more than 20 PhD candidates hired at other departments and universities. We did not count these PhD candidates in the tables in appendix A, as in contrast to our DKE PhD candidates, these PhD candidates are not officially hired by DKE and DKE does not receive any official revenues. The high number of these PhD candidates however shows that DKE's expertise is valuable and that DKE researchers are well-respected research partners.

Between 2015 and 2020, DKE researchers served in examination committees of more than 60 non-DKE PhD theses, demonstrating the recognition of DKE's expertise.

Relevance to society – Marks of recognition by societal groups

Financial and material support by stakeholders for projects with high societal relevance

IBM Research sponsors two postdocs to closely collaborate in quantum computing, a technology that has the potential to become a major game changer in certain fields of artificial intelligence and data science (see case study 2 in appendix B). Facebook sponsored a joint project on language similarities in machine translations ($200K) to improve machine translations for languages where only small datasets are available. Co-funding is also provided by end users and business partners that joined us in the H2020 innovation actions (€1.2Mio. for CoRoSect, €1Mio. for MaTHiSiS, €1.2Mio PROCare4Life). CoRoSect aims to secure sustainable food produced in insect farms. MaTHiSiS developed AI for personal learning for children with learning disabilities. PROCare4Life focusses on technologies for elderly care and assistive living.

DKE often benefits from in-kind support by end users including elderly care facilities, schools, and businesses. The Port of Rotterdam and other businesses support us in the NWO SWARMPORT project where DKE, TU Delft, and TNO teamed up to provide a better understanding of the harbour's logistics. Through the strong involvement of stakeholders and end users, DKE tries to ensure that research outputs are relevant. In for example the EDMO, SmartMaze, and MaTHiSiS projects, collaborations with schools enable the testing and improving of newly developed methods and robotic equipment. In the ICT4Life, PROCare4Life, and SmartDice projects, DKE collaborates with and benefits from the support of elderly and their caregivers. DKE's research on bioinformatics and in the biomedical field is supported by doctors and hospitals, who contribute domain expertise and data. As a partner of the Field Lab Robotics[2], DKE benefits from access to costly industrial robots, financial support of the region of Limburg, expertise of industrial partners, and space for conducting experiments and for disseminating scientific output.

Awards for societal impact

- In recognition of the impact of her work on dynamic game theory, Dr. K. Staňková won the prestigious NWO Stairway to Impact prize (worth €50,000) for her research on improving the quality of life and treatment of cancer patients[3].
- Dr. D. Cámpora won the LHCb Early Career Scientist award for co-leading the exceptional effort that allowed to deliver ALLEN, an HLT1 trigger fully implemented on GPUs.
- Dr. R. Möckel won the Impact prize at Maastricht University (worth €1000) and in 2019, the Data Science Research Proposal Award (worth €5000) with his colleagues, for research on social robotics for children and elderly.

[2] https://www.fieldlabrobotics.com/
[3] NWO Stairway to Impact prize: https://bit.ly/3ur7LRT

Memberships in committees and societies with societal relevance

DKE is active in committees and societies with two foci, which work for the betterment of our society:

- One DKE focus is to promote the responsible use of artificial intelligence, data science, and robotization. For this, we support the Dutch AI coalition[4] in the Research and Innovation committee and the Human Capital team that aims to prepare the Dutch labour market for the responsible use of AI. DKE is a member of Maastricht University's Ethical Review Committee for the Inner-City faculties. DKE is also a member of the steering committee of the Field Lab Robotics in Roermond and regularly participates in its activities. In the Field Lab, the public can learn about robotization and artificial intelligence and their impact on businesses and daily life.
- Our second societal focus is to promote equal opportunities for women in computer science and mathematics and to attract more women to these fields. Here DKE is active in the Dutch Network of Women Professors (LNVH), European Women in Mathematics as well as in the ICT Research Platform Nederland - Equity Diversity Inclusion committee.

Media coverage

The media regularly cover DKE's high-impact interdisciplinary research, as well as its work on the responsible use of AI. To provide some examples: DKE's #metoo chatbot project featured in 3 major newspapers in Spain, the Netherlands, and Belgium, as well as in an online tech magazine. DKE's chair (until 2020) Prof.dr. G.B. Weiss was interviewed on the implications of AI, on the necessity of regulation and on its societal embedding. He also wrote essays for leading German newspapers[5]. Dr. K. Stankova's Stairway to Impact award and her research on game theory to aid cancer treatment received widespread media attention including in Dutch newspaper Trouw, I/O Magazine and international media. The Digital Ludeme Project featured on MIT Tech Review and VICE, in addition to newspaper reports in national media.

3.3 Demonstrable Use of Research Products

Research quality - Use of research products by peers / Relevance to society – Use of research products by societal groups

We consider citation numbers of DKE research articles and the use of datasets, software, and hardware being made available by DKE researchers as indicators of the use of research products by peers and end users.

Citation of articles

According to Google Scholar, DKE researchers were cited 856 times on average between 2016 and August 2021 (median: 617). This average takes into account senior and junior researchers at DKE, including assistant professors, but excludes PhD students. The 10 DKE researchers with the most citations between 2016 and August 2021 reached 1494 citations on average (median 979). It must be noted that all DKE researchers are free to publish with or without their line managers. Thus, at DKE there are no central P.I.s who would benefit from high citation numbers due to a large pool of junior researchers adding them as co-authors on their publications.

Overall, the citation numbers show that DKE research is valuable and considered worth citing. Several publications from the evaluation period received relatively high numbers of citations, thus illustrating the

[4] https://nlaic.com/

[5] Example of expert opinions are https://www.sueddeutsche.de/wirtschaft/samstagsessay-ki-als-schulfach-1.4573491?view=overlay and https://zeitung.faz.net/faz/wirtschaft/2019-12-16/dc7fe7bb60c18e4997ec7f28df5810cb/ and an example of an and interview is https://maastrichteurope.nl/made-in-europe-has-the-potential-to-become-a-very-valuable-quality-label-for-ai-says-gerhard-weiss/

scientific impact of DKE research. For example, the article by Kroner et. al (Table 1) already received a remarkable number of 35 citations in less than one year. Some of DKE's Q1-journal articles published between 2015 and 2020 reached more than 60 citations by August 2021.

Use of datasets, software, (robotic) hardware

DKE tries to avoid hiding datasets, open-source software and hardware behind virtual registration walls that might repel potential end users. As a result, we often do not keep track of the use of these research outputs. However, some examples reveal part of the reach of DKE research products:

- The official website for the Ludii software application and dataset has been viewed over 125,000 times since its launch two years ago, with more than 8,000 accesses of its download point, and the open source Ludii code base on GitHub has been cloned more than 2,400 times.
- The original research article for the Singular Spectrum Decomposition algorithm for the adaptive and data-driven decomposition of nonlinear and nonstationary time series counts 64 citations to date.
- The original research article featuring the dataset and work on "Social Emotion Mining Techniques for Facebook Posts Reaction Prediction", published at ICAART 2018, counts 42 citations to date.
- The software package MYOKIT for the simulation of models of myocytes has already been used in research and education in 13 different institutes located on 5 continents.
- The GPU framework ALLEN will be used by the Large Hadron Collider beauty experiment at CERN.
- Two Dutch schools started exploring the use of DKE's EDMO robots for STEM education of children. DKE's smart dice are explored by a kindergarten and an elderly home.

3.4 Conclusions

DKE's research is highly relevant for society, as holds true for artificial intelligence and data science in general. Within these areas, DKE's strategy of focussing on the development of methods while teaming up with stakeholders (e.g. businesses and end users) and researchers from other disciplines sets DKE up for a wide spectrum of high-impact applications. In the past years, DKE has successfully extended its collaborations while making significant contributions to computer science, artificial intelligence, data science, their mathematical foundations and robotics, facilitating interdisciplinary research in the Biomedical and healthcare areas, at the intersection of archaeology and games, as well as in neuroscience, physics, logistics, and industry. As a result, DKE is well recognized by its peers, its partners, and by the public.

4 PHD POLICY AND TRAINING

This section describes the policies and support structures that DKE provides for high-quality PhD training and supervision.

4.1 PhD training, supervision, and support

DKE PhD candidates are treated as staff members and colleagues. They are trained to become independent researchers. DKE is committed to providing our PhD candidates with a stimulating environment where PhD candidates can develop their talents, and where they are prepared for a successful career both inside and outside academia.

DKE PhD candidates receive training and support from their supervision team, within their research area groups, from the FSE STEM graduate school (since 2020), as well as from the national research schools SIKS, DISC, and/or LNMB. Training and supervision are targeted towards the individual situation and needs of PhD candidates. DKE researchers (co-)supervise PhD candidates of several categories, including PhD candidates who are on DKE's payroll but also PhD students who are enrolled at other departments or universities, who work for companies, or who receive a scholarship.

All DKE PhD candidates are supervised by a team of researchers to ensure high-quality supervision and to guarantee that PhD candidates can turn to several DKE colleagues for advice. The **supervision team** provides guidance and freedom for the PhD candidate to develop into an independent researcher. To ensure professional supervision, at least one senior researcher must be present in the supervision team alongside the daily supervisor(s) with expert knowledge on the PhD candidate's research. This senior researcher provides managerial support and advice, and guides the PhD candidate in their career development.

