Summary

The Bernoulli Institute (BI) is the only research and educational institution in the Netherlands that combines mathematics, computer science and artificial intelligence. Established in 2018 by merging the Johann Bernoulli Institute for Mathematics and Computer Science (JBI) and the Institute of Artificial Intelligence and Cognitive Engineering (ALICE), the mission of the BI is to conduct outstanding academic research and teaching in the areas traditionally covered by the three disciplines; to contribute to society in its broadest sense; to transfer its results to other areas of science and technology, and to initiate and expand inter- and multidisciplinary research collaborations. The BI is embedded in the Faculty of Science and Engineering (FSE) which is part of the University of Groningen (UG), a top-100 university.[1]

The BI's priorities during the current evaluation period were to create a stimulating research environment that nurtured the research interests of our staff members and provided opportunities for interdisciplinary collaborations along common themes, while improving the Institute's viability and visibility. To ensure a successful merger between the two Institutes, the BI fostered an environment of open dialogue with its academic staff and together identified future research directions and collaborative themes for the BI. These are built upon the strengths from the individual research groups. Strategic recruitment opportunities were implemented to contribute to the BI's newly identified themes and teaching, to strengthen its viability and reputation, and to improve gender diversity. Activities were implemented to improve public engagement, via science education, and to integrate stakeholders in our research through externally funded research and innovation projects and internships with companies in the region. New structures were established to help PhD students to progress in their research while feeling nurtured and supported.

As a result the BI has seen a substantial growth in staff (by 40%), funding (by 50%),[2] research output (exemplified by publication and conference awards, and academic distinctions) and societal involvement (as mentioned above). The institute has maintained or increased its reputation in areas where it has strong tradition and/or coverage (Systems and Control, Software Engineering, Machine Learning and Visualization) and has achieved national visibility for initiatives such as Hybrid Intelligence and Cognitive Systems and Materials. It has initiated interdisciplinary collaboration within three themes (Geometry & its applications; Systems, data & society; Computing & cognition) and has initiated or become a major participant in several FSE and UG research initiatives that bring together multiple disciplines and sciences such as engineering, astronomy, physics, medical sciences: Center for Data Science and Systems Complexity, Center for Cognitive Systems and Materials, Fundamentals of the Universe, Health Technology Research and Innovation Cluster, to name a few. Together this demonstrates that the BI is on the right course towards achieving its mission.

[1] According to the 2021 ARWU Shanghai Ranking and the Times Higher Education World University Rankings.

[2] In particular external funding through national and international grants, as well as CogniGron funding, see Table Funding.

APPENDIX B: CASE STUDIES

Quality of BI research and use of research products by peers:

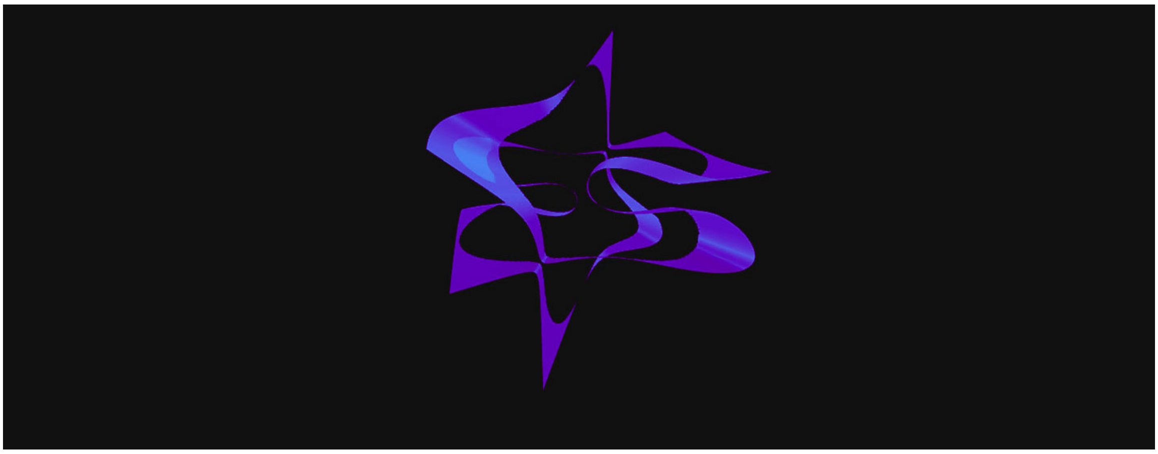
B.1 Breaking a curse by applying geometry

