



Evaluation of Mathematics, ICT and Technology (EVALMIT) 2023–2024

Self-assessment for research groups

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1 Organisation and strategy

1.1 Research group's organisation

Organisation & Leadership. With a staff of more than 400, The Department of Informatics (IFI) at UiO is a “powerhouse” for informatics training and research in Northern Europe. It is the largest such unit in Norway and the one with the strongest international rankings. Around a comprehensive core in computer science, IFI interprets informatics in substantial breadth: from microelectronics or signal processing, to participatory design or digital innovation. In 2023, IFI hosts five BSc and eight MSc study programmes, with close to 2500 students. The department is organized in four thematic sections. PSY is part of the *Programming* section at IFI, which comprises five research groups.

PSY was established by Professor Ole-Johan Dahl (Turing Award 2001), with a focus on formal methods, deductive verification and algebraic specification. PSY was led by Professor Olaf Owe until 2020, and by Professor Einar Broch Johnsen from 2021. The group has increasingly focused on executable formal methods and distributed systems. Today, PSY aims to strike a balance between foundational and methodological research, centred around formal methods and logic-based descriptions of systems.

The group is very international, with English as its everyday working language. Group members in the reporting period have originated from 17 countries, including Austria, China, Germany, Greece, India, Indonesia, Iran, Italy, the Netherlands, Norway, Peru, Romania, Spain, Taiwan, USA, Uruguay, and Vietnam.

Permanent Staff. In the evaluation period, the group's permanent faculty members have been Professors Einar Broch Johnsen, Peter Csaba Ölveczky, Olaf Owe (retired 2020), Martin Steffen and Arild Waaler, and Senior Adviser Geir Horn. After Owe's retirement, Associate Professor Silvia Lizeth Tapia Tarifa was recruited from January 2023, thereby adding a female faculty member to PSY just after this evaluation period. Since 2023, the group's permanent staff also includes one technical programmer, Rudolf Schlatter. Waaler and Horn have gradually become affiliated with PSY through Sirius, an externally funded Centre for Research-driven Innovation (SFI, 2015–2023). Tapia Tarifa and Schlatter were also previously affiliated with PSY, employed as researchers in Sirius.

Early Stage Researchers. The group includes a significant number of early stage researchers (PhD fellows, Postdoc fellows and researchers). In the reporting period, 25 PhD fellows have successfully defended their doctoral degrees within the group, 12 of which have been female. Today, the group employs 7 PhD fellows, 1 Postdoc and 2 researchers (in contrast, Table 1 reports numbers from October 2022).

Many of the group's former PhD and Postdoc fellows now hold permanent faculty positions at universities, including University of Oslo, University of Bergen, NTNU, Western Norway University of Applied Sciences,

Høyskolen Kristiania, TU Chalmers (Sweden), University of Southern Denmark, Reykjavik University (Iceland). Some have gone to research institutes, e.g., SINTEF, the Norwegian Computing Centre, Norwegian Meteorological Institute and Statistics Norway, and some have gone to typical software companies, e.g., Microsoft, Computas, Accenture, Posten. The majority have chosen to continue their careers in Norway.

Organisation of Research. Research in PSY is typically organised in terms of *projects*, which may be either funded through UiO initiatives or through external sources. In the reporting period, PSY has been heavily involved in Sirius, a Centre for Research-driven Innovation (SFI) with 8-year funding from RCN (2015–2023), directed by Waaler and co-initiated by Johnsen. Sirius, with its focus on innovation, involved extensive industrial collaboration with central companies in the Norwegian energy sector. PSY aims to strike a balance between foundational research and domain-oriented, typically methodological research. The group's foundational research has mostly been funded through basic funding at UiO in the reporting period, but also through RCN Fripro and Young Research Talents projects, and through the EU's FET and MSCA funding schemes. Methodological research is typically funded through projects, and has in the reporting period mostly centred around distributed systems and cloud, as well as the modelling of systems and processes from the engineering and energy domains (through Sirius and associated projects). The group has been very active in European projects through the FP6, FP7, H2020 and Horizon Europe research programmes, and has a large international network.

PSY has recently started to organise research around *laboratories*. We believe this provides a more high-level structure that is easier for industry as well as students to relate to than a portfolio of short-term projects. As the Sirius Centre has ended in 2023, we have established a Sirius lab under PSY as a means to continue industry collaboration and innovation that builds on activities from the Sirius centre. We have also recently established a digital twin lab to conduct research on data-driven modelling and analysis.

Table 1: List of number of personnel by categories.

	Position by category	No. of researcher per category	Share of women per category (%)	No. of researchers who are part of multiple (other) research groups at the admin unit	No. of temporary positions
No. of Personnel by position	Professor (1013)	4	0%	0	0
	Senior adviser (1364)	1	0%	0	0
	Researcher (1109)	3	33%	0	3
	Postdoctoral Fellow (1352)	1	0%	0	1
	Doctoral Research Fellow (1017)	8	37.5%	0	8
	Adjunct Associate Professor (1011)	3	66%	0	3

1.2 Research group's strategy

a) Describe the research group's main goals, objectives and strategies to obtain these (e.g. funding, plans for recruitment, internationalisation etc. within the period 2012–2022.

Objective 1: Increase international visibility through

- Top-tier publications
- Community service, in particular chairing and hosting international events

Strategy:

- Increase quality of papers and software artefacts, systematically target leading conferences / journals
- Engage in international research community, both in program committees and in organising events

Objective 2: Obtain funding to sustain and grow research activities across funding arenas:

- Long-term funding: national centres of excellence (SFI or SFF)
- European funding: European framework programmes
- National funding: Norwegian basic and thematic research funding
- Institutional funding: UiO strategic initiatives

Strategy: Work long-term towards establishing SFI and SFF consortia. Engage in consortia-building for, and possibly lead, competitive proposals towards European and Norwegian funding opportunities. Make research relevant to industry. Share experiences and networks to facilitate learning process within group.