In addition, DKE PhD candidates are embedded in at least one **DKE research area group**. Here the PhD student gets inspired by and exposed to other DKE research projects, which ensures that the PhD candidate is not only focused on their own topic. Research groups help candidates to test their research ideas, to practice communicating these ideas, and to deal with constructive feedback from peers outside the candidate's supervisory team.

Furthermore, many DKE PhD candidates are integrated in large-scale projects (e.g., H2020 ITN, RIA, IA projects) where they work closely with a network of national and international partners.

Since 2020, our Faculty of Science and Engineering (FSE) features the **FSE STEM graduate school**. DKE is actively involved in this school and helps to build and develop it. Since 2020, DKE enrols all its PhD candidates, unless a candidate is officially registered at another faculty. The FSE graduate school provides training through courses and events like annual PhD conferences and thus offers valuable opportunities for PhD candidates to connect with colleagues from other departments and disciplines.

The FSE graduate school's monitoring and feedback includes biannual progress evaluations, which are organized between the PhD student and supervision team, as well as online questionnaires where PhD students can provide feedback to the **PhD counsellor**. The PhD counsellor supports the PhD candidate in case of conflict. In addition, the monitoring approach uses a **professional training and supervision plan** and a **personal research plan**. These plans are developed within the first 8 weeks of the PhD project by individual PhD candidates and their supervisory team. Both plans are evaluated biannually and can be updated according to the progress of the PhD project and candidate's development. The training and supervision plan identifies required training, assessment criteria, and obligations of the PhD candidate as well as the supervision team. The personal research plan notes long-term and short-term research goals as well as a work plan.

In addition to the FSE STEM graduate school, DKE supports three **national research schools**: in computer science (SIKS), in systems and control theory (DISC), and in mathematics for operations research (LNMB). DKE PhD students typically enrol in (at least) one of these national research schools according to their research profile. The schools allow them to meet other junior and senior researchers (also outside Maastricht University) and to help them build a research network. Each graduate/research school offers a full curriculum of PhD-level courses with credit points, taught by research experts in the field. DKE staff is also involved in lecturing courses at these schools. The schools organize winter and summer schools, with dedicated research themes and international expert speakers, as well as annual conferences at the level of the Benelux.

4.2 PhD duration and success rates

PhD enrolment and success rates for the period 2012-2020 can be found in Table A.6 (Appendix A). The table covers only PhD candidates who are enrolled at DKE and who will defend their thesis at Maastricht University.

From the 13 PhD candidates enrolled at DKE between 2012 and 2016, none defended within 4 years + 3 months. 3 candidates (about 23%) defended within 5 years, and 7 candidates (about 54%) had ongoing PhD projects on December 31st, 2020. Thus, DKE has not yet met its goal to have a majority of PhD candidates graduate in 4 years + 3 months. This is also partially due to COVID-19 and partially because some PhD-students supported education for strongly increasing student numbers.

PhD candidates on DKE's payroll are appointed for a fixed term of generally four years (a one-year appointment followed by a subsequent appointment for the remaining period). Committed candidates who get delayed often receive contract extensions mostly combined with part-time teaching obligations. Our faculty and university also provided additional funds to extend contracts of PhD candidates who suffered from delays due to COVID-19. However, contracts of candidates who join DKE with a scholarship (e.g., from the Chinese Scholarship Council) typically cannot get extended due to contractual obligations that come with the scholarship.

Since 2017 DKE continuously works on improving policies, and on building additional supervision support and training for PhD students and supervisors to reduce the duration of PhD projects while maintaining high research standards. Among others, these efforts have resulted in the aforementioned FSE STEM graduate school, which provides additional support for DKE PhD students and tools for the monitoring of PhD progress, as well as the policy to include senior researchers on each PhD supervisory committee. We are creating more awareness among DKE staff for early career support and talent development.

We are proud that DKE PhD candidates typically defend theses of high quality. Many DKE PhD candidates co-author high-quality journal and conference publications. Some of them win awards, such as Dr. M. Cluitmans, who also continues his research lines with an NWO VENI grant. Dr. M. Clerx went as postdoc to Oxford University and is now a Senior Research Fellow at Nottingham University. Two PhD graduates from the evaluation period, Dr. K. Schüller and Dr. C. Sironi, stayed at DKE as lecturer and postdoc respectively and are planning long-term careers at our department. In general, all DKE PhD graduates quickly find jobs in academia or in industry.

5 WORKING ENVIRONMENT AND PERSONNEL POLICIES

As part of Maastricht University, DKE research staff must adhere to the Netherlands Code of Conduct for Research Integrity[6]. A professional research integrity and diversity[7] setting has been established at university level. DKE is fully embedded in this setting and has established structures and policies to promote and safeguard good research practice as well as an open and safe working environment for all DKE staff. DKE supports the open science ambition of Maastricht University[8], including its ambition to become to become a FAIR university by 2023.

5.1 Diversity

DKE actively follows hiring and talent development procedures that promote diversity in our community. Table A.3. from Appendix A provides an overview of the diversity of gender and nationality of DKE's research staff, and Table A.4. an overview of the age distribution of scientific staff at DKE in 2020. DKE is proud to be a truly international community. The DKE community includes staff from 25 nationalities when PhD candidates and postdocs are included. 79% of DKE's scientific staff members and 86% of DKE's postdocs and PhD candidates are non-Dutch. During the evaluation period, DKE made significant progress in gender balance among tenured and tenure-track research staff, including in the DKE management team. This shows that policy changes and efforts to attract more female staff take effect: In 2015, female researchers represented less than 10% of the total scientific staff. There were no female Full or Associate Professors. In 2020, 21% of DKE's research staff members, 33% of DKE's Full Professors and 29% of DKE's Postdocs and PhD candidates are female. Three out of eight members of the DKE management team are female. The management team is also diverse regarding the ages of its members, with 1-2 members in each age group above 31 (Table A.4). The majority of DKE's scientific staff (55%) is aged between 31-40.

[6] http://www.vsnu.nl/files/documents/Netherlands Code of Conduct for Research Integrity 2018.pdf
[7] https://www.maastrichtuniversity.nl/about-um/diversity-inclusivity
[8] https://www.maastrichtuniversity.nl/research/open-science

DKE's success in hiring international staff lies partially in its educational programmes that are taught entirely in English, but also in the fact that the DKE community embraces diversity and offers an inclusive community. DKE's success in attracting more female staff members is also due to changes in DKE's hiring procedures. Thanks to our communications officer and managing director, job advertisements are phrased in a more gender-neutral way, contributing to more applications and hires of highly qualified female researchers.

5.2 Openness, (social) safety and inclusivity:

To support safe and inclusive working environments, DKE implemented and promotes a management structure with flat hierarchies, transparent policies, and open communication. There is an open-door policy at DKE that encourages all DKE colleagues to talk directly with any member of the management team. DKE colleagues can choose which member of the management team they prefer to approach with problems and suggestions and benefit from a diverse management team (see section 5.1) that is involved in all decisions. In addition, all DKE members can talk to their direct line managers and are embedded in one or multiple research area groups. Further communication happens through regular staff meetings and retreats that are used for team building, open problem discussions, and training. DKE has a blame-free open communication culture, where DKE members can communicate openly about problems and ideas without fearing negative consequences e.g. for their careers. DKE facilitates career building and promotion policies that aim to facilitate community building (section 5.4).

DKE benefits from being embedded in professional settings for social safety and inclusivity at Maastricht University and our Faculty of Science and Engineering. Both at the university and faculty level, DKE colleagues can find further support[9]. In addition to providing contact points where problems can be reported, Maastricht University offers workshops and training to support working in an international environment and to promote healthy and secure work environments. DKE supports these workshops and encourages DKE colleagues to join them.

5.3 Research integrity

As mentioned, DKE staff must adhere to the Netherlands Code of Conduct for Research Integrity. Since we are working with sensitive data including human video and voice recordings and medical data, DKE is aware of its responsibilities and determined to follow the highest standards of research integrity. DKE is also fully aware of its responsibility and the societal impact of its research in artificial intelligence, data science, and robotics. We promote the responsible use and development of artificial intelligence, data science, and robotics within DKE, Maastricht University, and society. Discussions in the Dutch parliament on the #MeToo-chatbot developed at DKE show that we are being closely watched by society. DKE's chair (until 2020) Prof.dr. G.B. Weiss published several essays on the implications of AI, its necessary regulation, and its societal embedding. He is also a member of the Ethics Review Committee Inner City faculties, an interdisciplinary team of experienced researchers that evaluates research studies regarding ethical concerns. DKE strongly encourages all DKE researchers to conduct any studies with human participants and personally identifiable data only if the study received approval from the Ethics Review Committee. In 2020, DKE appointed a chair in Explainable Artificial Intelligence to further strengthen research and awareness for the responsible development and use of artificial intelligence.