Besides pursuing practical applications, BI researchers also apply geometry to outstanding problems in pure mathematics. For instance, the rational solutions of so-called Diophantine equations such as x^2+y^2=1 have fascinated mathematicians for millennia. Nowadays, these solutions are interpreted as rational points on the geometric object defined by the equation. Yet even in the simplest case, when this object is a curve, many examples remain unsolved. One particularly stubborn and important example, defined by (-y-1)x^3 +(2y^2 +y)x^2 +(-y^3 +y^2 -2y +1)x+(2y^2 -3y)=0, was even dubbed the cursed curve.

An ambitious research program initiated by M. Kim in the mid-2000s drew on ideas from physics to lay a theoretical foundation for tackling many unsolved curves. Despite receiving much attention,[1] it long remained unclear whether Kim's approach could really be applied to handle previously intractable examples, and many researchers were skeptical. This changed with an article published in 2019 in Annals of Mathematics, the most prestigious mathematics journal, by BI assistant professor S. Müller and four co-authors, including former BI graduate J. Tuitman.[2] Building on Kim's ideas, their work provably finds all rational points on the cursed curve. A crucial ingredient is p-adic geometry, partially developed by BI emeritus M. van der Put.

Even before it was published, the article received attention in media such as Quanta magazine, where it was called a "watershed moment" in the study of Diophantine equations, and Nemo Kennislink. Its techniques were the subject of graduate schools, workshops and seminars in several countries such as the US, France, Germany, Italy and Spain. Since then, much work has gone into extending and applying the methods of the paper, and several BI researchers continue to play an active and leading role in this.

Figure: A plot of the cursed curve



[1] https://www.quantamagazine.org/secret-link-uncovered-between-pure-math-and-physics-20171201/

[2] Balakrishnan, J., Dogra, N., Müller, J. S., Tuitman, J., & Vonk, J. (2019). Explicit Chabauty--Kim for the split cartan modular curve of level. Annals of mathematics, 189(3), 885-944. https://doi.org/10.4007/annals.2019.189.3.6

B.2 A Groningen tradition: Hamiltonian systems in Geometry and its applications

A prominent line of research connected to the BI research theme Geometry & its applications concerns the study of Hamiltonian systems. In the past decade H. Broer, K. Efstathiou, H. Waalkens and more recently N. Martynchuk and T. Görbe have made major contributions to the geometry of singular Lagrangian fibration of integrable Hamiltonian systems. This concerns in particular the obstruction to triviality of torus-bundles introduced by Duistermaat in 1980 and referred to as Hamiltonian monodromy.

These researchers' contributions include work on parallel transport along Seifert manifolds which has led to a general theoretical perspective on fractional monodromy, and was published in Communications in Mathematical Physics.[1] An extension of monodromy to non-compact cases has led to the notion of scattering monodromy.[2] These works formed the main parts of the PhD thesis of N. Martynchuk which was defended with cum laude in 2018. Another work introduced monodromy to the context of superintegrable systems and was published as an editors' choice in Physical Review Letters.[3] Monodromy manifests itself quantum mechanically as a lattice defect in the joint spectrum of commuting operators that are the quantum analogues of the classical integrals.

Expanding this line of research on integrable systems and in particular strengthening the expertise on the quantum mechanical aspects of this direction formed the contents of the GQT NWO grant proposal that has led to the funding of one tenure track position (M. Seri) and one PhD position (F. Zadra).

The research on Hamiltonian systems and the interplay with their quantum mechanics were also the basis for several joint bachelor and master students with theoretical physicists from the Van-Swinderen Institute in Groningen and the PhD position of E. Pap which together formed one of the pillars on which the research theme FotU was set up and which was awarded with 9 PhD position from the FSE in 2020.

