SIRIUS Final Report

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Foreword by centre director

I am proud to present the final report of the SIRIUS Centre for Research-Based Innovation. SIRIUS started operation in November 2015. After eight years of intense collaborative work, our team of researchers and their collaborators in the partner companies concluded their work in October 2023.

This report summarizes the main achievements of SIRIUS, addressing all aspects of its operation, ranging from the work of our PhD students to the innovation projects driven by our corporate partners. The material ranges in style from statistics in tables to quotes from PhD students and partner representatives that capture their individual experience of the centre.

Particular care has been taken in the development of a detailed and exhaustive list of publications. The sections about research results summarize our main achievements with reference to published material. Further information about SIRIUS can be found in our annual reports from the centre and on the SIRIUS web pages.

Arild Waaler

Professor
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Foreword by head of host institution

The Center programs by the Research Council of Norway (RCN) have long been of particular importance to the University of Oslo (UiO). Under this scheme, the SIRIUS Center for Research-Driven Innovation has made a particularly strong contribution to the overall innovation activities at UiO and specifically at the Department of Informatics.

In addition to enhancing research activities at the core of computer science, SIRIUS has developed a robust collaboration with the Norwegian business sector and international research partners. SIRIUS has also devised new mechanisms for implementing this type of project at a research-intensive university such as the University of Oslo. A recent strategic initiative by the UiO Faculty for Mathematics and Natural Sciences, the UiO Centre for Computational and Data Science (dScience) has utilized experience from SIRIUS when it was established in 2021, and former SIRIUS staff have taken on central roles in developing dScience.

Over the life span of SIRIUS, several research and innovation results have been produced. Of these, we mention two high-impact examples: (i) Key SIRIUS researchers have been part of developing novel concepts of knowledge-driven machine learning, together with the SFI BigInsight and collaborators at UiO and beyond. The SIRIUS research program entitled Domain Adapted Data Science was instrumental for this achievement, and the new SFF Integreat is built on these foundations. (ii) The interdisciplinary SIRIUS research program on Information Modelling of Industrial Assets and Facilities, combining logic, engineering knowledge, and emerging semantic web technologies, has received international attention from both academic researchers and industry. The results have contributed to extended networks, impacted standards, and secured funding from the Horizon Europe framework program. This program has also initiated novel initiatives in digital twin technologies.

On behalf of the University of Oslo and our department, I am proud to observe that SIRIUS has built new competences in the realm of computer science that are important for the Norwegian society at large, and for industry in particular.

Stephan Oepen
Head of Department
Department of Informatics
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Summary

Brief description of primary objective

The primary objective of SIRIUS has been *to accelerate the development and adoption of innovative data access technology in the Oil & Gas industry via broad-based collaboration with a short feedback loop across the whole value chain.*

The objective has matured and been made more concrete over the lifetime of the centre in response to new knowledge and current trends in the industry. The key priority has been to demonstrate how interplay between innovative data access technologies enables new ways of accessing actionable information in industry data, thereby enabling data-driven decision making and transformed work processes. Three trends of particular importance have been the transformative power of Artificial Intelligence, digital transformation of document centric workflows through structuring of industry data, and increased industry focus on digital twins.

Brief description of the consortium and categories of partners

The SIRIUS consortium consisted of research institutions and corporate partners that span the oil and gas value chain. Academic researchers contributed from University of Oslo, NTNU, University of Oxford, Simula Research Laboratories, and SINTEF.

Company partners include the operator Equinor; three engineering contractors, two service providers and fifteen suppliers, within IT and engineering services. Two of these are vendors for scalable computing, four are consultancy companies, and six of them are SMEs.

Scientific results

Fundamental research within six research programs was applied to the partners' business challenges related to subsurface data, engineering, and operational data. We also looked at cross-sectoral applications for healthcare and environmental data. Research on industrial transformation was conducted using the demonstration work.

SIRIUS researchers have published extensively and received wide international recognition. In total SIRIUS delivered 257 peer reviewed publications and 10 best paper awards.

The award-winning Geological Assistant applies logic-based technology to enable explorationists to express interpretive uncertainty as scenarios with potential alternative interpretations. With this approach, geologists' knowledge and rules of thumb are explicitly represented in a tool that allows interaction with collected data.

We have developed a new modelling methodology that quantifies heterogeneity and resource contention in MPI-based reservoir simulations. This is implemented in the OPM (Open Porous Media) open-source framework. Equinor uses this to achieve more efficient and faster reservoir simulations.

We have also, through the OTTR Reasonable Ontology templates, provided tools that simplify the use of semantic models in industrial applications. This prize-winning research supported a large program of translation and application that established good practices for digital twins and the IMF language for structuring engineering information using system principles. This work has been linked with the PeTWIN Norway-Brazil project and the DSYNE INTPART network on digital requirements.

Results and impact for industry, public sector, and society at large.

SIRIUS has used an innovative, research-based process, the partner canvas, to engage with companies to ensure alignment of their goals with the centre. This improved the focus of activities and added to the impact of the centre.

Research on semantic asset modelling has created impact around Industry 4.0 in the oil and gas industry, addressing the structure of facility asset information, the way that it is created and exchanged through the value chain of the industry, and the application of logic and semantic web technology to information modelling. This has resulted in a family of new languages for information modelling that enable facility assets to be documented as scalable knowledge graphs. The languages are in use in several companies, they are under implementation in the oil and gas industry, a DNV Recommended Practice document is under development, and a process for ISO standardization has been initiated.

Researcher training

The SIRIUS centre has emphasized training young researchers, with initiatives to attract and retain talented candidates. PhD level training is provided within specific disciplines. The centre also offered additional courses on the oil and gas industry and organized field trips. A mentoring program brought mentors from industry to support the career development of SIRIUS researchers. This fostered collaboration and promoted diversity. Our experience is that a formal and structured mentoring program that connects senior industrialists with junior researchers is valuable for collaborative innovation.