DKE started to facilitate policies to encourage the FAIR (findable, accessible, interoperable, and reusable) distribution of research results, including publications, data, software, and hardware. DKE encourages all of its researchers to publish open access whenever possible, and is grateful for the efforts of the Association of Universities in the Netherlands (VSNU) that negotiated open access publishing opportunities with major scientific publishers. DKE shares Maastricht University's ambition to become a FAIR university by 2023. DKE supported the 2017 founding of, and collaborates with, Maastricht University's Institute of Data Science that

[9] https://www.maastrichtuniversity.nl/about-um/diversity-inclusivity

specialises in FAIR data and software. DKE benefits from the Institute of Data Science as well as from Maastricht University's library, who built and continuously improve infrastructure for secure computing and research data management[10].

DKE has many examples of high-impact datasets, software, and (robotic) hardware that DKE researchers made publicly available (section **Fehler! Verweisquelle konnte nicht gefunden werden.**). However, not all DKE research output follows all FAIR principles. E.g. preparing and maintaining the necessary documentation to be fully compliant with all FAIR principles is often not possible for researchers due to time constraints. Further efforts will be required to achieve the ambitious goals that we share with our university and faculty.

5.4 Talent Management

DKE strongly supports the efforts of the Association of Universities in the Netherlands (VSNU) to increase the number of permanent contracts at Dutch universities also for early and mid-career researchers (see e.g. the most recent Collective Labour Agreement of Dutch Universities (CAO-NU) valid from 1 January 2021) and tries to avoid unnecessary short-term employments. We e.g. select and hire talented postdocs typically with the idea in mind that they would become assistant professors at our department.

DKE also strongly supports Maastricht University's efforts to establish new and transparent recognition and reward criteria that give room for a diversity of talents and evaluate more than just the currently predominant quantitative measurement of research output. Part of DKE's and in general Maastricht University's HR and talent management policy are annual evaluation and appraisal meetings between DKE staff members, their line managers, and where useful additional advisors e.g. from HR. These meetings aim at transparent communication and at formulating precise agreements on the short and long-term plans of the employee, as well as the obligations of DKE and the evaluated staff member. Criteria for promotion can be discussed as well as training opportunities. Training is offered by DKE but also by Maastricht University's Staff Career Centre, Institute for Education Innovation (EDLAB), Language Centre, and by the Maastricht Young Academy in particular also for early-career researchers. Agreements are typically tailored to the individual situation of the employee, while DKE's requirements are openly discussed and simultaneously taken into account. Agreements and criteria are set on an individual basis and, if necessary, can be revised again in a future evaluation if the employee's situation or priorities change.

To stimulate constructive leadership and teamplay, DKE established and communicated policies that reward colleagues engaged in community building and who support DKE in creating an open, inclusive working environment. As a result of these policies, a few colleagues who focus on their own research career and visibility mostly, left DKE to take other positions over the past years. DKE policies are also set to limit the power of individual DKE staff members: e.g., DKE is led by a team. The chair of DKE can only serve two consecutive terms of 3 years. This limitation of terms stimulates teamplay and allows DKE staff members to train and demonstrate their management skills in various positions.

DKE researchers are not alone, but are embedded in the DKE community that supports them in developing their talents. Many of DKE's early-career researchers are supported by informal DKE mentors. All DKE researchers are supported by experienced line managers. Furthermore, DKE researchers also benefit from additional support and training by our communications officer (helping with research dissemination), business developer (helping with business contacts and public-private partnerships), project officer (helping with research proposals), and education development officer (regarding education). They are further supported by a managing director and by our management team.

[10] https://library.maastrichtuniversity.nl/research-support/rdm/

5.5 Conclusions

DKE is well aware of its responsibilities towards its employees, students, research community, and society. The department embraces diversity and encourages all of its members to follow the highest ethical standards and to help create a workspace that is safe, respectful of individual needs, and inclusive. DKE creates an atmosphere of team spirit and strives to lead by example through its senior members, who are approachable by all DKE colleagues. DKE knows that maintaining such an open environment requires continuous efforts from all and considers this environment highly valuable and worth the effort.

6 STRATEGY FOR THE NEXT SIX YEARS

In this section a SWOT analysis of the current research situation at DKE is provided (Section 6.1). Next, the strategy for the coming years is described (Section 6.2).

6.1 SWOT analysis

6.1.1 Strengths

A key strategy and strength of DKE is that we target high-impact applications together with partners while DKE researchers **focus on the development of novel methods**. This strategy allows us to build expertise in a variety of applications while focusing our research on methods that are widely applicable.

DKE is active in a **broad range of high-impact research topics** within areas of computer science, artificial intelligence, data science, robotics, and their mathematical foundations, which allows DKE to target collaborations with a variety of applications of high societal relevance. Within its broad research portfolio, DKE also benefits from strong expertise in the **mathematical foundations of AI, data science, and computer science,** such that DKE can also target more recently emerging high-impact research fields around reliable and explainable AI.

At DKE we grow research and education hand in hand, as we see both mutually benefiting from each other. A continuous parallel growth in research and education allows DKE to **grow in a sustainable, viable way** where sudden disruptions in the funding landscape do not trigger financial disruptions, where **long-term contracts and personal development plans can be offered to talented researchers**, and where DKE research benefits from the young talents we train in our educational programmes.

DKE is a team of **highly committed and talented staff members** who maintain high quality of research and education. Due to the team effort of its staff, DKE managed to continuously grow its research FTE and overall staff numbers despite facing challenges like COVID-19. Due to the openness and fairness of its staff, DKE manages to maintain a **strong, open, and inclusive academic community** that meets the diverse needs of its members.

Within Maastricht University, within our Faculty of Science and Engineering, and within the Dutch community, DKE is embedded in a strong academic community with a **professional research integrity, diversity, and HR setting**. Within this setting, DKE develops and implements guidelines and policies together with its staff members and stakeholders.

6.1.2 Weaknesses

While DKE's research **visibility** (within Maastricht University, and at the national and international level) and **funding** acquisition has continuously increased over the past years, there is still room for further improvement. To gain more visibility, DKE is integrating into strategically important networks and actively approaches potential partners. DKE continues growing its efforts in talent development and staff training to help DKE researchers approach strategically important partners and attract funding for additional collaborations.

We consider the **broadness of the research topics** at DKE strategically important (see strengths) and necessary to provide the broad expertise required to cover DKE's educational programmes. However, at DKE's current size, one might argue that a stronger focus into fewer research topics might allow DKE to gain more visibility and impact in these fewer focus areas. DKE is counteracting this weakness by following a strategy of sustainable growth with focus as laid out in section 6.2.

DKE's staff is experiencing a **high workload** because of extensive teaching and organisational duties. Research time for most DKE researchers is scattered and limited. The COVID-19 pandemic has added substantially to this workload. To counteract some of the causes for high workload, DKE has taken several actions, in particular: (1) With funding from the sector plans and the support of Maastricht University and our faculty, DKE has invested in new staff. (2) Management tasks have been distributed among more colleagues. (3) A norm-hour system for educational tasks has been introduced to better balance teaching duties.

DKE is not satisfied with **current durations of PhD trajectories** and is committed to reaching a standard PhD trajectory duration of 48+3 months. As explained in section 4, in the past years new structures and policies were implemented that help us reduce the duration of PhD trajectories at DKE while maintaining high quality.

With DKE growing, we realise that DKE must start **formalising policies and guidelines** in writing. In the past, questions and advice regarding policies and guidelines could be handled over a coffee break or by simply approaching a senior DKE staff member at any time. This is not always possible anymore with DKE's increasing size. DKE has started identifying policies and guidelines to be formalized.

6.1.3 Opportunities

Opportunities for DKE arise e.g. through the highly stimulating multi-disciplinary research environment within our **Faculty of Science and Engineering** and within **Maastricht University**. Partners with whom we aim to further intensify research collaborations include but are not limited to the Institute of Data Science, Maastricht Centre for Systems Biology, Physics (e.g. ETpathfinder), the Faculty of Psychology and Neuroscience, the School of Business and Economics, the Faculty of Health, Medicine and Life Sciences, and the academic hospital Maastricht UMC+.

DKE is building several **Public-Private Partnerships** and is actively exploring opportunities to establish ICAI labs at Maastricht University. DKE is situated in Limburg, an area that is populated with many innovative companies that would benefit from the expertise of DKE specifically in artificial intelligence, data science, and robotics. DKE is involved in a variety of national and regional networks (e.g., Dutch AI coalition, Big Data Alliance, Brightlands Smart Services Campus, Regitel, Field Lab Robotics) and in contact with global players to establish and to intensify mutually beneficial partnerships. Through its honours programme KE@Work, started in 2014, DKE has been collaborating with over 40 regionally based companies on student projects. With some of these companies research contracts are currently being explored.

National and European Funding instruments (e.g. from NWO and Horizon Europe respectively) represent important opportunities for DKE to attract more research funding and to allow DKE staff to free up time for research. We also see these public funding instruments as a strong opportunity to **intensify our collaborations with other Dutch universities**.