Objective 3: Recruitment and internal visibility

- Attract excellent students at Master and PhD level
- Improve visibility at the department level

Strategy: Propose master topics that are understandable to students, implement buddy system to welcome new PhD and Postdoc fellows, recruit actively through international network, engage in teaching of large bachelor-level courses at IFI, engage in boards and committees at the department.

b) Please describe the benchmark of the research group. The benchmark for the research group should be written by the administrative unit in collaboration with the research group. The benchmark can be a reference to an academic level of performance (national or international) or to the group's contributions to other institutional or sectoral purposes.

- **Benchmark 1:** On average, the group should produce 3–5 times as many papers in international peer-reviewed journals or conferences as there are permanent faculty members; the group should contribute to 3–4 top-tier publications per year, either at A/A* ranked conferences, in leading journals or as distinguished papers. Group members should play a significant role in these papers.
- **Benchmark 2:** On average, the group should lead 1–2 and contribute to 2–3 competitive proposals per year at the European or national level (centres, projects or networks), and receive funding from at least some of these applications.
- **Benchmark 3:** The group should attract a substantial number of candidates for MSc and PhD projects. All permanent faculty members should play an active role in the supervision of both MSc and PhD students. On average, each permanent faculty member should supervise at least 2 PhDs and lead 1 Postdoc or researcher.

c) Describe the research group contribution to education (master's degree and/or PhD).

Ölveczky is member of a committee aiming to coordinate and streamline education in formal methods internationally (see their white paper on formal methods within higher education curricula [\[link\]](#)).

PSY teaches courses at the master and PhD level spanning from formal topics in programming languages to system modelling and analysis: compiler construction, models of concurrency, static analysis, rewriting logic, and specification and verification of parallel systems. All these courses can be taken by both master and PhD students. In addition, the group has two new courses under development: one course an introduction course in formal methods for late bachelor / early master students, the other a project-driven course on digital twins. The group also teaches courses at the bachelor level on topics including functional programming, computability and complexity, and modelling and analysis with Maude.

The group led Concurrent Security and Robustness for Networked Systems (ConSeRNS), a strategic research initiative for information security research at IFI (established 2014). Through ConSeRNS, members

of the research groups ND, PSY, DESIGN, ITS collaborated to focus on information security and robustness. ConSeRNS led to the establishment of the Security study programme and the SEC research group at IFI.

PSY supervises master theses in formal methods and associated topics. To attract more students to the group, we have broadened the range of topics we offer to students. In particular, topics related to digital twins have been very popular the last years, with topics related to the “climate barometer for the Oslo fjord”, the integration of knowledge models and simulation-based prediction in SMOL, the integration of static and dynamic data in knowledge models, etc. Topics on the analysis of self-adaptive systems and robot control also appeal to students. PSY also supervises master theses on “traditional” topics in formal methods, e.g., deductive verification, actor-based modelling, type systems. The number of master students in PSY is increasing, from 2 completed in 2018 to 9 in 2022. These numbers continue to grow.

PSY is active in PhD training and supervision. The group has a good number of PhD fellows and is part of the MSCA ITN training network REMARO. Topics span from theory (e.g., programming language semantics, symbolic execution), language design (e.g., resource models) and general analysis techniques (e.g., model checking in Real-Time Maude, hybrid systems) to the development of domain-specific techniques (e.g., railroad, cloud, data privacy, autonomous systems, underwater robots).

d) Describe the support the host institution provides to the research group (i.e., research infrastructure, access to databases, administrative support etc.).

The Department of Informatics provides very good technical support (both technical support staff and IT infrastructure), as well as some financial support for research infrastructure for the digital twin lab since 2022 (e.g., sensors, actuators and compute nodes for a small greenhouse digital twin). IFI also provides some general administrative support, like financial management of projects. The MN Faculty has an EU team that provides advice in developing and realising EU projects.

1.3 Relevance to the institutions

Describe the role of the research group within the organisation. Consider the group’s contribution towards the institutional strategies and objectives and relate the group’s benchmark to these.

Group members are highly engaged in activities at IFI and UiO. In particular, Johnsen was UiO’s representative in the board of *SINTEF ICT* until 2015, and is currently member of the scientific council of UiO’s *dScience* centre. Johnsen was also the leader of IFI’s *Student Research Track* (2016–2022). Ölveczky is member of the board for the *PROSA study program* (and will lead the board from 2024). Owe was the leader of ConSeRNS, a strategic research initiative for information security research at IFI (from 2014), which led to the establishment of the SEC research group and the SECURITY study program at IFI. PhD fellow Juliane Päßler is member of the department’s *Green Council*.

There is a strong strategic focus on **European funding**. The group has been highly successful on the European arena, with a number of European projects, including REMARO, the first MSCA network in which IFI has been a beneficiary. Johnsen participated in UiO’s strategic committee defining UiO’s *Activity Plan for Horizon Europe* in 2021. The department’s *Strategic Plan 2014–2017* has a major strategic goal was to be awarded an SFI or SFF centre. Waaler and Johnsen were instrumental in succeeding in this goal with SIRIUS, the **first SFI awarded** to IFI. Waaler was the director and Johnsen the strategy director of Sirius during its lifetime (2015—2023). Sirius also fits well within the priority application areas identified in IFI’s strategic plan, and specifically *Energy and the Environment*.

IFI’s *Action Plan 2019–2021* emphasises theory and methods inspired by and aimed at societal challenges, in particular **health** and **energy**, and the MN faculty’s strategy emphasises **sustainability**. PSY’s focus on model-based analysis fits in these contexts. In the last years, PSY has started to work on model-based analysis in the context of digital twins, an approach that is particularly well-suited to combine data-driven

model construction with analysis techniques. There is high interest in digital twins in the energy sector; we are starting to build on this interest in follow-up projects to Sirius. Further, PSY has been awarded a project on sustainability, where we collaborate with the Departments of Biology and Mathematics at UiO and the Norwegian Meteorological Institute to develop a digital twin to explore climate changes in the Oslo Fjord. PSY also leads the first project of UiO's newly established Pandemic Centre, where we collaborate with UiO's Faculty of Medicine and Departments of Biology and Philosophy to develop methods based on digital twins to study the global effects of vaccination strategies for an emerging "Pandemic X".