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[1] Martynchuk, N., & Efstathiou, K. (2017). Parallel transport along Seifert manifolds and fractional monodromy. Communications in Mathematical Physics, 356(2), 427-449. https://doi.org/10.1007/s00220-017-2988-5

[2] Martynchuk, N., Dullin, H. R., Efstathiou, K., & Waalkens, H. (2019). Scattering invariants in Euler's two-center problem. Nonlinearity, 32(4), 1296-1326. https://doi.org/10.1088/1361-6544/aaf542; Martynchuk, N., & Waalkens, H. (2016). Knauf's degree and monodromy in planar potential scattering. Regular & chaotic dynamics, 21(6), 697-706. https://doi.org/10.1134/S1560354716060095

[3] Dullin, H. R., & Waalkens, H. (2018). Defect in the joint spectrum of hydrogen due to monodromy. Physical Review Letters, 120(2), . https://doi.org/10.1103/PhysRevLett.120.020507

B.3 Impactful PhD research: Dr. Godliver Owomugisha's research on machine learning, spectral data and crop diseases

Our PhD students are encouraged to become researchers in their own right who build upon their interests and backgrounds. Thesis awards and high quality publications testify to the success of this approach. Dr. Godliver Owomugisha's high impact research in machine learning, with contribution to the BI theme Systems, data & society, is a notable highlight.

Dr. Owomugisha started as an external PhD with a project about the acquisition and machine learning analysis of spectral data developed at the UG and the Makerere University in Kampala/Uganda, with which BI researchers have collaborated for more than 10 years. She received her degree in 2020 with the project Project: "Early detection and diagnosis of crop diseases in asymptomatic plants: acquisition and machine learning analysis of spectral data." The project resulted in low-cost hardware solutions and put forward advanced machine learning techniques for the early detection and diagnosis of crop plant diseases, based on photographic images and spectral information. Several journal and conference publications of high quality have documented the scientific impact of her thesis project (Appendix A.3 and A.4).

At societal level, the aim of her research is to establish low-cost technical solutions and reliable analysis methods which, in particular, enable smallholder farmers to detect outbreaks of viral crop plant disease as early as possible. In turn, this facilitates early countermeasures and will increase food security and farmers' income in the region. In this respect, Owomugisha established an intense collaboration with the National Crops Resources Research Institute (NaCRRI) of Uganda. She coordinated the joint efforts from data acquisition in the field to the planning and design of screenhouse experiments and the machine learning based analysis. Currently, she is a senior lecturer at the Busitema University/Uganda within the Faculty of Engineering where she launched the new group for Artificial Intelligence and Interdisciplinary Research, and from where she continues the collaboration with the BI, the Makerere University and the NaCCRRI.

Owomugisha received the Google AI Award for Social Good, a Data Science Africa (DSA) Research Award, and the Best Engineering PhD Thesis Award of the Groningen Engineering Center.

Image: data collection with a CI-710 miniature leaf spectrometer (Owomugisha, G. (2020). Computational intelligence & modeling of crop disease data in Africa. University of Groningen. https://doi.org/10.33612/diss.130773079, p. 67)

B.4 ERC project CardioZoom - High Fidelity Cardiovascular Modeling from Super-Fast MRI

One of the strengths at the BI is research in the theoretical as well as the computational aspects of dynamical systems and integrating data obtained from dynamical phenomena, such as fluid flows, into mathematical models. Another such strength is the construction of (graphical) models interfaces, with special attention being paid to modeling and engineering aspects. Both contribute to the BI theme Systems, Data and Society, as well as Geometry and its Applications, and to its intended application area in healthcare and medicine. The quality and application potential of the research collaboration between the two is exemplified by the CardioZoom project of Dr. Cristobal Bertoglio (Math), which was awarded an ERC Starting Grant in 2020. Its focus is on new inverse problems and solution methods for reduced imaging data. It concerns optimal measurement design with PDEs modeling fluid-structure interaction using data from novel Magnetic Resonance Imaging modalities, aiming to provide new means of diagnosing cardiovascular disease (aortic stenosis, heart failure, etc. for instance).