International cooperation

SIRIUS has been involved in international collaborations, notably with Brazil, the United Kingdom, and the European Union. In Brazil, SIRIUS played a leading role in the annual November conference in Rio de Janeiro. We have built collaboration with Brazilian universities. SIRIUS has been a partner in 12 European projects and has been active in standardization initiatives with membership in DEXPI, AutomationML and the Industrial Digital Twin Association. This has built SIRIUS a strong network in German industry.

Added value of organising the activities as a centre

SIRIUS has addressed real-world problems in industry. Such problems tend to be many-faceted in that they seldom fall nicely within the ambit of a single research community. SIRIUS' research achievements are a result of applying a combination of techniques in new ways motivated by industry problems. The broad-based collaboration between researchers and partners across the value chain has made this research possible. The centre's construction, scale, and long-term time span have been instrumental in enabling enduring collaboration between researchers and partners. We have established networks that have created value both in terms of knowledge and innovation. SIRIUS played a key role in several joint industry programs aiming towards better standards for sharing of industry data.

Future plans for the centre

All research groups in SIRIUS have been able to raise funding to continue the research programs after closing of the centre. SIRUS was key in establishing Integreat, a new Centre of Excellence for knowledge-driven machine learning. The SIRIUS SFI continues as the *SIRIUS laboratory* located under Dept. of Informatics at the University of Oslo. SIRIUS researchers are involved in six ongoing European projects organised by the SIRIUS laboratory.

The dScience Centre at the University of Oslo has established a partner program which will maintain SIRIUS' network and seek opportunities for funding of research-based innovation.

Sammendrag

Kortfattet beskrivelse av målsetning

Målsetningen til SIRIUS har vært *å akselerere utvikling og bruk av innovative teknologier for dataaksess i olje og gassindustrien gjennom bredt samarbeid, og med rask tilbakeføring av erfaring, gjennom hele verdikjeden.*

Målsetningen har blitt modnet og gjort mer presis gjennom senterets levetid i respons til ny kunnskap og aktuelle trender i industrien. Hovedprioriteringen har vært å demonstrere hvordan samspill mellom innovative teknologier for dataaksess muliggjør nye måter å aksessere informasjon som ligger i industridata og på den måten legge til rette for data-drevne beslutninger og transformerte arbeidsprosesser. Tre spesielt viktige trender har vært den transformative kraften i kunstig intelligens, digital transformasjon av dokument-sentrert arbeidsflyt gjennom strukturering av industridata, og øke fokus i industri på digitale tvillinger.

Kortfattet beskrivelse av konsortiet og kategorien av partnere

SIRIUS-konsortiet bestod av forskningsinstitusjoner og partnerselskap som utspenner verdikjeden i olje og gassindustrien. Akademiske forskere har bidratt fra Universitetet i Oslo, NTNU, Universitetet i Oxford, Simulasenteret og SINTEF.

Bedriftspartnere inkluderer operatøren Equinor, tre kontraktører, to service-selskap, og femten leverandærer av IT og ingeniørtjenester. To av disse er leverandører av datateknologi for tungregning, fire er konsulentselskaper og seks av dem er SMBer.

Vitenskapelige resultater

Grunnforskning innen seks forskningsprogram ble anvendt på problemstillinger nyttet til undergrunnsdata, ingeniørdata og driftsdata motivert fra forretningssiden i partnerselskapene. Vi arbeidet også med anvendelser innen andre sektorer, spesielt helse og miljødata. Forskning på industriell transformasjon ble utført som del av demonstratorarbeidet.

SIRIUS-forskere har hatt utstrakt publikasjonsvirksomhet og høstet bred internasjonal anerkjennelse. SIRIUS har totalt levert 257 fagfellevurderte publikasjoner og 10 utmerkelser for beste artikkel.

Den prisvinnende Geologiske Assistent anvender logikk-basert teknologi for å sette eksperter innen leting i stand til å uttrykke usikkerhet ved tolkning som scenarioer med potensielt alternative tolkninger. Geologenes kunnskap og tommelfinger-regler blir dermed eksplisitt representert i verktøy som tillater interaksjon med innsamlede data.

Vi har utviklet en ny modelleringsmetodologi som kvantifiserer heterogenitet og ressurskonflikt i MPI-baserte reservoar-simuleringer. Dette er implementer i OPM (Open Porous Media)-rammeverket. Equinor bruker dette til å oppnå mer effektive og raskere reservoar-simuleringer.

Vi har også, gjennom OTTR-templates, levert verktøy som forenkler bruk av semantiske modeller i industrielle anvendelser. Denne prisvinnende forskningen understøtter et omfattende program for oversettelse og anvendelse av beste praksis for digitale tvillinger, samt IMF-språket for strukturering av ingeniør-informasjon ved bruk av system-prinsipper. Dette arbeidet har blitt linket til PeTwin- prosjektet, et norsk-brasiliansk samarbeid, og DSYNE, et INTPART-nettverk satt opp for å studere digitale krav.

Resultater og effekt for industri, offentlig sektor og samfunn

SIRIUS har brukt en innovativ forskningsbasert prosess, partner canvas, for å engasjere selskaper og sikre sammenfall mellom deres mål med senterets mål. Dette ga forbedret fokus og økte effekten til senteret.

Forskning på semantisk anleggsmodellering har økt effekten til Industri 4.0 i olje og gassindustrien gjennom å adressere strukturen til anleggsinformasjon, måten den er skapt og blir utvekslet gjennom verdikjeden til industrien, og anvendelse av logikk og semantisk webteknologi i informasjonsmodellering. Dette har gitt en familie av nye språk for informasjonsmodellering som gjør at anlegg kan dokumenteres som skalerbare kunnskapsgrafer. Språkene er i bruk i flere selskap, de er under implementasjon i olje og gassindustrien, et DNV RP (Recommended Practice)-dokument er under utvikling, og en prosess for ISO-standardisering har blitt initiert.