PSY has also contributed to IFI's strategic goal of improving **gender balance**. Among 25 PhD dissertations at PSY 2012–2022, 12 have been female. In the same period, PSY has had five female Postdocs. We recruited a female associate professor to the one faculty position announced in the group in the evaluation period.

1.4 Research group's resources

Describe the funding portfolio of the research group the last five years (2018–2022).

Permanent staff is funded through **basic funding** from UiO. Basic funding also includes PhD and Postdoc positions awarded competitively from IFI and from the MN Faculty through, e.g., UiO's strategic initiatives. Following our funding strategy, PSY has succeeded in obtaining long-term centre funding in the evaluation period 2018–2022 through the SFI Centre of Excellence funding scheme. PSY has also been successful on the European and national arenas. Here is an overview.

Long-term funding: SIRIUS (RCN SFI, 2015–2023), in total 17 380 kNOK was allocated to PSY from the Centre in the evaluation period 2018–2022.

European funding: The group has been involved in the following EU projects in the evaluation period: *HyVar* (H2020, 2015–2018, 703 000 €), *MELODIC* (H2020, 2016–2020, 653 911€), *MORPHEMIC* (H2020, 2020–2023, 558 713 €), *OntoCommons* (CSA H2020, 2020–2023, 505 125 €), *Eur3Ka* (H2020, 2021–2023, 262 500 €), *Remaro* (MSCA ITN, 2020–2024, 584 000€), *NebulOuS* (Horizon Europe, 2022–2025, 643 421 €), *Re4Dy* (Horizon Europe, 2022–2025, 323 750 €), *Plooto* (Horizon Europe, 2022–2026, 556 250 €).

National funding: The group has been involved in the following Norwegian projects in the evaluation period: *Cumulus* (RCN, 2015–2018, 10 460 kNOK), *ADAPt* (RCN Young Research Talents, 2018–2022, 8 000 kNOK), *Smart Journey Mining* (RCN, 2020–2023, 4 063 kNOK).

Institutional funding: The group has obtained the following projects through competitive strategic funding initiatives at UiO: *Climate Barometer for the Oslo Fjord* (UiO Sustainability, 2022–2025, 1 PhD, 1 Postdoc), *ConSeRNS* (UiO Strategic Research Initiative, 2014–2020, 2 PhDs), *Gemini Centre on IoT* (SINTEF + UiO, 2016–2020, 1 PhD). These positions are included under basic funding in Table 2.

Table 2: Describe the sources of R&D funding for the research group in the period 2018–2022.

	2018 (kNOK)	2019 (kNOK)	2020 (kNOK)	2021 (kNOK)	2022 (kNOK)
Basic funding	8 083	8 636	10 308	6 632	5 957
Funding from industry and other private sector sources					
Commissioned research for public sector					
Research Council of Norway	4 567	5 500	5 400	7 335	7 905
Grant funding from other national sources					
International funding e.g. NIH, NSF, EU framework programmes	3 120	1 450	4 100	4 880	5 935
Other					

1.5 Research group's infrastructures

Research infrastructures are facilities that provide resources and services for the research communities to conduct research and foster innovation in their fields. These include major equipment or sets of instruments, knowledge-related facilities such as collections, archives or scientific data infrastructures, computing systems communication networks. Include both internal and external infrastructures.

a) Describe which national infrastructures the research group manages or co-manages.

None

b) Describe the most important research infrastructures used by the group.

- **Open-source software:** The PSY group maintains the following open-source software:
 - **Real-Time Maude:** a modelling and analysis tool for a broad range of real-time systems, based on rewriting logic [[website](#)];
 - **ABS:** an active-object based language and simulation environment for executable models of resource-aware systems such as services deployed on the cloud [[website](#)];
 - **SMOL:** a language and runtime system for orchestrating digital twins that integrates semantic technologies for knowledge bases with dynamic configurations of data-driven and model-based analysis tools [[website](#)]; and
 - **OTTR:** a language and tools for representing and instantiating RDF graph and OWL ontology modelling patterns [[website](#)].
- **Digital twin laboratory:** The group also runs a digital twin laboratory, with facilities to conduct data-driven digital twin experiments.

1.6 Research group's cooperations

Table 3: Reflect on the current interactions of the research group with other disciplines, non-academic stakeholders and the potential importance of these for the research (e.g. informing research questions, access to competence, data and infrastructure, broadening the perspectives, short/long-term relations).