Aiming to facilitate diagnosis, which involves the development of an innovation chain, the project initiated collaborations between BI researchers in computational mathematics (Math), with researchers in visualization of medical data (CS), and the University Medical Center Groningen. In particular, the research collaboration led to the development of an advanced geometric (parametric) cardiac valve representation together with Dr. Jiri Kosinka (CS). The new computational model has already been applied to extract the three-dimensional valve shape from preoperative medical images, in collaboration with the Radiology and Interventional Cardiology departments of the UMCG. Using the 3D valve shape, CardioZoom provided additional, simulation-based hemodynamic parameters to refine the clinical severity of valvular disease. The clinical value of this novel information is currently under study in a pilot data set of 20 patients, which can be easily extended due to the large size of the total cohort (1000 patients, 4 new patients per week).

In the meantime, research continues on the computational inverse problem for valve shape estimation. First theoretical results were published in an Inverse Problems paper, which was produced in the framework of a double degree PhD project co-supervised with the University of Chile.[1] Next, a validation study will be performed using experimental phantom data already provided by King's College London, where the actual valve shape is known and hence it can be used for validation of the inverse approach. If all these steps end up being successful, the project is set to estimate the valve shape and relevant clinical information from velocity-encoded MRI data in patients provided by the Academic Medical Center in Amsterdam.

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[1] Aguayo, J., Bertoglio, C., & Osses, A. (2021). A distributed resistance inverse method for flow obstacle identification from internal velocity measurements. Inverse problems, 37(2), https://doi.org/10.1088/1361-6420/abced8

B.5 BI research in systems, data and society in the regional agenda for health technology

The BI has connected to various initiatives at the UG to feature its research in the regional research agendas for scientific research (in relation to astronomy, physics, engineering) as well as to applications in smart industry, energy, digitization, and healthcare. The Health Technology Research and Innovation Cluster in Groningen (HTRIC), which was established to showcase medical technology developed in the region and increase its impact, is a natural connection that the BI has fostered internally with discussions and communication about HTRIC activities. Among the BI researchers who have become prominent in the profile of HTRIC is Prof. Raffaella Carloni. Her research, awarded H2020 LEIT and FET grants, focuses on the design, modeling and control of compliant robotic systems, novel (soft) actuators, and prosthetic devices, and brings cutting edge research in robotics, systems and control to the prosthetics technology.

In her LEIT project Prof. Carloni leads a consortium to develop a new generation of transfemoral prosthetic legs that can be intuitively operated, sensed, and trusted as the healthy and reliable counterpart for a variety of tasks. The project involves collaborators from other Dutch and European Universities, as well as the Radboud University Medical Center and prosthetics companies from Europe and Australia. The Robotics Lab focuses on the mechanical design of the transfemoral prosthesis, which includes innovative variable stiffness actuators and light-weight composite materials, and on the design of a bio-inspired control architecture, which relies on both model-based and artificial intelligence-based methods. A generic musculoskeletal model of people with an osseo-integrated unilateral transfemoral amputation is developed and used together with deep reinforcement learning to gain better understanding of the complex interaction between the user's nervous system and the prosthesis' control system.In another European-funded project, Magnify, Prof. Carloni and her partners from France and Italy do research on bio-inspired soft robots/actuators to develop a new generation of artificial muscles for robotic systems, whose design relies on polymeric nanofibers, controlled by external electrical stimuli. In close collaboration with a multi-disciplinary team of chemists and material scientists, Prof. Carloni's Robotics Lab focuses on the fabrication of nanofibrous bio-inspired soft actuators/robots, their electro-mechanical characterization, and (model-based and model-free) control.

At HTRIC, Prof. Carloni's research is involved in helping Carloni is one of the team leads in helping develop the "operation room of the future," i.e. implementation of robot-assisted, highly complex interventions in surgery. As part of this endeavor, she has received one of the four PhD grants for a collaborative project together with Prof. Han Houdijk from UMCG.