Opptrening av forskere

SIRIUS har lagt vekt på opptrening av unge forskere med initiativer for å tiltrekke og beholde talentfulle kandidater. Opptrening på PhD-nivå har blitt gitt innenfor spesifikke disipliner. Senteret har også tilbudt innføringskurs i olje og gassindustrien og organiserte feltturer. Et mentoring-program bragte mentorer fra industrien sammen å støtte karriereutvikling av SIRIUS-forskere. Dette har ledet til økt samarbeid. Vår erfaring er at et formelt og strukturert mentorprogram som kobler seniorressurser fra industri med unge forskere er verdifullt for samarbeid og innovasjon.

Internasjonalt samarbeid

SIRIUS har vært involvert i internasjonalt samarbeid, spesielt med Brasil, Storbritannia og EU. SIRIUS spilt en nøkkelrolle i den årlige Novemberkonferansen i Rio de Janeiro. Vi har bygget samarbeid med brasilianske universiteter. SIRIUS har vært partner i 12 EU-prosjekter og har vært aktive i standardisering knyttet til DEXPI, AutomationML og Industrial Digital Twin Association. SIRIUS har på denne måten bygget et sterkt nettverk i tysk industri.

Økt verdi ved organisering av aktivitetene i form av et senter

SIRIUS har adressert reelle problemer fra industri. Slike problemer er ofte mangesidete siden de sjelden faller pent innenfor fokus til et bestemt forskningsområde. Forskningen i SIRIUS har kommet som et resultat av å anvende en kombinasjon av teknikker på nye måter, motivert av industriproblemer. Det brede samarbeid mellom forskere og partnere gjennom verdikjeden har gjort denne forskningen mulig. Senterets konstruksjon, omfang og langsiktighet har vært instrumentell for å fremme vedvarende samarbeid mellom forskere og partnere. Vi har etablert nettverk som har skapt verdi i form av kunnskap og innovasjon. SIRIUS har spilt en nøkkelrolle i flere industriprogram, som industrien selv har finansiert, for å fremme bedre standarder for deling av industridata.

Fremtidsplaner for senteret

Alle forskningsgrupper i SIRIUS har utløst videre finansiering. SIRIUS spilte en nøkkelrolle i etableringen av Integreat, et nytt SFF på kunnskapsdrevet maskinlæring. SIRIUS videreføres som *SIRIUS-laboratoriet* ved Institutt for informatikk, UiO. SIRIUS-forskere er involvert i seks pågående EU-prosjekter organisert gjennom SIRIUS-laboratoriet.

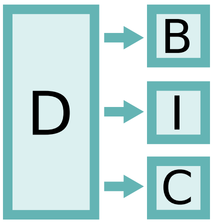
dScience-senteret ved UiO har etablert et partnerprogram som vil videreføre industrinettverket til SIRIUS og arbeide for videre finansiering av forskningsbasert innovasjon.

1 Vision and objectives

The primary objective of SIRIUS has been *to accelerate the development and adoption of innovative data access technology in the Oil & Gas industry via broad-based collaboration with a short feedback loop across the whole value chain.*

During the centre period the primary objective has been gradually matured and concretised in response to new knowledge and current trends in the industry. We have supported the twin transition of the oil & gas industry towards digital transformation and decarbonisation. By data access technology the SIRIUS consortium means methods, languages, and computer implementations that enable users to lift information that currently reside in data repositories and technical documents into computable information structures that can support the data driven decision making and transformed work processes needed in the twin transition. This is a vital component in the digital transformation of our end-user partners' operations.

SIRIUS data access methods and technologies are designed to enable lifting of data (**D**) into three types of computational information structures:



B: Models of system behavior, including models expressed in terms of differential equations and agent-based models.
I: Models of semantic information, including knowledge graphs that interplay with background knowledge and contextual information expressed in terms of ontologies.
C: Computable models, including methods for optimizing computer programs that exploit high performance computers and cloud resources.

SIRIUS' primary objectives are listed in the following table. For each objective, we highlight the achievements the centre has made in fulfilling the objectives.

O1 Accelerate the innovation process for data access in the Oil & Gas domain	• IMF and related technologies developed and verified in JIPs where the methods have been applied to ongoing field development projects. • Establishment of reference models and best practices for digital twins in O&G industry. • Contribution to revitalization of standardization initiatives in manufacturing and the process industries. • Knowledge modelling and support for digital geology. • Improved numerical methods for reservoir simulation.
O2 Transfer knowledge and expertise via feedback loop in the innovation cycle	• Establishment of a project innovation cycle for driving innovation based on fundamental ICT research through Beacon programs. • Use of the partner canvas as a mechanism for documenting and aligning partner's aims and expectations.
O3 Transform end-user work-practices	• Qualitative research on work processes in digital geology and field development projects. • Reference models and best practices for defining and implementing digital twins.

O4 Deliver scalable information systems for accessing disparate data sources	• Domain-adapted language models for oil & gas documentation. • Semantic-based machine learning for recognition of diagrams in technical geoscience documentation. • Open implementation of the Volve dataset for research on scalable data access. • Semantic methods and pipelines for handling time-series data. • OTTR as a tool for creating and maintaining large semantic models.
O5 Deliver scalable, efficient, and robust computational environment	• Contributed to the next generation of NUMA architecture processors and high-capacity switches. • Development of robust tools for optimal deployment of complex cloud systems. • Contributed to technical basis of RDFox and ONTOP graph databases.
O6 Reinforce mutual understanding and shared vision	• Development of centre strategy based on research programs and beacon projects. • Additional partners in life of centre from large companies (Bosch, Aker Solutions, Aibel, TechnipFMC) and software vendors (Billington, Prediktor, Ontopic, MetaPhacts, Envester, Bouvet). • Shift of focus from big data to industrial digital transformation and Industry 4.0. • New collaborations in Brazil: UFRGS, UFES, Petrobras. • New collaborations in Europe: University of Bielefeld, TU Dresden, OVGU Magdeburg, Ålborg University, Evonik, Siemens, Bosch, DEXPI, Industrial Digital Twin Association, AutomationML association, Knowledge Graph Association. • Further education courses at M.Sc. level on industrial digitalization and digital twins. • High proportion of female PhD fellows and early-career researchers. • Network for female researchers. • Successful, high-impact mentoring program. • Use of fourth year for PhD students to work with partner on implementation of research results.
O7 Establish SIRIUS as an internationally recognized Centre of Excellence	• Additional RCN funding: PeTWIN, DSYNE and FRIPRO Yong research talent grant for Lizeth Tapia Tarifa. • Horizon 2020 and Horizon Europe projects: MELODIC, Ontocommons, Eur3ka, Re4Dy (https://re4dy.eu), Plooto (https://www.plooto-project.eu), Tech4Maase, and Sm4tenance (https://sm4rtenance.eu).