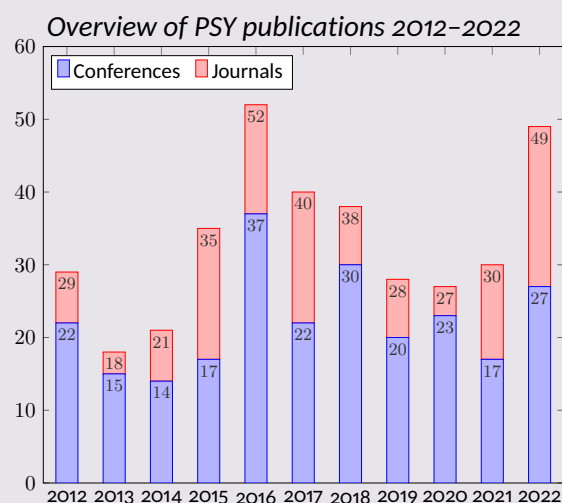
Interdisciplinary (within and beyond the group)	PSY has a core in <i>formal methods</i> but the group's scope is broader, including <i>logic-based knowledge representation</i>, based on semantic technologies, and solutions for <i>autonomous and distributed systems</i>, centred around projects on cloud. There is active collaboration internally between these areas. Inside IFI, the group has long running collaborations with ASR on combining knowledge representation with formal methods in the context of digital twins, and with SEC on formal methods for privacy and security. PSY has a <i>broad international network</i> and collaborates actively with related and complementary groups at leading US and European institutions, including UIUC (US), Cornell (US), Sorbonne (Fr), POSTECH (Korea), ENS Lyon (FR), ETH (CH), Oxford (UK), TU Darmstadt (DE), KIT (DE), RWTH Aachen (DE), U Bochum (DE), U Turin (IT), CNR Pisa (IT), U Bologna (IT), Complutense Uni Madrid (ES), Uppsala (SE), ITU Copenhagen (DK), CWI (NL), TU Eindhoven (NL), TU Delft (NL), Radboud Uni (NL). The group collaborates with roboticists and AI-researchers through the REMARO project. The formal methods and logic research community in Norway is small, but growing. Former PSY students now have permanent faculty positions at several other universities in Norway. We are actively maintaining this network.
Collaboration with other research sectors e.g. higher education, research institutes, health trusts and industry.	Collaboration with research institutes and industry is mostly through Norwegian or European research projects, and through co-supervision of MSc students. Through the SIRIUS centre and several associated EU-funded collaborative projects, the group has an extensive network of companies in the energy sector and a history of joint projects with several of them. In particular the group has had several EU projects with Equinor, DNV, and Aibel, three companies in the Norwegian oil&gas industry. These companies have not only been trying out PSY tools such as ABS and OTTR (which is currently used in production at DNV), but have also been recruiting completed MSc and PhD students from the group over many years—also researchers and senior staff have in periods held part-time positions at the companies to facilitate transfer of knowledge. Among other examples, PSY collaborates with SINTEF in the Smart Journey Mining project, an industry-driven research project on advanced modelling and analysis of user journeys that involves the PSY tool ABS, and collaborated with the RailComplete company in the RailCons project, with a very successful industrial PhD project on station planning for railways. Papers from our research collaboration with industry have received multiple best paper awards.
Transdisciplinary (including non-academic stakeholders) <i>Transdisciplinary research involves the integration of knowledge from different science disciplines and (non-academic) stakeholder communities with the aim to help address complex societal challenges.</i>	• PSY collaborates with epidemiologists on model-based analyses for pandemic prediction (in particular, on how to prevent and control future pandemics), by means of digital twin technology (a first paper appeared in PNAS 2023). This work will be expanded to study global vaccine strategies in 2024–2025 through a project led by Johnsen and funded from the recently established Pandemic Centre at UiO in collaboration with NC Stenseth (Biology, UiO), G Grødeland (Medicine, UiO) and A Strand (Philosophy, UiO). • PSY is also actively involved in transdisciplinary research related to sustainability and digital twins, in collaboration with, e.g., NC Stenseth, Ø Langangen, A Eiler (Biology, UiO); A Jensen (Fluid mechanics, UiO); KH Christensen (Oceanography, Norwegian Meteorological Institute). This is reflected in the project <i>Climate Barometer for the Oslo Fjord</i>, which is supported by funding from the Sustainability initiative at the MN Faculty at UiO.

2 Research quality

2.1 Research group's scientific quality

PSY develops methods and tools for the modelling and analysis of systems, with a core in logic and formal methods, that aim to be practical and applicable to large and sophisticated systems, often demonstrated through real-world, possibly industrial, case studies. Our methods and tools are often quite general and can be applied to different domains. Prominent application domains for our work in the evaluation period are distributed services deployed on cloud, with many EU projects, but also asset models in engineering processes; in particular, Waaler has been heavily involved in research and innovation underlying the standard *ISO/NP 23726 Ontology Based Interoperability* and the work item *ISO/NP 23726-3 Industrial Data Ontology*. Other application domains include digital twins, application control and self-adaptation, transport protocols, robotics, automotive, railways, user journeys, privacy and security. This line of work is complemented by foundational research on modelling languages, semantics and analysis techniques.

PSY maintains open-source software tools (Real-Time Maude, ABS, SMOL, OTTR). Our research contributions are often centred around these tools, which are also used in research and teaching at other universities and in industry. PSY has a good paper production, with more than 370 international peer-reviewed papers 2012–2022 (see figure right) and 40 NVI “level 2” papers. PSY regularly publishes at flagship (core ranking A/A*) conferences in the field, in recent years including CAV, CONCUR, CSF, ECOOP, ESWC, FM, ICFP, ICSE, ISWC, OOPSLA, SEAMS, TACAS, and in leading journals, including ACM Computing Surveys, FMSD, Foundations and Trends in Programming Languages, Formal Aspects of Computing, IEEE Computer, JSS, Science of Computer Programming, SoSyM, TCS, and TSE. Papers by PSY have received distinguished paper or artefact awards at, e.g., iFM 2016, FMCAD 2018, FSEN 2019, ECOOP 2019, ESWC 2022, SEFM 2022, EdbA 2022, FORTE 2022.



The group is well-integrated in the international research community, as witnessed through a number of European projects (7 active per 2022), many of which have been initiated and coordinated by PSY members, and 23 international conferences hosted or chaired by PSY members, including FM, SEFM, iFM, ICTAC, FASE, FACS, and the FTSCS workshop series (and contributed to a total of 233 program committees for international events). The group has also co-organised 4 international PhD schools, in addition to the schools organised by the REMARO MSCA network. Johnsen is board member of Formal Methods Europe, member of the advisory board for the DIGIT centre at Aarhus University (Denmark), member of the PhD Programme Steering Committee at the Department of Computer Science at University of Turin (Italy), and has been member of Advisory Boards for European projects. PSY members have acted as opponents for 34 PhD theses at foreign universities (Asia, Europe, US) since 2012. Johnsen and Ölveczky have given a number of keynotes at international conferences and lectures at international PhD schools in recent years.