Being located closely to the German and Belgium border, DKE is also an attractive partner for **cross-border partnerships**. Cooperations have been established e.g. with the RWTH IT Center in Aachen (Germany) and Hasselt University (Belgium). Discussions to intensify research collaborations with the RWTH and FH Aachen are ongoing.

6.1.4 Threats

While growing in a sustainable way, DKE faces the threat of a **lack of talented and highly qualified staff on the job market**. In the past, this lack of candidates for open positions often led to time-intensive hiring procedures where open positions had to be advertised several times before suitable candidates could be found. This threatens the continuous growth of DKE. Like other Dutch computer science departments, DKE faces a high competition on the job market where private businesses can often offer better conditions and where Dutch and international universities try to attract each other's talented researchers. With its high-quality educational programmes and PhD projects, DKE contributes to the education of young research talents. However, it will take a joint national effort to satisfy the demand for computer science experts in the Netherlands.

A possible future saturation or reduction of student numbers poses a threat to DKE's growth. In recent years, we saw increasing competition with other universities in the Netherlands, Germany, and Belgium that are establishing new educational programmes in artificial intelligence and data science. Demographic changes are expected to lead to intensified competition for students. Also, priorities of businesses and society might shift again in the future to other domains e.g. Internet of Things, cybersecurity, quantum computing, and cognitive robotics. As mitigation we are looking to expand into other educational programmes and target a diversification of our educational and research portfolio.

6.2 Strategy

To achieve the strategic aims described in section 2.1, DKE will continue to follow its team-based approach. As part of this, DKE develops new policies and structures under leadership of its management team and in close collaboration with DKE staff members and partners at our faculty and university. DKE continues to maintain an attractive, open, inclusive, and diverse culture for all employees. We will keep teaming up with our university and faculty to offer additional training for DKE researchers, PhD students, and management in order to generate more awareness, knowledge and support for topics such as high-quality PhD supervision, open science, and FAIR research output.

DKE is in the process of formalising policies. Following the continuous growth of DKE, we find this necessary to maintain transparency and to keep all staff well informed. During the formalisation process we take care to allow sufficient flexibility to maintain our inclusive work environment and to allow us to flexibly react to situations of individual staff members.

Finally, DKE is determined to use the current research evaluation to identify points for further improvement. We will use the feedback to form an advisory board of experts to help us in our future development.

6.2.1 High-impact open science and viability

DKE will continue to focus its research efforts on a broad spectrum of high-impact methods within the areas of computer science, with a particular focus on artificial intelligence, data science, robotics, and their mathematical foundations. In the coming years, DKE will retain its focus on methods in which DKE already has a strong track record. These methods include rigorous methods for reliable artificial intelligence (AI) and data science, signal processing, multivariate data analysis, robotics and control, game theory, game AI, search techniques, explainable AI and machine learning, natural language processing, computer vision, artificial neural networks, and high-performance computing. DKE will further invest into quantum machine learning and remains open to additional high-impact investments. Following an internal SWOT analysis early 2021, DKE is updating its research structure into six research area groups: algorithms, systems and control, games, explainable AI, cognitive systems, and quantum computing. The update brings together DKE researchers working on similar methods and integrates researchers with experience in funding acquisition in all research teams. This will help DKE to continue and strengthen its efforts to attract research funds from the Horizon Europe and NWO programmes as well as public and private partners.

DKE will also continue to team up with partners to demonstrate newly developed methods on applications with high societal impact. To increase visibility and research funding, DKE continues to strengthen and extend its network of partners while focusing on high-impact applications in areas such as biomedical sciences, healthcare, neuroscience, physics, and law, as well as smart industry, logistics, and agriculture. Knowing that DKE can offer highly demanded research to businesses, DKE is determined to use more of its potential for engagements in public-private partnerships. To help DKE's research staff in the process of building business networks and contracts, DKE hired a professional business developer in 2021. Furthermore, DKE collaborates with Maastricht University's Brightlands Institute for Smart Society (BISS), connecting itself to the Brightlands Campuses in Limburg. Since 2021 DKE even has an office at the Brightlands Smart Services Campus.

DKE intends to continue growing its research areas and educational programmes in parallel. With the support of Maastricht University and our faculty, DKE targets a diversification of its research and educational portfolio in the areas of computer science, cognitive robotics, and quantum computing.

Finally, DKE is determined to intensify its engagement in the responsible use of artificial intelligence and data science, as DKE is convinced that all AI and data science researchers have a particular responsibility towards our society.

6.2.2 PhD Policy and Training

DKE is committed to providing its PhD candidates with a stimulating and safe working environment and continues its efforts to reduce the average duration of PhD projects. We intend to improve PhD supervision and monitoring in close collaboration with our faculty, while keeping our focus on training open-minded, independent researchers. DKE has invested into new research computing infrastructure, supervision policies, and ongoing support of the newly created FSE STEM graduate school and monitoring infrastructure to accelerate PhD projects. We expect to see the effect of these investments in the coming two years.

6.2.3 Academic Culture and Human Resources Policy

DKE continues its efforts to maintain an open and inclusive working environment that embraces diversity. For this, DKE maintains its open communication culture where DKE colleagues can reach out to each other and communicate openly without fear of negative consequences. DKE management remains approachable by all colleagues for suggestions and problems. DKE embraces diversity and commits itself to sustaining its attractive work environment, wherein colleagues with diverse talents and backgrounds can grow their talents, progress in their career, contribute to our community, and are rewarded for their work and commitment. DKE continues to promote and to hire highly qualified team-players who, like DKE, support an open and diverse community.

DKE is determined to continue its efforts to attract and to train more highly qualified female researchers also through its HR policies. DKE aims to attract more female researchers by raising awareness of the importance of diversity among DKE staff and by phrasing job advertisements in a gender-neutral way. This is in line with best practices as suggested by an IPN study on the recruitment, onboarding and promotion of women in computer science[11].

To remain attractive for early-career researchers, DKE expands its talent development efforts for early-career researchers including PhD students and postdocs. DKE focusses on efforts to scout talent early and to offer early-career researchers attractive long-term career tracks. and the department is also aligning its mentoring with the recognition and reward policies. Many DKE early-career researchers are supported by informal DKE mentors.

[11] M. Huisman, A. Serebrenik: Women in Dutch Computer Science: Best Practices for Recruitment, Onboarding and Promotion (May 2021), https://ict-research.nl/edi-working-group/outcomes/

7 SUMMARY

The Department of Data Science and Knowledge Engineering (DKE) of the Faculty of Science and Engineering (FSE) of Maastricht University (UM) undertakes high-impact research in computer science, artificial intelligence, data science, robotics, and their mathematical foundations. Within these areas, DKE focusses on novel widely applicable methods. DKE consists of team players and contributes to regional, national, and international projects, where DKE successfully applies its research to high-impact applications – such as assistive technologies, healthcare, logistics and industry – in collaboration with end users and partners. DKE's research supports innovation in Dutch businesses and society, and improves overall quality of life.

DKE is aware of its responsibilities and promotes the responsible use of artificial intelligence and data science, and follows the highest standards of research integrity. DKE is visible: mainstream media regularly cover high-impact research and contributions to the responsible use of artificial intelligence and data science.

In addition, DKE researchers are well recognized by their peers. DKE researchers:

- regularly publish high-quality peer-reviewed articles in scientific journals and conference proceedings in areas such as Game AI, Game Theory, Machine Learning, Signal Processing, Bioinformatics, Computer Vision, Natural Language Processing, Affective Computing, Algorithms, Cognitive Robotics, and High-Performance Computing.
- regularly win awards for their research and high-impact contributions, such as personal, best paper, and best poster awards. The same applies to DKE students.
- regularly win and participate in various prestigious national and European research grants.
- are well-connected, participating in national and international networks, and strengthening Maastricht University's research ecosystem.
- organize and chair major international scientific events in collaboration with colleagues.

DKE is a strong community and is committed to providing all employees with a simulating, safe, and inclusive environment. DKE embraces diversity and actively follows hiring and talent development policies that promote diversity and responsibility both towards this community and towards society.

DKE follows a sustainable growth approach. In the future, we remain determined to continue growing our research and high-quality educational programmes in parallel, so that we may keep serving Dutch society with high-impact research and applications and so we can provide new generations of talented researchers. To strengthen our relevance further we diversify our portfolio and respond actively to the highly dynamic research areas of artificial intelligence and data science.

We remain a strong partner for society, our Dutch and international partners, and our university. Also in the future, DKE will continue strengthening Maastricht University's local ecosystem by contributing to the Brightlands campuses and by bringing innovation to local businesses and public partners in the region of Limburg. DKE continues to strengthen its Dutch and international networks such as the Dutch AI coalition and its partnerships with the other Dutch universities. In the past 5 years, DKE strategically invested into new research infrastructure and four new full professorships in areas with high societal impact such as explainable artificial intelligence, data fusion and intelligent interaction, machine reasoning, and strategic optimization. Through these new professors growing these research areas at DKE, new partnerships with global players and local partners, new large-scale projects, and strategic investments into techniques such as quantum computing that have the potential to become game changers, DKE is determined to remain a key player in the national and international artificial intelligence and data science landscape and to keep increasing its impact.