B.6 NWO Gravitation/Gravitationkracht project Hybrid Intelligence

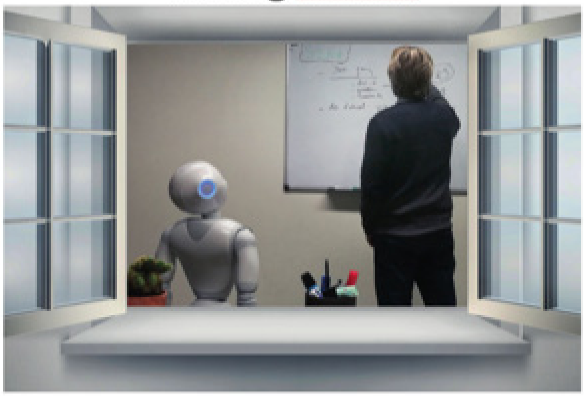
In 2019, the project “Hybrid Intelligence: Augmenting Human Intellect” was awarded a the NWO Gravitation/Gravitationkracht grant (https://www.hybrid-intelligence-Center.nl/), which is a grant intended for scientific consortia that have the potential to become world leaders in their field. The project runs for 10 years (2019-2029), is organized as a collaboration between 6 universities in the Netherlands, and is generously funded (20M€). The key idea underlying the Hybrid Intelligence project is that human intellect can be augmented by the proper combination of human and machine effort. Such a hybrid combination can benefit from the strengths of both humans and machines, and their weaknesses can be mitigated. The project is well-received, as shown by the fact that the paper in the journal Computer about the project (Akata et al., 2020)[1] won the 2020 best paper award of the journal Computer, awarded by the IEEE Computer Society.

The project has four research lines: Collaborative, Adaptive, Responsible and Explainable (CARE). Each connects to a central research problem in current artificial intelligence, robotics and human-machine collaboration. In the Collaborative line, the focus is on joint teams of humans and machines. In the Adaptive line, the focus is on the handling of changing circumstances. In the Responsible line, the focus is on ethical system design. In the Explainable line, the focus is on transparent system behaviour. In its first two years, the project has already led to a number of original research papers and demos and there has been significant exposure on Hybrid Intelligence in the media (see https://www.hybrid-intelligence-Center.nl/in-the-media/). In June 2022, we are organizing the first international conference on Hybrid Human-Artificial Intelligence, with several aligned workshops and a hackathon.

Presence of the Bernoulli Institute in the Hybrid Intelligence project

The BI topic Cognitive AI is heavily involved. Three members, namely, Prof. Rineke Verbrugge, Prof. Bart Verheij and Prof. Davide Grossi, have significantly contributed to the writing of the original project proposal. Furthermore, Verbrugge (co-applicant) is a member of the executive board and leads the educational and training activities for the five postdocs and the 27 PhD students in the HI project throughout the Netherlands. For example, she leads a bi-weekly journal club and PhD colloquium and develops national graduate courses on subjects such as ‘Explainable AI’ and ‘Responsible AI’, partly in cooperation with the SIKS graduate school. Verbrugge, Verheij and Grossi participate as researchers and PhD advisors. Verheij co-coordinates the responsible Hybrid Intelligence research line. Currently, three Groningen PhD students are funded by the project (Orzan, Steging, one accepted to start soon), and two more are co-supervised by Verbrugge, Verheij and Grossi but have their main affiliation at other universities (Erdogan, van Woerkom).

Building AI.nstein



[1] Akata, Z., Balliet, D., de Rijke, M., Dignum , F., Dignum, V., Eiben, G., Fokkens, A., Grossi, D., Hindriks, K., Hoos, H., Hung, H., Jonker, C., Monz, Christof, Neerincx, M.A., Oliehoek, F., Prakken, H., Schlobach, S., van der Gaag, L., van Harmelen, F., van Hoof, H., van Riemsdijk, B., van Wynsberghe, A., Verbrugge, R., Verheij, B., Vossen, P., & Welling, M. (2020). A Research agenda for Hybrid Intelligence: augmenting human intellect by collaborative, adaptive, responsible and explainable Artificial Intelligence. Computer 53 (8), 18-28. https://doi.org/10.1109/MC.2020.2996587

Use of research products by societal target groups:

B.7 The VISDOM and 4NSEEK projects bridge research and innovation for private and public stakeholders

Research at the BI produces fundamental insights as well as innovation for societal stakeholders. The innovation projects are generally developed through externally funded research and innovation projects, such as VISDOM and 4NSEEK, both of them awarded European funding. The beneficiaries range from large to small companies, and from private partners to public offices.