	• Leading role in the annual Norway-Brazil November Conference. • Key researchers are now participants in the INTEGREAT SFF. • Industry publications and presentations on big data, digitalization, and Industry 4.0. • Contribution to industry and international standards: DNV, DEXPI, ISO. • Recognized international contributor on semantic technologies and industrial knowledge representation.

2 Basic facts about the centre

2.1 Research Partners, Company, and Public Partners

2.1.1 Research partners

The research partners in the centre were the University of Oslo, NTNU, the University of Oxford and Simula Research Laboratories. SINTEF became a partner in 2018.

2.1.2 Company partners

SIRIUS draws together a consortium of leading industrial organisations across the oil & gas value chain, including operators (Equinor), service companies (SLB, Aibel, Aker Solutions, Bosch, TechnipFMC and DNV) and IT companies (Computas, TietoEvry, Dolphin Interconnect Solutions, IBM, Kadme, Numascale, OSISoft, Billington Process Technology, ONTOPIC, Oxford Semantic Technologies, Prediktor, Envester, metaPhacts GMbH, Bouvet and SAP).

2.2 Organization

2.2.1 Main organisation of centre

SIRIUS research centre was organized as a matrix organization, with a dynamic interplay between centre management, work package leaders, and research program leaders.

Projects were organised into either business-related work packages, called beacon projects, or technically oriented research programs. Each researcher works in a research program and may be involved in one or more beacon projects. The research programs provided a foundation of methods and tools that can be prototyped and piloted in the beacon projects. Such a matrix organisation enabled us to obtain the right balance of fundamental research and focus in innovation and industrial applications.

SIRIUS had five work packages:

1. Subsurface: beacon projects in subsurface applications
2. Operations: beacon projects in the design, construction, operation, maintenance, and decommissioning of complex industrial facilities.
3. Cross-domain Applications: applications in areas outside and beyond the natural resources industries, notably health and environmental applications.
4. Research Programs: SIRIUS' computer science results that can be applied in projects in several of the business work packages. It is here that we achieved excellence in computer science research.

5. Strategy and Outreach: projects that define the direction of SIRIUS' research and innovation, including education, equal opportunity. and dissemination.

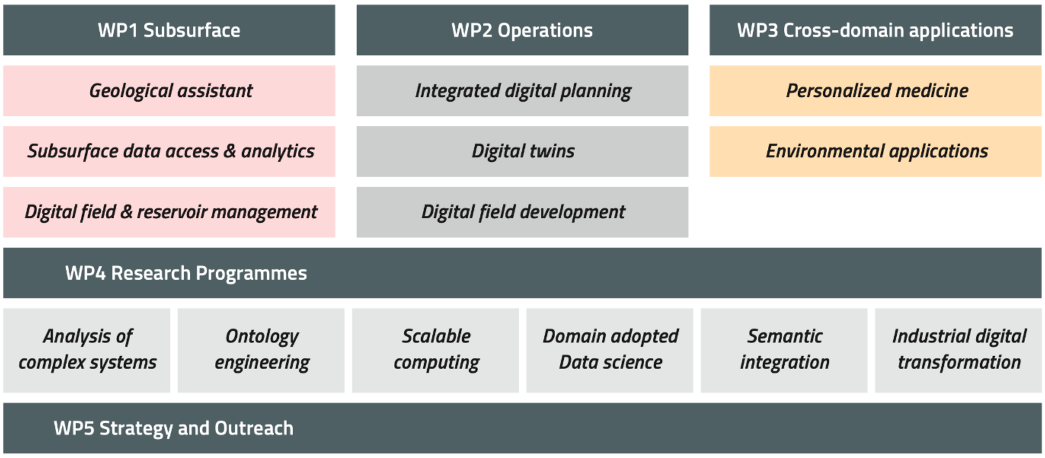


Figure 1. SIRIUS work packages.

Each work package had a manager, with responsibility for the portfolio of projects in that work package. Each beacon had a leader, with responsibility for the projects in that beacon. Each research program had a leader, who had responsibility for the technical quality of the program and for the researchers who work in it.

SIRIUS had twenty industrial partners and five research partners. Staff from industrial partners participate in projects in all work packages, although, in the early life of the centre, much partner effort has been used in strategy projects.

SIRIUS' ambition remains to deliver innovation through prototyping and pilot projects that have clear linkages to business problems and our partners' software and hardware. These projects were organised as innovation projects. These were governed by a separate project agreement and usually have specific provisions for confidentiality and ownership of intellectual property. This framework allows competing companies to work in SIRIUS without risk of losing intellectual property and competitive advantage. Innovation projects require much effort from both academic and industrial participants. This means that we are working to obtain additional funding from the Research Council, the European Union, joint industry programs and companies.

The innovation projects build on and feed into the foundation of fundamental projects in the centre. These projects were long-term and were built around PhD fellowships. Our ambition was that all SIRIUS fellows have a four-year contract, where the fourth year will be used for innovation and centre- related activities. Industrial partners contribute to these projects by supervising and mentoring students and by supplying software, hardware, and services as in-kind.

2.2.2 General Assembly

SIRIUS' General Assembly was the body that makes final decisions in the centre. It consists of one high-level representative from each partner. We organized the General Assembly twice a year, in spring and fall. The General Assembly in spring was considered a researchers' event focused on the research output of the centre. The Fall GA focused on the current year's reporting and planning for the following year. All partners (academic and Industrial) and researchers actively participate in both General Assemblies.