APPENDIX A: TABLES

Table A.1: Choice of indicators (Table E1 in the SEP)

		Quality domains	
		Research quality	**Relevance to society**
Assessment dimensions	**Demonstrable products**	*1. Research products for peers* Peer-reviewed articles in journals and conference proceedings Datasets, software, and (robotic) hardware	*4. Research products for societal target groups* Peer-reviewed applied and interdisciplinary publications Datasets, software, and (robotic) hardware
	Demonstrable use of products	*2. Use of research products by peers* Citations of articles Datasets, software, and (robotic) hardware	*5. Use of research products by societal groups* Citations of applied and interdisciplinary publications Datasets, software, and (robotic) hardware
	Demonstrable marks of recognition	*3. Marks of recognition from peers* Individual and major collaborative research grants Awards Memberships in scientific committees and organizations, organization of major scientific events	*6. Marks of recognition by societal groups* Financial and material support by stakeholders for projects with high societal relevance Awards Memberships in committees and societies with societal relevance Media coverage

Table A.2: Research staff (Table E2 in the SEP)

	2015	2016	2017	2018	2019	2020
Full professor	2 / 0.7 FTE	3 / 0.9 FTE	3 / 1.1 FTE	3 / 1.1 FTE	4 / 1.1 FTE	6 /1.6 FTE
Associate professor	4 / 1.8 FTE	3 / 1.4 FTE	4 / 1.5 FTE	8 / 3 FTE	10 / 3.5 FTE	11 / 4.7 FTE
Assistant professor	15 / 7.2 FTE	16 / 7.3 FTE	17 / 7.6 FTE	17 / 7.3 FTE	14 / 6.4 FTE	16 / 7.2 FTE
Total scientific staff	**21 / 9.7 FTE**	**22 / 9.6 FTE**	**24 / 10.2 FTE**	**28 / 11.4 FTE**	**28 / 11 FTE**	**33 / 13.5 FTE**
Postdocs (incl. researchers)	2 / 1.8 FTE	4 / 2.7 FTE	3 / 2.7 FTE	4 / 3 FTE	7 / 3.8 FTE	10 / 6.4 FTE
PhD candidates	14 / 12.4 FTE	14 / 13.5 FTE	15 / 14.5 FTE	17 / 16 FTE	13 / 12 FTE	11 / 10.5 FTE
Total PD + PhD	**16 / 14.2 FTE**	**18 / 16.2 FTE**	**18 / 17.2 FTE**	**21 / 19 FTE**	**20 / 15.8 FTE**	**21 / 16.9 FTE**

The table above counts staff at DKE on December 31st of the respective year and research FTE accumulated over the respective year. The table counts staff with an appointment of more than 0.2 research FTE only. Thus, lecturers at DKE whose research time is labelled to 0.2 FTE and all non-research staff are not counted. When staff has been promoted or new staff has been hired, research FTE have been counted only for the months the staff was at DKE. Thus e.g. there are 3 full professors counted at DKE on December 31st in the years 2016 and 2017. However, the research FTE for the respective years vary as an associate professor has been promoted to full professor during the year 2016 and thus in 2016 the corresponding research FTE of this staff member are distributed over the two categories “Associate professor” and “Full professor”.

Research FTE are calculated from a research factor, shown in Table A.2a below, in proportion of time labelled to research, for each indicated academic position (in Dutch: “UFO-profiel”), as used at DKE.

Table A.2a: Research factor to estimate research FTE of DKE researchers

	Research factor
Full professor (HGL)	0.35
Associate professor (UHD)	0.45
Assistant professor (UD)	0.50
Post-doc (onderzoeker)	0.90

The factors in the table above have been set by DKE management and are used as multipliers to compute the available research FTEs from the amount of scientific staff positions. They are consistent with previous DKE self-evaluation reports on education and research.

Next to performing actual research, research time also includes activities such as: grant writing, PhD student supervision, conference and workshop organisation, paper and proposal reviewing.

Table A.3: Diversity of research staff: Gender and nationality

	2015				2016				2017				2018				2019				2020			
	Female		Male		Female		Male		Female		Male		Female		Male		Female		Male		Female		Male	
	NL	int	NL	int	NL	int	NL	int	NL	int	NL	int	NL	int	NL	int	NL	int	NL	int	NL	int	NL	int
Full Professor			1	1			2	1			2	1			2	1			3	1		2	3	1
Associate Professor (UHD)			4				3				3	1			3	5		1	4	5		1	4	6
Assistant professor (UD)		2	4	9		2	4	10		3	4	10		3	4	10		2		12		4		12
Total scientific staff		**2**	**9**	**10**		**2**	**9**	**11**		**3**	**9**	**12**		**3**	**9**	**16**		**3**	**7**	**18**		**7**	**7**	**19**
Postdocs (incl. researchers)			1	1		1	1	2		1		2		1		3		2	1	4		2	1	7
PhD candidates		6	2	6		7		7		7		8		6	2	9		4	2	7		4	2	5
Total PD + PhD		**6**	**3**	**7**		**8**	**1**	**9**		**8**		**10**		**7**	**2**	**12**		**6**	**3**	**11**		**6**	**3**	**12**

The table above counts staff from December 31st of the respective year. The table counts staff with an appointment of more than 0.2 research FTE only. Thus, lecturers at DKE whose research time is labelled to 0.2 FTE and all non-research staff are not counted. As a result, in 2020 two female Dutch, one female Belgium, and one male Dutch lecturer at DKE are not shown in the table above.

While we recognize that there are other categories than male and female to describe gender, we have decided not to ask our staff with what gender they identify themselves most, for privacy reasons.

Table A.4: Diversity of research staff: Age distribution of scientific staff in 2020

	21-30	31-40	41-50	51-60	> 60
Full professor	0	2	1	2	1
Associate professor (UHD)	0	4	3	1	3
Assistant professor (UD)	0	12	3	1	
Total Scientific staff	**0**	**18**	**7**	**4**	**4**

The table above counts staff from December 31st of the respective year. The table counts staff with an appointment of more than 0.2 research FTE only. Thus, lecturers at DKE whose research time is labelled to 0.2 FTE and all non-research staff are not counted.

Table A.5: Funding and expenditure (Table E3 in the SEP)

Amounts x € 1.000	2015	2016	2017	2018	2019	2020
Funding:						
research						
direct funding		€279 / 7%	€403 / 10%	€430 / 8%	€432 / 8%	€420 / 6%
research grants	€419 / 10.8%	€508 /13%	€484 / 12%	€681 / 13%	€616 / 11%	€790 / 11%
contract research	€13 / 0.3%					€66 / 0.9%
other	€74 / 1.9%	€65 / 2%	€56 / 1%	€61 / 1%	€38 / 1%	€4 / 0.1%
total research funding	**€506 / 13%**	**€852 / 22%**	**€943 / 24%**	**€1,171 / 23%**	**€1,086 / 20%**	**€1,279 / 18%**
education						
funding	€3,372 / 87%	€2,985 / 78%	€3,061 / 76%	€3,914 / 77%	€4,293 / 80%	€5,997 / 82%
Total funding	**€3,878**	**€3,837**	**€4,004**	**€5,085**	**€5,379**	**€7,276**
Expenditure:						
personnel costs	€2,654 / 77%	€2,897 / 77%	€3,284 / 78%	€3,874 / 77%	€4,573 / 75%	€5,265 / 72%
other costs	€813 / 23%	€878 / 23%	€913 / 22%	€1,187 / 23%	€1,551 / 25%	€2,005 / 28%
Total expenditure	**€3,467**	**€3,775**	**€4,197**	**€5,061**	**€6,124**	**€7,270**
Result from operating activities	**€411**	**€62**	**- €193**	**€24**	**- €745**	**€6**

(1) Direct funding = funding by university ("basisfinanciering")

(2) Research grants = grants obtained in national and international scientific competition e.g., grants from NWO and KNAW, and ERC. **(Note: this deviates from SEP, where ERC grants are listed under 3)**

(3) Contract research = funding for specific research projects obtained from external organisations, such as industry, government ministries, and charitable organisations.

Table A.6: PhD candidates (Table E4 in the SEP)

	Enrolment			Cumulative success rates:					
				PhD candidates graduating within					
Starting year	Male	Female	Total	4 years + 3 months	5 years	6 years	7 years, but until Dec 31, 2020	Ongoing on Dec 31, 2020	Discon-tinued by Dec 31, 2020
2012	2	2*	4		2 / 50%	1 / 25%	1 / 25%		
2013									
2014		1	1			1 / 100 %			
2015	2	2	4		1 / 25 %			3 / 75 %	
2016	3	1	4					4 / 100 %	
Total					**3 / 23%**	**2 / 15%**	**1 / 8%**	**7 / 54%**	
2017	1	1**	2					2 / 100 %	
2018	4*		4					4 / 100 %	
2019		1*	1					1 / 100 %	
2020	2**	2	4					4 / 100 %	
Total	**14**	**10**	**24**	**-**	**-**	**-**	**-**	**18**	

*VSNU category 2b (CSC): 2012 (2x), 2018 (1 x), 2019 (1x)

**VSNU category 3: 2017 (1x), 2020 (1x)

During the evaluation period DKE researchers were invited to co-supervise more than 20 PhD students hired at other departments and universities. We did not count these PhD students in the table above, as in contrast to our DKE PhD students, these PhD students are not officially hired by DKE and DKE does not officially receive any revenues. The high number of these PhD students shows that DKE's expertise is very valuable and that DKE researchers are well-respected research partners.