The VISDOM project (https://iteavisdom.org/) is part of ITEA, the Eureka Cluster on Software Innovation. ITEA projects are led by industry and are meant to produce tangible innovation that can be directly embedded in offered products and services. VISDOM is a collaborative project developed between 2018 and 2022 among 4 SMEs, 3 large industries and 4 universities across the Netherlands, Finland and Spain, with a budget of 7 mil. euro. The aim of the project is to develop new types of visualizations that utilize and merge data from several data sources within DevOps environments (toolchains that bridge Development and Operations). The visualizations are meant to provide simple but actionable "health checks" about the state of the development process, the software system and its operation. One such crucial check concerns Technical Debt: a metaphor reflecting the shortcuts taken during development that help to achieve short-term goals, but negatively influence the internal quality of software in the long term (i.e. maintenance and evolution). If technical debt remains hidden, making changes to the software becomes very difficult and development velocity decreases. In the worst case, Technical Debt can even 'bankrupt' a software project and its developing organization. To tackle this problem, the BI partner in VISDOM (Prof. P. Avgeriou, budget of 480k, 1 PhD and postdoc) has created a tool that is able to classify and visualize technical debt, by mining several sources in DevOps tools. It is the first of its kind to combine multiple sources, while the classification uses a machine-learning approach to automatically identify technical debt with high accuracy. The tool will be released with an Open-Source license at the end of the project.

The 4NSEEK project[1], developed between 2019 and 2021 and funded by the EU (1.1 mil. euro), was developed by an international consortium[2] of law enforcement agencies (LEAs) and Universities, including UG under the leadership of Dr. George Azzopardi (budget 73k, one shared PhD position). Its aim was to develop an AI-based tool to help LEAs in their investigations against child sexual exploitation. While the other entities were concerned with the construction of tools (e.g. identification of naked bodies) that identify child sexual exploitation material (CSEM) from large repositories, the objective of the work package (WP) of Azzopardi focused on the determination of the camera device that was used to capture a given image or video file. This is akin to determining the specific firearm that was used to fire a bullet found in a crime scene. The achievement of this objective would equip LEAs with a tool that allows them to determine a connection between a device owned by an offender and the produced CSEM, as well as establishing links between different CSEM (possibly in different cases overseen by various LEAs) with the same alleged offender. Therefore, it would facilitate building stronger cases. This main objective was investigated together with the PhD student Guru Swaroop Bennabhaktula, and in collaboration with Prof. Dimka Karastoyanova (BI) and Prof. Enrique Alegre (University of León, Spain).

[1] Co-financed by the EU through the financing program Internal Security Fund - Police, ISFP-2017-AG-CYBER call.

[2] INCIBE - A Spanish organisation dependent on the Ministry of Economic Affairs and Digital Transformation, the Secretary of State for Digitalisation and Artificial Intelligence, Malta Police Force, Cuerpo Nacional de Policía (Spain), Guardia Civil (Spain), Portuguese Association for Victim Support (APAV)

B.8 Bernoulli startup Researchable

Based on the opportunities in their field several BI students in CS opted to bridge the gap between research and application, and to create startups. This choice is facilitated by the internships in which CS students are involved during their programme at the BI and the connections with the GDBC and GEBC, which exposes them to the needs of the stakeholders.

Although our startups are not many, they enjoy considerable success as measured through awards and contracts. One of them is Researchable (10 employees), a software development and data company dedicated to helping organizations in building software applications with core analytical components like forecasting, machine learning, real-time intelligence, and statistical analyses. Researchable provides data-driven solutions that help organizations benefit from automation. Its scientific background is what sets it apart and has turned it into a knowledge-intensive software development partner. It works with organizations such as Vitens, UMCG, Leiden University, the Ministry of Defense, and the University of Twente

In 2021 it worked on implementing ISO27001 - a norm for information security. This is generally a certification that companies go for once they are more mature, and is often not for startups. With this certification Researchable separates itself from its competitors. Collaboration with BI is still ongoing through externally funded projects, supervision of student internships, master theses and software engineering projects, and teaching whereby the company gives guest lectures for courses like Web and Cloud computing.