2.2.3 Executive Committee of the General Assembly (Board)

The Executive Committee of the General Assembly acts as a board member for the centre. They act on behalf of the General Assembly to exercise regular oversight over plans and progress.

The committee in 2023 consisted of:

- Knut Sebastian Tungland, Equinor, Chairperson
- Per Eivind Solum, SLB
- Elisabeth Nøst, TechnipFMC
- Terje Pedersen, IBM
- Thomas Østerlie, NTNU
- Einar Rustad, Numascale
- Thomas Pettersen, Computas
- Pål Rylandsholm, DNV
- Hugo Kohmann, Dolphin Interconnect Solutions
- Arild Waaler, University of Oslo, with Ingrid Yu, University of Oslo, as deputy

2.2.4 Operations Board/Centre Management

The Operations Board (or Centre Management team) was responsible for the centre's day-to-day operations, definition of the work plan that implements the decisions of the Executive Board. It is chaired by the Operations Manager (Centre Coordinator) and consists of the Centre Leader, Administration Manager, Mentor and Education Coordinator, Work Package Leaders, and Research Program Leaders.

Role	Name	Affiliation
Chair of General Assembly	Knut Sebastian Tungland	Equinor ASA
Centre Director	Arild Waaler	University of Oslo
Deputy Centre Director	Ingrid Chieh Yu	University of Oslo
Centre Coordinator	Adnan Latif	University of Oslo
Scientific Coordinator	Evgeny Kharlamov	University of Oslo / Bosch
Administration Manager	Lise Reang	University of Oslo
Subsurface Beacons	Adnan Latif	University of Oslo
Operations Beacons	David Cameron	University of Oslo
Cross-Domain Beacons	Laura Slaughter	University of Oslo
Strategy and Outreach	Einar Broch Johnsen	University of Oslo
Analysis of Complex Systems	Silvia Lizeth Tapia Tarifa	University of Oslo
Ontology Engineering	Martin G. Skjæveland	University of Oslo
Data Science	Basil Ell	University of Oslo
Semantic Integration	Guohui Xiao	University of Oslo / Ontopic
Scalable Computing	Geir Horn	University of Oslo
Industrial Digital Transformation	Thomas Østerlie	NTNU

Table 1. Centre´s Management Team

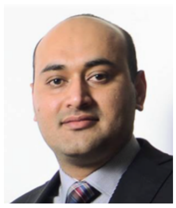
2.2.5 Senior researchers

Note: All researchers are at the University of Oslo unless otherwise noted.

SIRIUS was led by the centre director, **Professor Arild Waaler**. His educational background is in engineering, logic and philosophy and was previously the coordinator of the Optique project. His research interests focus on knowledge modelling of industrial systems, and he has led the centre's work on digital field development.

The centre's deputy director role was filled by two researchers in formal methods. **Professor Einar Broch Johnsen** filled this role from the start of the centre before handing it over to **Associate Professor Ingrid Chieh Yu.** Both researchers have a background in formal methods and worked in the Analysis of Complex Systems program. Professor Broch Johnsen also led the Strategy and Outreach work package, while Professor Chieh Yu led the centre's education, mentoring and diversity work. Professor Broch Johnsen also led SIRIUS' collaboration with the CIRFA SFI in Tromsø.

The translational aspect of the centre was addressed by the recruitment of workers with a background in the business disciplines in the centre and by the creation of the role of centre coordinator. **Dr David Cameron** is a chemical engineer, with 30 years' industrial experience and a Ph.D. from the University of Cambridge. He was coordinator of SIRIUS from its inception to November 2021. He also managed the operations work package. His research interests are in the application of digital twins in industrial applications. He has initiated and led the centre's engagement with Brazilian industry and academia.



Adnan Latif, M.Sc., MBA, is a geophysicist and was the coordinator of SIRIUS from November 2021. He managed the subsurface and contributed both as manager and researcher to the projects on digital geosciences and the application of data science and semantic technologies to the sub-surface data and analysis.

Keith Lewis joined the centre in 2018 after a lengthy career as a senior technical leader in Shell. He provided valuable insights into how the centre could achieve impact in the oil & gas industry.

The cross-sectorial applications work was led by **Dr Laura Slaughter**. Her research interests lie in the application of semantic technologies in healthcare and environmental applications. She led SIRIUS' involvement in the Bigmed RCN project on personal medicine and established SIRIUS' relationship with the Norwegian Centre for Biodiversity Information.

Associate Professor Silvia Lizeth Tapia Tarifa led the centre's program for analysis of complex systems along with running a prestigious Young Researcher Talent grant. Her research interests are formal methods for distributed systems both applying them and developing them, as well as combining them with other domains.

Dr Basil Ell led the centre's program for domain-adapted data science. He was employed by SIRIUS in a shared position with the University of Bielefeld in Germany. His research interests are in the exploitation of semantic methods to improve the performance of language models and machine learning.

SIRIUS' research on natural language processing was led by **Professor Lilja Øvrelid.** Her research interests in the centre focused on the adaptation of language models to technical vocabulary. **Dirk Hesse** is a Vice-President in Equinor and an adjunct associate professor at the University of Oslo. His academic background is in theoretical physics, but now he works with data science in Equinor and as a teacher and supervisor at the University of Oslo. He has had a leading role in the development of SIRIUS' data science program. He has worked with SIRIUS since 2020.

The involvement of the **University of Oxford** is focused on the semantic integration research program. Oxford's engagement with the centre was led by **Professor Ian Horrocks**. Professor Horrocks had a key role in defining the scope and scientific content of SIRIUS. His research group at Oxford has worked on providing the centre with fast, scalable tools for storing and querying semantic information. He has also run courses for SIRIUS researchers and partners on the theory of semantic technology.

Professor Boris Motik (University of Oxford) had had a senior role in defining the content of the semantic integration research program. His research interests were in applying ontology techniques to data management problems in databases and big data. Horrocks and Motik, together with colleagues founded **Oxford Semantic Technologies**, a startup company whose objective is to productise the RDFox semantic database and apply it in commercial applications.