Table A.7: Publications

	2015	2016	2017	2018	2019	2020
Journal publications, refereed	29	29	27	30	37	44
Conference publications, refereed	26	17	31	31	47	42
Book chapters	10	14	10	9	9	12
Books (monographs)				1		
Books (edited)	1		2	3	1	2
PhD thesis	5	3	3	2	4	2

Preprints (including arXiv) are not included in the table.

Other research output, such as patents, software, data sets, are not included in the table, but discussed in section 3.

APPENDIX B: CASE STUDIES

Case study 1: Strengthening of Explainable AI, Data Fusion and Intelligent Interaction research through sector plan investment

Thanks to the sector plan funding from the Dutch government, DKE was strengthened by two new full professorships for data science and AI research with highest societal relevance.

In 2020, DKE welcomed Prof. Nava Tintarev, new chair in Explainable Artificial Intelligence, and Prof. Anna Wilbik, new chair in Data Fusion and Intelligent Interaction. Both joined DKE thanks to sector plans that allow the Dutch government to make long-term targeted investments in research.

At a glance

- Two new chairs: *Explainable Artificial Intelligence* and *Data Fusion & Intelligent Interaction*
- Three new assistant professors, three postdocs and two PhD candidates will be hired

Research in Explainable Artificial Intelligence

As AI systems' actions and decisions will significantly affect their users and have a strong impact on society, it is important to be able to understand how and why an AI system produced the effect that it did. It is a well-known hurdle that many AI algorithms behave largely as black boxes. It is also known that AI systems, whose inner workings are not well understood, can produce heavily biased outputs and are thus not suitable to support humans in making well-founded decisions or for (semi-)automated decision systems. One key aim of explainability is therefore to make the inner workings of AI systems more accessible and transparent. This is crucial so that trust-worthy, well understood AI systems can be provided for the benefit of society, and so that biased AI systems can be identified and improved.

Thanks to sector plan funding, Prof. Tintarev was appointed Full Professor of Explainable Artificial Intelligence from October 2020. Prof. Tintarev leads and contributes to several projects on artificial advice-giving systems, such as recommender systems and (intelligent) search engines; studying a.o., factors such as fairness and bias. These include projects funded by IBM, and Twitter, as well as an EU Marie-Curie ITN on Interactive Natural Language Technology for Explainable Artificial Intelligence.

As part of this appointment, DKE's research on explainable AI will be strengthened further also by 2 assistant professors, 2 postdocs and 1 PhD candidate. This group will work on four key themes: mediating effects of individual characteristics on explanation effectiveness, new evaluation criteria and methodologies, explanation interfaces to deal with biases, and explanations for groups.

Research in Data Fusion and Intelligent Interaction

Today's complex network of systems can produce large amounts of data. People cannot deal with the amount and complexity of data by themselves, while machines alone are missing the required problem domain overview and context knowledge. Therefore, there is a need for intelligent interaction between human and machine. In the current business and societal context, such hybrid intelligence is becoming essential for effective and efficient operation management in many application areas, such as healthcare, smart manufacturing (Industry 4.0), logistics, and the service industry.

The sector plan funding allowed the appointment of Prof. Wilbik as of September 2020. As a full Professor in Data Fusion and Intelligent Interaction, she aims to bridge the gap between the meaning of data and human understanding in complex application environments, where data can be of various natures. As part of this

appointment, DKE's research on data fusion and intelligent interaction will be strengthened further also by 1 assistant professor, 1 postdoc and 1 PhD candidate.

A key application domain for Prof. Wilbik's research is Smart Industry. The competitive position of the European process and manufacturing industry depends on increased efficiency, more flexibility, and reduced cost, yet still being compliant to the safety and sustainability regulations. However, there is a low uptake in Europe for technologies that can accelerate the digital transformation of industry, such as those offered by simulation-based twin technologies and data driven approaches. Therefore, Prof. Wilbik will build agile research teams that can address industry challenges like the loss of expertise from employee turnover and that will perform research on data-driven decision support systems, data fusion and machine learning models validated in practical settings.

Case study 2: Quantum Computing Collaboration with IBM

At a glance

- Focus on addressing the computational needs of future physics experiments using quantum computing
- Two postdocs sponsored by IBM Research
- Collaboration with UM's physics department

On 5 October 2020, Maastricht University and IBM released the following statement:

"Maastricht University will become the first Dutch university to enter the IBM Q Network, a community of Fortune 500 companies, academic institutions, startups and national research labs working with IBM to advance quantum computing. The IBM-UM academic collaboration will focus on addressing the computational needs of the future Einstein Telescope and the LHCb detector at the High-Luminosity Large Hadron Collider at CERN.

The goal of the collaboration is to develop the high-performance computation power required for two next-generation advanced physics detectors: the Einstein Telescope (ET) gravitational wave detector and the upgraded LHCb particle detector at the High-Luminosity Large Hadron Collider (HL-LHC) at CERN.

Next-generation physics detectors require more computational power
Although both detectors are scheduled to be completed in 2035, researchers already foresee that conventional computing methods will fall short of meeting the expected data collection power and data analysis needs. Real-time data collection and processing is likely to become a bottleneck due to the future detectors' increased sensitivities and superior hardware, which will generate an unprecedented amount of data.

Quantum computing: a new approach to computation
Quantum computing is an entirely different approach to computation. Since quantum computers can potentially outperform conventional computers for certain tasks by many magnitudes, the technology may well be a solution for the ET and HL-LHC's challenging data processing needs.

Quantum physics observations by Einstein and others have existed for a century. Over the last 50 years, the field has evolved from theory to science to physical devices. Thanks to the efforts of key players including IBM, quantum computers continue to reach higher 'Quantum Volume' (a metric indicating the computer's performance) and the first quantum computers are already beginning to deliver research results and use cases. The timeline for completing the Einstein Telescope and HL-LHC – fifteen years from the start of the IBM-UM collaboration – is expected to provide a suitable timeframe for developing the required quantum computing technology in parallel.

Contribution of Maastricht University and IBM
The research collaboration aims to apply quantum computing technology to meet the data analysis specifications of the ET and HL-LHC. Within this context, research will focus specifically on developing dedicated algorithms.

Two departments of Maastricht University (UM)'s Faculty of Science and Engineering will join forces with IBM Research Europe: the Department of Data Science and Knowledge Engineering (DKE) and the Department of Gravitational Waves & Fundamental Physics (GWFP), the latter as a member of the national Nikhef collaboration. The UM departments will bring their expertise in gravitational wave physics, elementary particle physics, signal analysis and artificial intelligence.

In the first step of this collaboration, IBM Research will sponsor two postdocs with a dual appointment at IBM Research's lab in Zurich, Switzerland and at Maastricht University's Faculty of Science and

Engineering. IBM will support the projects with access to its quantum computing expertise and resources."

Key outputs
The quantum computing collaboration with IBM captured significant media attention following its formal launch in October 2020. The research group has also been invited for various interviews. A selection of (mostly Dutch) media features:

- Maastricht wil IBM's quantumcomputer gebruiken voor LHC-rekenwerk (online tech magazine, 5 October 2020) https://tweakers.net/nieuws/172962/universiteit-maastricht-wil-ibms-quantumcomputer-gebruiken-voor-lhc-rekenwerk.html
- Computable.nl: Universiteit Maastricht met IBM in quantum Computing (online tech magazine, 5 October 2020) https://www.computable.nl/artikel/nieuws/digital-innovation/7067613/250449/universiteit-maastricht-met-ibm-in-quantum-computing.html
- RTL Nieuws: Universiteit Maastricht werkt samen met IBM aan quantumcomputer (national news feature, 5 October 2020) https://www.rtlnieuws.nl/tech/artikel/5188198/universiteit-maastricht-werkt-samen-met-ibm-aan-quantumcomputer
- BNR Nieuwsradio: Universiteit Maastricht en IBM's kwantumcomputer (national radio, 7 October 2020) https://www.bnr.nl/podcast/digitaal/10423101/europa-trekt-tech-teugels-aan

Case study 3: AI meets Archaeology: The Digital Ludeme Project

The Digital Ludeme Project seeks to improve our knowledge of the development and dispersal of games throughout human history. This ERC-funded project advances the state-of-the-art in Artificial Intelligence while simultaneously pushing boundaries in other disciplines; an anonymous reviewer described it as "one of the probably most unusual AI uses in computer science".