Waalder and Johnsen were the main architects behind Sirius, the second SFI centre awarded to UiO, directed by Waaler. Waaler, Horn and Johnsen have been active on the European funding arena, and have all acted as coordinator or scientific coordinator of European projects in the evaluation period. Some of these funding schemes are very competitive. Johnsen co-architected the first European MSCA ITN network in which IFI is a benefactor. Johnsen also led an interdisciplinary SFF proposal, which got to the final selection round in 2022. Tapia Tarifa received a Young Research Talents grant from RCN 2018 (the only such grant awarded to computer science that year).

Please add a link to the research group's publication list at the research group's website:

<https://www.mn.uio.no/ifi/english/about/strategy/evalmit/psy.html>

Table 4: List of projects.

Project 1: <i>SIRIUS: Centre for Scalable Data Access in the Oil & Gas Domain</i> <i>(RCN SFI, 2015—2023)</i>	Project owner(s) (project leaders organisation)	UiO/IFI/PSY and ASR (Director: Arild Waaler, strategy director: Einar Broch Johnsen)
	Total budget and share allocated to research group	Total budget: 250 000 000 NOK PSY budget: 30 000 000 NOK
	Objectives and outcomes (planned or actual) and link to website	The SIRIUS Centre for Research-driven Innovation (SFI) aims to provide the oil & gas business with better ways to access and use the massive amounts of data that are generated in projects and daily operation. Problems with data access are made more acute by the rise of big data, the internet of things and digitalisation of enterprises. SIRIUS targets these problems using an interdisciplinary approach, as successful innovation depends on the combination of technologies. To this aim, SIRIUS does research on high-performance and cloud computing, formal methods, database technology, semantic technologies and natural language processing. The centre also includes researchers in the area of working practices involving novel technology. Website: http://www.sirius-labs.no
Project 2: <i>Optique: Scalable End-user Access to Big Data</i> <i>(EU FP7, 2012—2016)</i>	Project owner(s) (project leaders organisation)	UiO/IFI/PSY and ASR (Coordinator: Arild Waaler)
	Total budget and share allocated to research group	Total budget: 14 000 000 € UiO/PSY budget: 3 000 000 €
	Objectives and outcomes (planned or actual) and link to website	Scalable end-user access to Big Data is essential for the effective support of critical decision making in large companies. The Optique project develops new techniques and infrastructure that will bring about a paradigm shift for data access by (1) using Ontology Based Data Access (OBDA) to provide a semantic end-to-end connection between users and data sources; (2) enabling users to rapidly formulate intuitive queries using familiar vocabularies and conceptualisations; (3) seamlessly integrating data spread across multiple distributed data sources, including streaming sources; (4) exploiting massive parallelism for scalability far beyond traditional RDBMSs; and thus reducing the turnaround time for information requests to minutes rather than days. Website: https://cordis.europa.eu/project/id/318338

Project 3: <i>Envisage: Engineering Virtualized Services</i> (EU FP7, 2013—2016)	Project owner(s) (project leaders organisation)	UiO/IFI/PSY (Coordinator: Einar Broch Johnsen)
	Total budget and share allocated to research group	Total budget 4 701 639 € UiO/PSY Budget: 785 859 €
	Objectives and outcomes (planned or actual) and link to website	The main outcome of Envisage is a practical open-source framework for model-based development of virtualized services, including (1) a behavioural specification language for describing resource-aware models, extending ABS with resources; (2) a simulator with visualisation facilities; and (3) tool support for automated resource analysis, validation of SLA, code generation, and runtime monitoring of SLA for deployed services. The methodology and tools developed in Envisage will allow services to be delivered in a more effective, efficient, and reliable manner than today, accelerating the development cycle and lowering the operational costs for innovative networked services that make use of cloud computing. Website: http://www.envisage-project.eu
Project 4: <i>Morphemic: Modelling and Orchestrating heterogeneous Resources and Polymorphic applications for Holistic Execution and adaptation of Models In the Cloud</i> (EU H2020, 2020—2023)	Project owner(s) (project leaders organisation)	UiO/IFI/PSY (Coordinator: Geir Horn)
	Total budget and share allocated to research group	Total budget: 4 988 693 € UiO/PSY budget: 558 713 €
	Objectives and outcomes (planned or actual) and link to website	MORPHEMIC proposed a unique way of adapting and optimising Cloud computing applications by introducing the novel concepts of polymorph architecture and proactive adaptation. Depending on the application's requirements and its current workload, its components could be deployed in various forms in different environments to maximise the utility of the application deployment and the satisfaction of the user. Proactive adaptation is not only based on the current execution context and conditions but aims to forecast future resource needs and possible deployment configurations. Website: https://www.morphemic.cloud/

Project 5: <i>ADAPt: Exploiting Abstract Data-Access Patterns for Better Data Locality in Parallel Processing (RCN YRT, 2018—2023)</i>	Project owner(s) (project leaders organisation)	UiO/IFI/PSY (PI: Silvia Lizeth Tapia Tarifa)
	Total budget and share allocated to research group	Total budget: 8 000 000 NOK UiO/PSY budget: 8 000 000 NOK
	Objectives and outcomes (planned or actual) and link to website	The modelling of cloud computing systems is an essential step towards automatic management, but the modelling of cloud systems of such complexity remains challenging and yet, unaddressed. In fact, such modelling approaches might be key to predicting future outcomes. Results in the Young Research Talents project ADAPt consider how to derive models for cloud systems empirically. We do so based on models of deployed services in a formal modelling language; once the adherence to the real system is good enough, formal properties can be explored in the model. In the project, we have used data collected empirically from small scenarios to simulate the execution of higher-intensity scenarios, to predict resource consumption. A similar approach can be further used for other sorts of predictions. Website: https://prosjektbanken.forskingsradet.no/en/project/FORISS/274515
Project 6: <i>HyVar: Scalable Hybrid Variability for Distributed Evolving Software Systems (EU FP7 FET, 2015—2018)</i>	Project owner(s) (project leaders organisation)	Coordinator SANTER REPLY SPA (IT) Scientific coordinator: Einar Broch Johnsen (UiO/IFI/PSY)
	Total budget and share allocated to research group	Total budget: 2 793 870 € UiO/PSY budget: 703 750 €
	Objectives and outcomes (planned or actual) and link to website	HyVar developed a framework for continuous software evolution in distributed systems which combines the description of evolution as a software product line, a scalable cloud infrastructure to monitoring and customisation of software upgrades for remote devices, and over-the-air upgrade technologies. Website: https://cordis.europa.eu/project/id/644298