Associate Professor Guohui Xiao leads the semantic integration program. He has had an adjunct position at the University of Oslo and had a key technical role in the **Ontopic** start-up company. He came to the University of Oslo from the Free University of Bolzano, where the ONTOP tool was developed.

Professor Dimitris Kiritsis has been employed at SIRIUS since 2018. His research interests were in the application of semantic technologies and systems engineering in the manufacturing domain. He came to the University of Oslo after a lengthy career at EFPL in Switzerland. His background and network have proved invaluable in linking SIRIUS to ongoing European research on advanced manufacturing and cognitive digital twins.

The industrial digital transformation work in SIRIUS was performed by the research group at NTNU led by **Professor Eric Monteiro.** Professor Monteiro has worked for many years with the Norwegian oil & gas industry to explore the social and organizational implications of digital technologies and barriers to adoption.

The work program on digital transformation was led by **Associate Professor Thomas Østerlie**. He participated in activities related to both the subsurface and operations work packages. He also contributed to the development of the centre's innovation agenda.

Work on ontology engineering was led by **Dr. Martin G. Skjæveland**. After working for DNV, he returned to the University of Oslo where he earned his PhD with Professor Waaler. He was the inventor and leader of research on Reasonable Ontology Templates (OTTR). This set of tools was an essential foundation for our application of semantic technologies. Other senior researchers in semantic technologies with supervisory roles in SIRIUS were **Professor Martin Giese** and **Associate Professor Egor Kostylev**. Professor Giese leads the Analytical Systems and Reasoning group at the Department of Informatics and has research interest in digital twins and the combination of semantic technologies and data science. He is scientific leader of the PeTWIN NFR project. Associate Professor Kostylev came to the University of Oslo from the **University of Oxford**, where he worked with Professor Horrocks and Professor Motik.

Associate Professor Evgeny Kharlamov is an adjunct professor at the University of Oslo and works at **Robert Bosch** in Germany. His original involvement with SIRIUS was from the **University of Oxford**. He took over as scientific coordinator of SIRIUS from Professor Ian Horrocks in 2019. He has worked on the cognitive digital twin and machine learning activities in SIRIUS and has been responsible for supervising PhD candidates employed by **Bosch.**

Dr Geir Horn led the scalable computing activities in SIRIUS. He worked at Simula and SINTEF before coming to the University of Oslo. He has been the principal investigator and project leader of more than 19 European collaborative projects. In SIRIUS he has managed the work with Dolphin and NUMAscale and moved into grid and cloud computing in the Horizon 2020 projects MELODIC[1], MORPHEMIC[2] and NebulOuS[3]. His current research interests were on how to handle complexity and services choreography for large-scale distributed applications through adaptation, autonomic decisions, self-awareness, and emergence.

The engagement of **Simula Research Laboratories** has been led by **Professors Tor Skeie** and **Professor Xing Cai,** supported by **Associate Professor Håkon Kvale Stensland**. The all have a research background in scalable computing. Their involvement in SIRIUS has been linked to hardware development by **Dolphin** and **Numascale** and supervision of the work on improving performance of open-source reservoir simulators on high-performance computers.

2.2.6 Cooperation within the centre

To enhance cohesiveness at the centre, a variety of measures have been implemented:

- **Academic Seminars and Workshops:** The centre prioritized hosting regular academic seminars and workshops where different teams can share their research findings, experiences, and insights. This regular interaction promotes mutual learning and fosters a sense of community within the centre.
- General Assemblies and Research Gatherings:
- **Cross-Disciplinary Collaboration:** The centre encouraged collaboration between researchers from different academic disciplines and industrial backgrounds. This interdisciplinary approach helps to bring diverse perspectives to research projects and

[1] https://melodic.cloud/
[2] https://www.morphemic.cloud/
[3] https://nebulouscloud.eu/

promotes mutual respect and understanding among team members. This has been especially effective for our innovation projects.

- **Social Gatherings and Team-Building Events:** Alongside formal academic events, the centre also organizes social gatherings and team-building activities. These events provide opportunities for members to interact informally and form personal bonds, strengthening the sense of community within the centre.
- Professional **Development Opportunities:** The centre provides training sessions, workshops, and opportunities for continued professional development. This not only supports the growth of the team members but also fosters a culture of mutual growth and learning.

In terms of promoting active participation from industry partners in projects, the centre adopts the following strategies:

Engagement from Project Inception: Industry partners were involved from the initial stages of project planning. Their input helps to ensure that the research projects align with real-world industry needs and challenges.

- **Regular Feedback and Dialogue**: The centre maintained an ongoing dialogue with industry partners and actively sought their feedback. This open communication channel ensured that research stays relevant and practical, and that industry partners feel heard and valued.
- **Industry-focused Workshops and Seminars**: The centre hosted events specifically targeted towards industry partners, such as workshops demonstrating the application of research outcomes in real-world scenarios. This helps to keep the partners engaged and encourages active participation.
- **Recognition of Industry Contributions**: The centre acknowledged and appreciated the contributions of industry partners to research projects. This reinforced the value of their participation and encourages continued active involvement.

3 Financing through the life of the centre

3.1 Summary sheet for the main categories of partners (NOK million)

Contributor	Cash	In-kind	Total
Host	38 320	17 312	55 632
Research partners International funding		5 337	5 337
Companies	9 000	91 789	100 789
Public partners		7 465	7 465
RCN	96 000	-	96 000
Sum	143 320	121 903	265 223

3.2 Distribution of resources *(NOK million)*

Type of activity	NOK million
Research projects	221 164
Common centre activities	29 929
Administration	14 130
Total	265 223

Note: Administration includes managing the mentoring program.