At a glance

- €2 million ERC Consolidator Grant for Dr. Cameron Browne
- Five-year project hosted at DKE
- Wide range of disciplines (including Artificial Intelligence, Computer Science, History and Archaeology) joined in a new field of study: Digital Archaeoludology

The Digital Ludeme Project utilizes the connection between the development of games and the development of human culture. Games offer a rich window of insight into our cultural past, but early examples were rarely documented and our understanding of them is incomplete. While there has been considerable historical research into games and their use as tools of cultural analysis, much is based on the interpretation of partial evidence with little mathematical analysis.

To improve our understanding of traditional games, their history, and their role in the development of human culture and the spread of mathematical ideas, the Digital Ludeme Project focuses on three aims:

1) Model the 1,000 most important traditional strategy games throughout history in playable digital form,
2) Reconstruct missing rule sets from the available evidence, and
3) Map the development of games throughout history.

To achieve these goals, the team behind the Digital Ludeme Project developed the Ludii general game system for modelling, playing, designing, evaluating, and reconstructing games. The Ludii system now represents the state-of-the-art in the field of General Game Playing. Furthermore, the Digital Ludeme Project is in the process of compiling a database of evidence of the world's traditional strategy games over the last 5,000 years. In combination with its digital implementations, this database will provide an unprecedented resource for games scholars in all fields. Ludii and the evidence database are freely available via https://ludii.games/.

Ultimately, the Digital Ludeme Project will produce family trees (or networks) of games based on the underlying functionality. This research may reveal new insights into the games' development and indicate possible "missing links" suggesting historical games that may have existed, but for which no evidence has yet been found. The project is laying the foundations for a new field of study called Digital Archaeoludology, which draws from a range of different research disciplines to shed light on this topic.

The Digital Ludeme Project is a five-year project, funded by the European Research Council (ERC Consolidator Grant #771292) and led by Dr. C. Browne. The project started in April 2018. Dr. Browne joined DKE because of its internationally renowned Game AI & Search group that due to its research on Game AI, and in particular its seminal contributions to the field of Monte Carlo Tree Search, offers a perfect environment for the Digital Ludeme Project.

Selection of key outputs

Scientific publications

- E. Piette, D.J.N.J. Soemers, M. Stephenson, C. Sironi, M.H.M. Winands and C. Browne (2020) "Ludii – The Ludemic General Game System", European Conference on Artificial Intelligence (ECAI 2020), Santiago de Compestela.
- C. Browne (2020) "AI for Ancient Games", Künstliche Intelligenz, Springer, 34:1, pp. 89–93.

- C. Browne (2018) "Modern Techniques for Ancient Games", IEEE Computational Intelligence and Games (CIG 2018), Maastricht, pp. 490–497. [Runner up for best paper.]
- C. Browne, D.J.N.J. Soemers, E. Piette, M. Stephenson, M. Conrad, W. Crist, T. Depaulis, E. Duggan, F. Horn, S. Kelk, S.M. Lucas, J.P. Neto, D. Parlett, A. Saffidine, U. Schädler, J.N. Silva, A. de Voogt and M.H.M. Winands (2019) Foundations of Digital Archaeoludology, Report on Dagstuhl Research Meeting.

Media coverage

- MIT Technology Review: Machine learning is about to revolutionize the study of ancient games, 20-6-2019.
- VICE: Scientists Are Discovering Long-Lost Rules for Ancient Board Games, 21-8-2019.
- Newspaper article: "Dit was het spel, maar wat waren de regels?" Trouw, 19-1-2019. (2-page spread, national newspaper)
- International radio interview: C. Browne talks about the Digital Ludeme Project on Top of Mind (US national radio), 19-11-2019.
- National radio interview: C. Browne talks about the Digital Ludeme Project on Dutch Business News Radio's (BNR) Science Today programme.
- Media coverage: Researchers Are Using Artificial Intelligence to Reconstruct Ancient Games, Atlas Obscura, 26-9-2019.

Case study 4: Intelligent Human-Machine Interaction for Healthcare and Education

The field of human-machine interaction strongly benefits from the latest developments in artificial intelligence such as affective computing. At DKE, we apply, enrich, and share our expertise within real operational end-user settings such as elderly care centres that require smart solutions. For this case study, we zoom in on health and education applications in context of European collaborations.

At a glance

- Expertise in computer vision, human-computer interaction and affective computing applied in elderly care and schools
- Partner in 3 large-scale European Horizon 2020 actions
- Total of €1.7 Mio funding acquired since 2016
- 10 new research positions generated

DKE has deep expertise in the areas of Artificial Intelligence, Computer Vision, Data Analysis and Human-Machine Interaction. DKE researchers are extensively involved in international networks within these fields of research, where they contribute to the most recent developments in AI and, specifically, in deep learning. DKE researchers focus on the design, implementation, evaluation, and dissemination of novel architectures of deep neural networks that do not only achieve competitive results, but that are also flexible and modular enough to be embedded and tested in real operational settings. This successful work led to a high number of research papers in top-ranked peer reviewed venues, and made DKE a trusted partner for large-scale projects. In such projects, DKE partners up with international research institutes as well as partners from industry, school networks, hospitals, NGOs, and policy makers.

Since 2016 DKE participates in, or has participated in, the following Horizon 2020 Research and Innovation actions with Dr. Stelios Asteriadis as PI:

1. **MaTHiSiS (2016-2019; 18 partners).** MaTHiSiS created an AI-driven ecosystem for personalized education using devices such as educational robots and smart mobiles, mainly intended for individuals with special learning needs. Rather than using performance as the sole criterion in personalized learning, MaTHiSiS brought the student's particular needs in the center of the e-learning interface through AI technologies that capture human emotion and intents. DKE played a key role in the project through conducting research in human emotion recognition, recommender systems, multimodal fusion, and learning analytics.
2. **ICT4Life (2016-2019; 9 partners).** ICT4Life built an AI-driven solution to support individuals with neurodegenerative diseases and conducted research within the area of integrated care. DKE provided ambient-assisted living solutions using smart sensors and AI to detect cases requiring attention (such as a patient acting in an abnormal or potentially safety-threatening manner) and communicate these cases to caregivers or medical doctors.
3. **ProCare4Life (2020-2022; 14 partners).** ProCare4Life aims to deploy solutions for monitoring the physical and cognitive status of patients with dementia, and to do so on a large scale at various end user locations across Europe. DKE focuses on automated behaviour recognition through sensorial data, as well as multimodal fusion of user behavioural cues and medical information, to assist in intelligent recommendations of the right services for the patient.

Taken together, these actions generated over €1.7 Mio in funding and 10 research positions. They have also allowed DKE to solidify its standing in the European AI community and with end users of its AI applications.

Key publications

The main research outputs of this case study include top-rated research publications, but also news items that appeared in the press. Typical examples are the ones listed below:

- Khaertdinov, B., Ghaleb, E., & Asteriadis, S. (2021, March). Deep Triplet Networks with Attention for Sensor-based Human Activity Recognition. In *2021 IEEE International Conference on Pervasive Computing and Communications (PerCom)* (pp. 1-10). IEEE.

- Dotti, D., Popa, M., & Asteriadis, S. (2020). Being the Center of Attention: A Person-Context CNN Framework for Personality Recognition. *ACM Transactions on Interactive Intelligent Systems (TiiS)*, *10*(3), 1-20.
- Dotti, D., Ghaleb, E., & Asteriadis, S. (2020, November). Temporal triplet mining for personality recognition. In *2020 15th IEEE International Conference on Automatic Face and Gesture Recognition (FG 2020)* (pp. 379-386). IEEE.
- Ghaleb, E., Popa, M., & Asteriadis, S. (2019, September). Multimodal and temporal perception of audio-visual cues for emotion recognition. In *2019 8th International Conference on Affective Computing and Intelligent Interaction (ACII)* (pp. 552-558). IEEE.
- Alvarez, F., Popa, M., Solachidis, V., Hernández-Peñaloza, G., Belmonte-Hernández, A., Asteriadis, S., ... & Daras, P. (2018). Behavior analysis through multimodal sensing for care of Parkinson's and Alzheimer's patients. *IEEE Multimedia*, *25*(1), 14-25.
- ICT4Life was chosen by Computer Vision News as the Application of the Month of December: An article about our role in the ICT4Life project and the algorithmic techniques used for abnormal behaviour detection was published in the Computer Vision News magazine at pages 22-24: http://www.rsipvision.com/ComputerVisionNews-2016December/

Case study 5: DKE SwarmLab – Cognitive Robotics and Complex Self-Organizing Systems for Smart Logistics, Agriculture, Industry 4.0, Healthcare, and Education

Robotization, digitalization, and artificial intelligence are key innovation factors for businesses worldwide. The *DKE SwarmLab for Cognitive Robotics and Complex Self-Organizing Systems* is DKE's way of driving research and innovation at the intersection of robotics and artificial intelligence, together with and for its private partners and the public.

At a glance

- Investment into a laboratory for Cognitive Robotics and Artificial Intelligence, the DKE SwarmLab
- Part of a Public-Private Partnership (PPP) with innovative robotics companies in Limburg: the Field Lab Robotics in Roermond
- Coordinator of a large-scale European Horizon 2020 project
- Partner in several nationally funded projects.
- Total of €1.7 Mio funding acquired since 2016
- 9 new research positions generated
- State-of-the art robotic and computing equipment (value more than €150'000)

Following the motto "the intelligence is in the network", the DKE SwarmLab is involved in several public and private partnerships including projects with kindergartens, schools, elderly care facilities, various private partners, and almost all faculties of UM.