Project 7: <i>REMARO: Reliable AI for Marine Robotics</i> <i>(EU MSCA, 2020—2024)</i>	Project owner(s) (project leaders organisation)	IT-University of Copenhagen (DK) Co-initiator: Einar Broch Johnsen (UiO/IFI/PSY)
	Total budget and share allocated to research group	Total budget: 4 076 959 € UiO/PSY budget: 584 684 €
	Objectives and outcomes (planned or actual) and link to website	The network will educate 15 PhD research fellows on complementary aspects of reliable autonomy for underwater robotic applications. The REMARO research fellows will develop the first ever submarine robotics AI methods with quantified reliability, correctness specifications, models, tests, and analysis & verification methods. Website: http://www.remaro.eu
Project 8: <i>SJM: Smart Journey Mining</i> <i>(RCN IKTPLUSS, 2021—2025)</i>	Project owner(s) (project leaders organisation)	SINTEF
	Total budget and share allocated to research group	Total budget: 15 800 000 NOK UiO/PSY budget: 4 063 000 NOK
	Objectives and outcomes (planned or actual) and link to website	The overall goal of SJM is to increase the quality of service and support the successful digitalisation of services by uniting research on process mining and customer journeys using new developments in logic-based analysis and artificial intelligence. In SJM, we combine process mining of system logs to construct games between user and service, that can be explored by means of model checkers. Website: https://smartjourneymining.no

Project 9: <i>HATS: Highly Adaptable and Trustworthy Software using Formal Models (EU FP7 FET, 2009—2013)</i>	Project owner(s) (project leaders organisation)	Coordinator: Chalmers, SE
	Total budget and share allocated to research group	Total budget 7 301 979 € UiO/PSY Budget: 644 460 €
	Objectives and outcomes (planned or actual) and link to website	The HATS project delivered models for highly adaptable, long-lived systems, combining trustworthiness with a high degree of (spatial) variability to accommodate a range of requirements and operating conditions, and temporal evolvability to allow these parameters to change over time. The main outcome was the ABS modelling language, a formal notation of distributed, component-based systems. ABS allows precise description of software product line features and components and their instances. The main project outcome is a methodological and tool framework achieving not merely far-reaching automation in maintaining dynamically evolving software, but an unprecedented level of trust while informal processes are replaced with rigorous analyses based on formal semantics. This includes the perspective of designing self-adapting software systems. Website: https://cordis.europa.eu/project/id/231620
Project 10: <i>Melodic: Multi-cloud Execution-ware for Large-scale Optimized Data-Intensive Computing (EU H2020, 2016—2020)</i>	Project owner(s) (project leaders organisation)	UiO/IFI/PSY (Coordinator: Geir Horn)
	Total budget and share allocated to research group	Total budget: 4 890 223 € UiO/PSY budget: 653 911 €
	Objectives and outcomes (planned or actual) and link to website	MELODIC enabled data-intensive applications to run within defined security, cost, and performance boundaries seamlessly on geographically distributed and federated cloud infrastructures. MELODIC integrated and extended the results and the open source platforms from three projects with the Hadoop and Spark big data frameworks. Website: https://www.morphemic.cloud/

Table 5: Research group’s contribution to publications.

Paper 1: <i>HybridSynchAADL: Modeling and Formal Analysis of Virtually Synchronous CPSs in AADL/ CAV / 2021 / https://doi.org/10.1007/978-3-030-81685-8_23</i>	Authors	Jaehun Lee, Sharon Kim, Kyungmin Bae, Peter Csaba Ölveczky
	Short description	Provides a modelling language that extends the embedded systems modelling standard AADL to cyber-physical systems with continuous behaviours. Provides under-the-hood formal analysis capabilities to such models, integrated into the industrial modelling environment, and shows the effectiveness of the language and tool on autonomous collaborating drones.
	Research group’s contribution	Part of a long-term research program by Ölveczky, Bae, and José Meseguer at UIUC to equip an avionics/embedded systems modelling standard with effective formal analyses. Ölveczky contributed significantly to the research and write-up of the paper.
Paper 2: <i>Bridging the semantic gap between qualitative and quantitative models of distributed systems / OOPSLA / 2022 / https://doi.org/10.1145/3563299</i>	Authors	Si Liu, José Meseguer, Peter Csaba Ölveczky , Min Zhang, David A. Basin
	Short description	Shows a way of automatically transforming an untimed non-probabilistic (“qualitative”) into a timed and probabilistic model for a wide class of distributed systems. This makes possible model-based analysis of both correctness and performance without creating different models for these different purposes. The effectiveness of the approach is demonstrated on large cloud-based transaction system designs.
	Research group’s contribution	Ölveczky contributed significantly to the development of the ideas and proving their correctness, as well to the write-up of the paper.
Paper 3: <i>Automatic Analysis of Consistency Properties of Distributed Transaction Systems in Maude / TACAS / 2019 / https://doi.org/10.1007/978-3-030-17465-1_3</i>	Authors	Si Liu, Peter Csaba Ölveczky , Min Zhang, Qi Wang, and José Meseguer
	Short description	Showed how a wide range of consistency requirements of cloud-based transaction systems can be automatically analysed by a theory transformation, and demonstrated the effectiveness of the method on large industrial systems.
	Research group’s contribution	Ölveczky contributed significantly to the development of the ideas and to the write-up of the paper.