4 Results - Key figures

Note: The figures to be reported under each category must correspond to what is being or has otherwise been previously reported to the Research Council (cf. the centre's annual reports and the annual progress reports and final report submitted via "My RCN Web"). Years in this table are calendar years. Fill in relevant years. Present the figures and indicators most relevant for the centre, either in aggregate for the entire eight-year period and/or annually. As a minimum, the following performance indicators should be included:

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Total
Scientific publications (peer reviewed)	1	14	39	42	19	39	34	49	20	257
Dissemination measures for users	0	10	17	20	25	4	6	21	-	
Dissemination measures for the public	0	4	0	1	4	0	1	0	-	
PhD degrees completed (*with financial support from the Centre budget)	0	0	1	0	0	4	4	1	6	16
Master's degrees	0	0	0	0	5	8	10	8	-	
Number of new/improved methods/models/prototypes finalised	0	0	1	1	1	1	3	22	-	
Number of new/improved products/processes/services finalised	0	0	0	0	2	1	3	0	-	
Patents registered	0	0	0	0	0	0	0	0	0	
New business activity	0	0	0	0	0	0	0	0	0	

Category	2016	2017	2018	2019	2020	2021	2022	2023	2024
Journal publication	3	21	19	27	23	15	33	4	0
Conference presentation	6	9	7	15	6	6	14	0	0
Book	0	1	1	1	1	1	0	0	0
Report or thesis	0	1	1	1	0	5	5	1	0

Part of book	1	0	7	7	13	14	9	0	0
Translations	0	0	0	0	0	0	0	0	0
Media articles	0	0	0	1	0	0	0	0	0
Product	0	0	0	0	0	0	0	0	0
Information Material	0	0	0	0	0	0	0	0	0
SUM	10	32	35	52	43	41	61	5	0

5 The SIRIUS research plan

5.1 Organisation and development of the research plan

The SIRIUS research plan was developed in several scoping workshops with participation from partner companies and research teams with wide experience from industry collaboration, through research and innovation projects funded by the European commission and the Research Council of Norway. Striking the balance between research competence and partners' needs the centre activities were organised in a matrix with research programs in one dimension and use-case driven application areas, called Beacons programs, in the other dimension.

Projects were divided into Fundamental research projects and Innovation projects, the latter with significant participation from company partners. Projects in the research programs were mainly fundamental research projects while projects in the Beacon programs were innovation projects.

The research programs were coordinated in meetings of the Research Program Leader Group. Work package managers coordinated the Beacon programs. The Executive Committee of the General assembly served to further oversee and coordinate all projects and programs.

The development of the research plan was influenced by three tenets that gained increasing attention from both partners and researchers in the later part of the centre period: Artificial Intelligence, Digital transformation of exchange of technical information along the oil and gas value chain, and Digital Twin.

- AI and machine learning achieved a breakthrough in society and has attracted significant interest from both researchers and company partners. Techniques from machine learning have been used extensively in SIRIUS projects. The Domain Adapted Data Science program was shaped specifically for addressing opportunities and expectations arising from combining machine learning with semantic based knowledge representation.
- Structuring of technical facility asset information gained momentum in the industry, and projects were set up to investigate and pilot new and structured formats for information that currently exist in diagrams, figures, and semi-structured text documents. The SIRIUS Ontology Engineering research program was scoped to support initiatives in the industry set up to accelerate this form of digital transformation.
- The idea of deploying a Digital Twin, i.e., a digital replica, in the development and operation of facilities was launched by several companies after SIRIUS started its operation. This created an opportunity in SIRIUS for developing a shared research vision and demonstrating novel combinations of techniques from different research programs.

In response to the feedback from midterm evaluation, SIRIUS implemented three measures:

- Closer collaboration with partners through participation in existing partner programs
- Increased international collaboration and participation in EU projects
- Increased focus on standardisation and joint industry initiatives

5.2 Focus of the research programs

5.2.1 Analysis of Complex Systems

The research program focused on analysis of complex systems through models and developed both theoretical foundations for models, as well as practical tools support for practitioners. On the theory side, the focus lay initially with lightweight simulation with agent-based models and their analysis, and later turned towards the integration of structured semantic data into simulations. On the tool side, two modelling frameworks were developed and used throughout the research programs: ABS for agents-based models and SMOL for integration of semantic data. The turn was performed in reaction to the need of industry partners to connect agent-based simulations with data, and in reaction to the advent of the Digital Twin paradigm in model-based systems engineering.

For agent-based models, the following challenges were addressed:

- How can deployment in cloud-based systems be supported by analysis tools?
- How can resource-aware systems be modelled and faithfully simulated?
- How can agent-based simulations be visualized and connected with external data?

For integration of semantic data, the following challenges were addressed:

- How to connect concept modelling in knowledge representation with ontologies and data modelling in programming languages?
- How to efficiently simulate processes described by knowledge graphs?

5.2.2 Ontology Engineering

The research program focused on developing languages, tools and methods that improve the efficiency and quality of ontology development, maintenance and use in the industry. Ontologies are central for several important data management tasks:

- data integration: ontologies can mediate between data sources by lifting from the level of data to the level of information;
- data access: ontologies can be used to present information to end-users;
- requirement management: ontologies were used to represent, check, and solve complex combinations of definitions and constraints, based on, e.g., engineering designs of facility assets.

However, the construction, maintenance, and use of ontologies was far from straightforward. Creating and maintaining a high-quality ontology requires close collaboration between domain experts, information modellers, and ontology experts to ensure that the model works as intended. Tools and methods need to be tailored to different users' expertise and requirements, facilitating a separation of concerns, where each user group can focus on what they know best. Domain experts and programmers no longer need to become experts in logic and semantic technologies, whereas ontology experts and information modellers have the easier task of working with abstractions over the given domain. This was achieved by addressing the following challenges:

- How can domain experts be able to understand, build, and use ontologies without the support of ontology experts?

- What kind of software support do programmers and information modellers need to interact with, and exploit, the knowledge captured in the ontology with existing software platforms?
- What additional tools do ontology experts need to oversee the ontology engineering process?