Through its SwarmLab, DKE is a steering partner and participant in the Field Lab Robotics in Roermond (https://www.fieldlabrobotics.com/). The Field Lab Robotics is a knowledge and experience center for the public, and an innovation center for public and private partners in the areas of robotics and AI. Here, DKE collaborates with innovative robotics businesses and helped build a regional network. Since 2021, it includes the Eindhoven University of Technology, the Zuyd and Fontys Applied Universities (*hogescholen*), high schools, and several private partners.

Within the context of SwarmLab, DKE researchers are active in national and European research and innovation projects with high-impact applications:

1. **CoRoSect (2021-2023; 19 partners in total; H2020; DKE is coordinator).** The CoRoSect project aims to solve one of society's most pressing challenges: generating environmentally friendly food. The project develops "Cognitive Robotic Systems for Digitalized and Networked (Automated) Insect Farms (CoRoSect)" and is coordinated by Dr. Rico Möckel from DKE.
2. **SwarmPort (2017-2021; NWO; 5 partners in total).** The SwarmPort project aims at understanding and facilitating self-organization among autonomous agents in nautical processes in modern seaports (SWARMPORT). The project is a collaboration between DKE, the Port of Rotterdam, Delft University of Technology, TNO, and several private businesses specialized in nautical processes. Co-PIs from DKE are Dr. R. Möckel and Prof.dr. G.B. Weiss.
3. **Advanced Robot-Brain Interfaces (2015-2019; Luik 3; 2 partners in total).** This UM-internal project is a collaboration between DKE and the Faculty of Psychology and Neuroscience (FPN). The project aims to allow patients with limited movement capabilities to regain some of their autonomy and quality of life by enabling them to control intelligent assistive robots. Co-PIs from DKE are Dr. R. Möckel and Prof.dr. G.B. Weiss.

In addition, DKE SwarmLab researchers were and are active in various other projects: the H2020 Flying Forward 2020 project, the development of innovative robotic tools for children and elderly with private partners, the development of innovative robots for education (publicly available at https://www.maastrichtuniversity.nl/edmo), and the development of cognitive orthopaedic devices. Since 2016, members of the DKE SwarmLab won a total of 5 awards including best paper and best poster awards, and personal awards.

Taken together, DKE SwarmLab generated over €1.9 Mio in funding, 9 research positions, and now houses research equipment worth more than €150'000. SwarmLab allowed DKE to solidify its standing in the European and national robotics and AI community, as well as with end users and public and private partners.

Key publications

The main research outputs of this case study include top-rated research publications and awards such as the ones listed below:

- Benitez-Andonegui, A., Burden, R., Benning, R., Möckel, R., Lührs, M., & Sorger, B. (2020). An Augmented-Reality fNIRS-Based Brain-Computer Interface: A Proof-of-Concept Study. Frontiers in Neuroscience.
- Christopher, S. M., Urlings, C. C., van den Bongarth, H., Coppens, K. M., Hurks, P. P., Borghans, L., & Möckel, R. (2019, November). A Digital Wooden Tabletop Maze for Estimation of Cognitive Capabilities in Children. In International Conference on Social Robotics (pp. 622-632). Springer, Cham. (**Best Interactive Session (Finalist) Award**)
- R. Möckel, L. Dahl, S. M. Christopher, "Interdisciplinary Teaching with the Versatile Low-Cost Modular Robotic Platform EDMO", International Conference on Educational Robotics, 2019.
- B. Sorger, K. Tumanov, A. Benitez-Andonegui, M. Lührs, H. Boeijkens, G. Weiss, R. Goebel, R. Möckel, "An fNIRS-based brain-machine interface for remote robot control", Real-Time Functional Imaging and Neurofeedback Conference (rtFIN), 2017. (**Best poster award**)
- J. Hermans, G. Spanakis, R. Möckel, "Accumulated Gradient Normalization", Proceedings of the 9th Asian Conference on Machine Learning. Zhang, M-L. & Noh, Y-K. (eds.). Proceedings of Machine Learning Research, Vol. 77, p. 439-454, arXiv:1710.02368, Nov 2017.
- F. Fraenz, J. Paredis, R. Moeckel "On the Combination of Coevolution and Novelty Search", IEEE Congress on Evolutionary Computation, June 2017. (**Best paper award**)

Case study 6: Interdisciplinary research collaborations within Maastricht University

Data Science and Artificial Intelligence innovate a wide range of other research fields and applications with societal relevance. As a result, DKE collaborates with all six of Maastricht University's faculties to develop applications that have high impact in different research areas, while simultaneously advancing the state-of-the-art in Data Science and Artificial Intelligence itself. This case study highlights examples.

At a glance

- Longstanding collaborations within all six faculties of Maastricht University
- Reciprocal benefits: advancing the state-of-the-art in Data Science and Artificial Intelligence while working on solutions for other domains with high societal impact

Business and societal applications:

- The **Brightlands Institute for Smart Society** (BISS) connects Maastricht University's knowledge and expertise in data science with societal needs, with a strong focus on businesses. DKE contributes expertise in artificial intelligence and data science and supports business projects with DKE researchers and students.
- DKE, the **School of Business and Economics**, the **Faculty of Psychology and Neuroscience**, and **IDEE** collaborate on the development of smart assessment toys for children. The collaboration led to two awards.

Applications in Life Science and medicine:

- With the **Department of Physiology**, DKE investigates the complexity and level of organization of signals from the heart. This collaboration unites the development and application of methods from dynamical systems theory and signal processing to assess the complexity of the atrial substrate in patients suffering from atrial fibrillation. The broad goal is to help medical doctors define, evaluate, and tailor therapies.
- Together with the **Department of Cardiology,** DKE jointly set up the methodology for Electrocardiographic Imaging (ECGI). ECGI combines cardiac potentials that are measured on the body surface with geometric information about the heart and the torso, to estimate the corresponding potentials on the cardiac surface. The efforts on method development and validation have led to the 2016 Joint WG e-Cardiology ESC – CinC: Clinical Needs Translational Award (CTA).
- In collaboration with the **Department of Pathology**, DKE focuses on data analysis where different modalities are integrated to generate hypotheses (for instance mass spectrometry imaging, pathology and multi-omics).
- The **Department of Biochemistry** collects high-throughput data to better understand blood clot formation and the role of glycoprotein VI in the platelet cells that clump together to form a blood clot. The complex experimental designs result in hypercubes of data, which are difficult to analyse and interpret. DKE brings multivariate analysis skills to bear on these datasets and thereby allows additional interpretation and knowledge extraction.
- Several DKE researchers are associated with the **Maastricht Centre for Systems Biology** (MaCSBio), which focuses on two areas: computational biology of neural and genetic systems, and systems medicine of chronic disease. DKE researchers support MaCSBio in the data science and modelling aspects of their work by providing expertise in machine learning, control theory and deconvolution.

Applications in Law:

- DKE's collaboration with the **Faculty of Law** revolves around two themes: technology for law, and law for technology. Together with colleagues from the Faculty of Law, DKE works on applications that bridge the gap between citizens and the law by applying Natural Language Processing techniques to improve statute law retrieval. DKE conducts research into consumer protection by looking at niche areas like the Dark Web (using machine learning for sybil identification), and on the internet and social media (exploring ways of

enforcing legal frameworks on websites) or consumer forensics (e.g. identifying consumer complaints and assessing their legal basis). The collaboration enables DKE to engage with authorities that shape the regulatory framework of platform governance and AI.

Applications in Neuroscience:

- With the **Faculty of Psychology and Neuroscience (FPN)**, DKE developed a novel method for data-driven and adaptive decomposition of nonlinear and nonstationary time series data, named Singular Spectrum Decomposition (SSD). Prior to the development of SSD, classical methods could not adequately capture dynamic changes in the narrow frequency bands of interest, hampering the understanding of cognitive processes.
- Another collaboration with **FPN** aims to link the activity and structures in the visual cortex with deep learning architectures and artificial neuron operation. The joint work focusses on enhancing processing of visual information in deep neural networks, also to allow better understanding of the visual cortex structure, and to study the sensorimotor system in the brain.
- DKE and **FPN** collaborate on the development of advanced brain-robot and brain-computer interfaces.

Applications in Physics:

- DKE contributes high-performance computing solutions to cutting-edge physics experiments in collaboration with the **Department of Gravitational Waves and Fundamental Physics**. DKE researcher Dr. Daniel Cámpora Perez is one of the lead developers of the Allen project, a GPU-enabled software for particle collision reconstruction at the Large Hadron Collider (CERN).
- See also Case study 2: Quantum Computing Collaboration with IBM.

APPENDIX C: Other documents

The following table contains a list of additional documents that we provide to the assessment committee. These documents can be found on the separate SURFDRIVE provided to Maastricht University.

Document name	Description
DKE publication list	A list of DKE's publication during the evaluation period 2015-2020