Paper 4: <i>Ready, set, Go!: Data-race detection and the Go language / Science of Computer Programming / 2020 / https://doi.org/10.1016/j.scico.2020.102473 / https://martinsteffen.github.io/assets/download/20/readyssetgo-scp.pdf</i>	Authors	Daniel Schnetzer Fava, Martin Steffen
	Short description	Studies a crucial aspect of the concurrency model of the Go programming language and provides a formalisation of the Go memory model. This formalisation was used to find and fix a non-trivial bug in the Go data-race detector that ships with the Go distribution. Rooted in our theory, the improvements and the fix to the data-race detector were incorporated into release 1.16 of the Go language.
	Research group's contribution	This work was conceived and realised in its entirety by Fava and Steffen from PSY.
Paper 5: <i>Weighted Games for User Journeys / SEFM / 2022 / https://doi.org/10.1007/978-3-031-17108-6_16 / https://ebjohnsen.org/publication/22-sefm/22-sefm.pdf</i>	Authors	Paul Kobialka, Silvia Lizeth Tapia Tarifa, Gunnar Rye Bergersen, Einar Broch Johnsen
	Short description	Shows how system logs from user journeys in industry can be used to construct games in UPPAAL, and how model checking can then be used to automatically analyse user journeys and synthesizer optimal strategies for a service provider. This was the first paper using formal methods to analyse user journeys from the user perspective. Best paper award, SEFM 2022
	Research group's contribution	The development of ideas and the experimental design were done jointly by Kobialka, Tapia Tarifa and Johnsen. The technical work was conducted by Kobialka. All authors contributed to the analysis of results and to writing the paper.
Paper 6: <i>SAT modulo discrete event simulation applied to railway design capacity analysis / Formal Methods in System Design / 2021 / https://doi.org/10.1007/s10703-021-00368-2</i>	Authors	Bjørnar Luteberget, Koen Claessen, Christian Johansen, Martin Steffen
	Short description	Proposes a new method of combining SAT with discrete event simulation. This new method proved useful for designing a solver for capacity analysis in early phase railway construction design, based on capacity specifications suited for construction projects, expressing properties such as running time, train frequency, overtaking and crossing.
	Research group's contribution	Luteberget was the main driver for this work, and did all technical development. Johansen and Steffen both contributed significantly to the development of ideas and the write-up of the paper.

Paper 7: <i>Lazy product discovery in huge configuration spaces / ICSE / 2020 / https://doi.org/10.1145/3377811.3380372 / https://ebjohnsen.org/publication/20-icse/20-icse.pdf</i>	Authors	Michael Lienhardt, Ferruccio Damiani, Einar Broch Johnsen , Jacopo Mauro
	Short description	The work provides a lazy algorithm for finding valid configurations in huge configuration spaces by means of feature models and SMT solving, with a formalised proof of completeness for the configuration discovery process. The results are demonstrated on the configuration space of the Gentoo Linux distribution, and results in a complete package manager for the Gentoo.
	Research group's contribution	Johnsen and Mauro contributed significantly to the development of ideas and to the write-up of the paper. Johnsen did the experimental design and Mauro worked on the technical development.
Paper 8: <i>DPL: A Language for GDPR Enforcement / CSF / 2022 / https://doi.org/10.1109/CSF54842.2022.9919687 / https://ebjohnsen.org/publication/22-csf/22-csf.pdf</i>	Authors	Farzane Karami , David A. Basin, Einar Broch Johnsen
	Short description	Shows how programming languages can guarantee GDPR compliance for all programs by means of runtime checking (necessary to support the withdrawal of consent). An operational semantics for GDPR-aware program execution was formalised and proven correct in Maude.
	Research group's contribution	Karami was the main driver for this work, and did all technical development. Karami and Johnsen both contributed significantly to the development of ideas and the write-up of the paper.
Paper 9: <i>Programming and Debugging with Semantically Lifted States / ESWC / 2021 / https://doi.org/10.1007/978-3-030-77385-4_8 / https://ebjohnsen.org/publication/21-eswc/21-eswc.pdf</i>	Authors	Eduard Kamburjan , Vidar Norstein Klungre, Rudolf Schlatte , Einar Broch Johnsen , Martin Giese
	Short description	Proposes a novel integration of programming languages with semantic technologies, which enables several promising novel applications including the use of semantic technology, including reasoning, for debugging and validating the sanity of program states, and integration with external knowledge graphs. This work, which was done in collaboration with the ASR group, forms the basis for digital twin architectures in SMOL.
	Research group's contribution	Kamburjan was the main driver for this work. Johnsen and Schlatte contributed significantly to the development of ideas and write-up of this paper, as well as to the design of SMOL. Schlatte contributed to the implementation.
Paper 10: <i>Parallel Cost Analysis / ACM Trans. Comput. Log. / 2018 / https://doi.org/10.1145/3274278 / https://ebjohnsen.org/publication/18-tocl/18-tocl.pdf</i>	Authors	Elvira Albert, Jesús Correas, Einar Broch Johnsen , Violet Ka I Pun , Guillermo Román-Díez
	Short description	This paper considers static analysis of parallel cost, and captures the cost of synchronized tasks executing in parallel by exploiting the true concurrency available in the execution of distributed processes.
	Research group's contribution	This analysis was based on the concurrency model of ABS, developed by PSY. Pun and Johnsen contributed significantly to the development of the ideas for the paper, to the technical development and to the preparation of the manuscript.