B.9 The ComFLOW simulation method led to long-term collaboration with industry

The development of the ComFLOW method demonstrates that the step from academic ideas to their use in an industrial environment takes a long time. But it also shows that applications are strongly pushing scientific innovations.

Extreme ocean waves can cause significant damage to coastal areas and offshore constructions. This damage can be both economical (e.g. hurricanes in the Gulf of Mexico destroying oil rigs) and ecological (e.g. the accident with the MSC Zoe in January 2019 polluting the Wadden islands). Together with the offshore and shipping industry, over the last 25 years we have been developing new mathematical simulation techniques (Computational Fluid Dynamics) to predict the effects of these extreme waves, and implemented them in our ComFLOW simulation method. Together with the Dutch Maritime Research Institute MARIN, the method has been validated for the envisaged maritime applications, and is now being used in the offshore and ship building industry in their design processes.

The ComFLOW development started in 1995 in cooperation with the National Aerospace Laboratory NLR for studying sloshing of liquids onboard spacecraft. In February 2005, this culminated in the launch (on an ESA Ariane-5 test flight) of the Dutch Sloshsat FLEVO satellite. The latter is a small spacecraft, designed especially to carry out sloshing experiments in orbit, with which our ComFLOW simulations have been validated. In 1997, MARIN gave us the chance to show what we could do for extreme ocean waves and, after some preliminary MSc projects, they introduced us to the offshore industry. In a handful of PhD projects our mathematical approach was further developed. These projects had a total budget around 6 million Euro, funded by the EU and NWO-AES (70%) with co-funding by the industry (30%). Over the years, the development team consisted of several post-docs, a dozen PhD students (also at TU Delft Maritime Engineering) and about two dozen master students.

After having obtained sufficient confidence in the results, MARIN started using the ComFLOW method in their daily consultancy for the shipping and offshore industry (e.g., recently they have analyzed the accident with the MSC Zoe). Gradually more offshore companies (classification societies, shipyards and oil companies) began using ComFLOW for their daily design activities of offshore constructions. All users are united in a User Group which currently has 10 participants (4 from NL, 3 from Norway, 2 from USA, 1 from Korea). In 2019, UG (Prof. Arthur Veldman), MARIN and NWO-AES signed a cooperation agreement in which MARIN commits itself to perform the maintenance and user support of the simulation software, whereas UG remains owner of the source code.

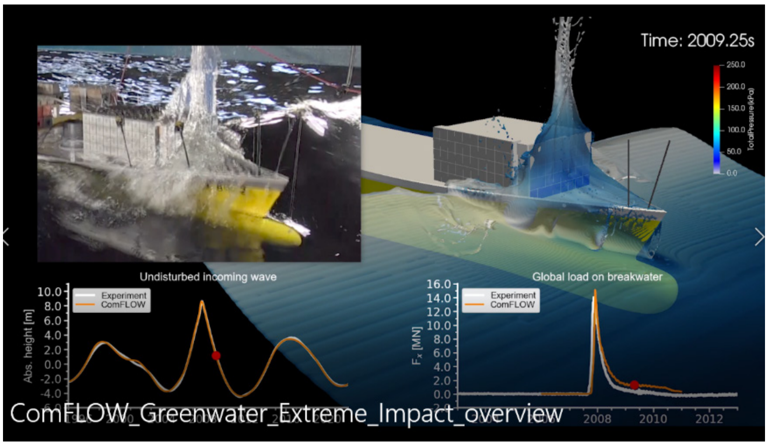


Image: Experiment (MARIN) versus numerical simulation (ComFLOW) of an extreme 'green water' wave impact on the fore deck of a container ship, thereby jeopardizing the cargo.