Table 6: Please add a list with the research groups monographs/scientific books. Max 10 listed: title, first three authors et al and link to webpage (if any)..

No.	Authors-Title (Please highlight group members) - link to webpage/review
1	Peter Csaba Ölveczky : <i>Designing Reliable Distributed Systems — A Formal Methods Approach Based on Executable Modeling in Maude</i> . Undergraduate Topics in Computer Science, Springer 2017, ISBN 978-1-4471-6686-3, pp. 1-298. (Published 2018.) Webpage: https://doi.org/10.1007/978-1-4471-6687-0

2.2 Research group's societal contribution

Describe the societal impact of the group's research. Consider contribution to education, economic, societal and cultural development in Norway and internationally.

A new ISO standard, ISO/NP 23726 *Ontology Based Interoperability*, has been established as a direct result of the work undertaken by SIRIUS partner DNV in collaboration with PSY researchers in SIRIUS and partners. Part 3, *Industrial Data Ontology*, is in the standardisation pipeline. ISO/NP 23726 is located in ISO Technical Committee 184, Sub-committee 4 Industrial Data.

A DNV Recommended Practice document about the *Information Modelling Framework* (IMF), a language developed by PSY researchers in SIRIUS in collaboration with the companies Aibel, DNV, and Equinor, has been prepared, providing a document that can be referenced in information delivery requirement specifications. This can potentially transform information deliveries and technical information along the oil&gas value chain. The further ambition is to include IMF as an ISO standard.

The group has been instrumental for several industry funded innovation projects, including:

- NORSOK Z-TI pre-project, funded by NORSOK through Standards Norway, for investigating semantics based digital requirements.
- READI Joint Industry Project, led by DNV, for developing and implementing digital requirements. The IMF concept was conceived in READI.
- Digital Design Basis Joint Industry Project, led by Aker Solutions, for developing a semantics based representation of digital design bases.
- Equinor and AkerBP have funded a project to recast datasheets into IMF Types.

The group is at the time of writing active in 7 EU funded research and innovation projects with participation from industry.

Table 7: The research group's societal contribution, including user-oriented publications, products (including patents, software or process innovations)

No.	Name of publication/product	Date of publication/product	Link to the document
1	Real-Time Maude open-source software		Website
2	ABS open-source software		Website
3	SMOL open-source software		Website
4	OTTR open-source software		Website
5	IMF open-source portal to IMF resources		Website
6	Article about position paper on resource-aware modelling: <i>Four Challenges Facing Exascale Application Prep</i> , HPC Wire	22 June 2015	Link
7	Article about the HyVar project: <i>Gjer smarte bilar smartare</i> , Uniforum	16 March 2015	Link (in Norwegian)
8	Interview with Einar Broch Johnsen about Envisage: <i>Forsker på smartere sky</i> , Finansavisen	18. Nov. 2013	Link (in Norwegian)
9	Article by Einar Broch Johnsen in Aftenposten: <i>Lavtrykk i dataskyen</i>	10 Oct. 2013	Link (in Norwegian)
10	Article about the Envisage project: <i>Slik skal pasientsensorer kommunisere bedre</i> , Teknisk ukeblad	16 July 2012	Link (in Norwegian)

3 Challenges and opportunities

Information about the strengths and weaknesses of the research group is obtained through the questions above. In this chapter, please reflect on what might be the challenges and opportunities for developing and strengthening the research and the position of the group.

Over the past years (2018–2023), PSY has been successful at balancing high quality academic research and top-tier publications with a broad portfolio of externally funded projects. PSY's international network and industry connections are both excellent. However, unless the group is supported by the department through fresh faculty positions, the maintenance of these networks and the further development of associated activities are completely dependent on external funding.

In the evaluation period, our success with the Sirius centre has provided a stable core for the group, around which many other projects have contributed additional funding and activity. Sirius ended in late 2023, resulting in a significant challenge for us in maintaining the acquired knowledge built around the centre, as well as the group's size and current levels of research activity and quality, e.g., ensuring stable conditions for research staff on external funding. Another challenge is the major change in the funding landscape in this period: Funding possibilities are becoming increasingly applied, with a shift away from methodological research and software engineering towards societal challenges in thematic calls, both at the national and European level.

However, we experience an increasing interest in formal methods and model-based analysis from industry, which makes it possible to mitigate this shift in the funding landscape. There is a growing dependence on increasingly complex systems in both industry and society, and an increasing interest in model-based analysis in other scientific disciplines. These tendencies create opportunities for the group that we aim to exploit. In particular, the group has started to develop a research program on digital twins, which combines our interest in model-based analysis with the huge industrial interest in model-centric decision making. This line of research is not only receiving strong interest from industry, it also opens many possibilities for interdisciplinary research; for example, we have already started collaborations related to geoscience, climate change in marine environments, and health. We believe that data-driven model-centric systems such as digital twins is a huge opportunity for PSY, both for new externally funded projects and to improve cohesion and consolidate different research interests and methods used within the group.

To maximise impact of the Sirius centre under these conditions, we have created a *Sirius lab*, in which we can build on activities and industry networks established in the Sirius centre. We are actively preparing new projects in the context of these industry networks. We have also created a *Digital Twin lab*, to organise our research on digital twins. We believe the creation of labs will make our research easier to find across the various projects for both industry, other universities and research institutes and potential students.

Another challenge that we experience, is to ensure good local recruitment given the increasingly applied educational focus of the local students. For this reason, PSY members are now engaging in the larger Bachelor-level courses (e.g., functional programming, domain-specific languages) to improve our internal visibility and trigger the interest of local students for PSY topics. We have also engaged in the board of the *programming* study program, and in course renewal at the master level to give the students better opportunities for training in formal methods and computer science theory. We are experiencing that students relate to topics that intersect formal methods with other subjects; e.g., analysis techniques for underwater robots, a digital twin of the Oslo Fjord, and similar MSc thesis topics attract many students.