5.2.3 Semantic Integration

The Semantic Integration research program designed and developed scalable infrastructure that supports semantic integration using large ontologies (with many thousands of classes) and massive data sets (many billions of tuples) into knowledge graphs. Specifically, the program has worked with ontology reasoners capable of supporting the development of large-scale ontologies and semantic data stores which answer realistic ontology-based queries over massive data sets. The Semantic Integration research program collaborates with the Oxford University and the two SMEs Oxford Semantic Technologies and Ontopic.
Over the years, the research plan has covered all major aspects of Semantic Integration: foundational theoretical results, tool development, deployment in innovation projects, and commercialization. The program addressed the following challenges:

- What is the theoretical foundation of semantic integration, considering different requirements of balancing expressiveness and computational complexities?
- How to build practical systems based on the developed theory so that the system can support common international standards?
- How to show the usefulness of developed theory and systems through practical use cases in different domains?

5.2.4 Domain Adapted Data Science

Initially, the research program was concerned with the connections between data access and analytics. There was a focus on research activities that address questions such as how data access can help analytics, how data analytics can help access, and how everything can work together. An observation was that in the field of knowledge representation one typically deals with structured data, for example in the form of trees and graphs, while current statistical methods in data analytics (e.g., in machine learning) are based on vector-shaped data.

Over the following years we put a particular focus on developing approaches that combine the use of structured knowledge with learning from data in the machine learning process. Our ambition involved addressing the following challenges:

- How can we combine machine learning and machine knowing such that we can realize approaches that learn from experience (data) and with knowledge (e.g., ontologies).
- How can we combine symbolically represented knowledge (e.g., as in ontologies) and distributionally represented knowledge (e.g., as in vector space embeddings)?
- How can we combine symbolic processing (e.g., via rules) and neural processing (e.g., via deep neural networks)?
- How can we build approaches that make use of both unstructured data (e.g., texts) and structured data (e.g., ontologies), such that all available knowledge can be considered for machine learning approaches?
- How can we make machine learning approaches more explainable, e.g., by incorporating declarative domain knowledge?

5.2.5 Industrial Digital Transformation

The research program's academic goal was to develop theory on the nature and dynamics of the transitions industrial companies go through as they become increasingly information- and data-driven; what is often referred to as digitalization or digital transformation. In the oil and gas industry, these transformations take emergent and forms in interesting ways that are different from most other academic research on similar phenomena.

The research program's role in SIRIUS was based on our complementary expertise to the other, technically oriented research programs. Our engagement with other research programs and industrial partners was based on a key insight from the Information Systems field: translating new digital technologies from prototypes to working solutions woven into business organizations' everyday routines requires insight into existing ways of working and organizing. Building upon research methods, concepts, and experiences from digital transformation processes in organizations, our aim is to inform technology implementation, adoption, and use as outlined in the SIRIUS Innovation Cycle.

Initially, we focused particularly on transformations relying heavily on Internet of Things and other sensor-based data, as these remained uncharted and academically intriguing. This work formed the basis of the Geological Assistant, which was initiated and initially lead by researchers in the Industrial Digital Transformation research program. Over time, our focus has shifted towards challenges associated with digitalization and standardization in the offshore engineering sector.

5.2.6 Scalable Computing

The Scalable Computing (SC) research program was about making data access and processing faster to SIRIUS projects. This was achieved by building knowledge in High Performance Computing (HPC) and scalable Cloud computing to support scalable big-data application processing. Specifically, we looked at solutions for scalable and reconfigurable hardware, software design for parallel numerical simulations, and automatic hybrid across Cloud application deployment, management, and reconfiguration using hardware accelerators.

The research topics of SC encompassed parallelization schemes, partitioning algorithms, communication overhead reduction strategies, software implementation and optimization techniques, use of heterogeneous clusters that consist of both conventional processors and cutting-edge hardware accelerators, in addition to adopting HPC for applications. Over the years of SIRIUS, the SC research programme has addressed the following three research questions:

- How can the HPC platforms be made better and more flexible?
- How can the distributed applications be automatically managed and scaled to consume just the computing resources needed for their current tasks?
- How can demanding computations from the industrial partners in SIRIUS be made more efficient?

The first question has been answered by developing hardware solutions allowing individual computers in HPC clusters to share memory and operate as one single machine. Furthermore, using distributed software-enabled disaggregation, we have been able to demonstrate simultaneous device lending for 30 computing cluster nodes simultaneously using the eX3[4] infrastructure.

The second question has been answered through three European collaborative research projects led by the SC research programme. The result of the MELODIC[1] project was a multi-Cloud application management platform. This is available as open source from the main European open-source community OW2[5], or as a supported and installed package on standard commercial

[4] https://www.ex3.simula.no/
[5] https://gitlab.ow2.org/melodic

terms. MORPHEMIC[2] extended the results of MELODIC by proactive adaptation based on real time series prediction of the measurements of the running application's execution context and perform the optimization and reconfiguration early so that the Cloud resources will be available when they are needed by the application. Furthermore, MORPHEMIC added support for artificial intelligence (AI) applications allowing them to benefit from using specialized hardware when training their algorithms. These results are taken forward in NebulOuS[3] to include computing of sensor data closer to the sensors by including computing at the Edge of the network.

The third question has been addressed by improving reservoir flow simulations, which can also be used to study geological CO_2 storage, by enhancing the performance and capabilities of the Open Porous Media (OPM[6]) framework.

5.3 Beacon Programs

The beacon programs aimed to demonstrate methods and results from SIRIUS research and development that could solve pressing industrial problems and improve work processes where access to a particular type of information in data sources is essential. The project teams in the beacon programs have been comprised of discipline experts, largely from partner companies, and SIRIUS researchers.

There were eight beacon programs, and they fall into three categories: subsurface exploration and production, facilities engineering and operations, and cross-domain application. Each beacon had been associated with a work package.

Subsurface exploration and production (WP1)	Facilities engineering and operations (WP2)	Cross-domain applications (WP3)
Geological assistant	Integrated digital planning	Personalized medicine
Subsurface data access & analytics	Digital twins	Environmental applications
Digital field and reservoir management	Digital field development	

5.3.1 Subsurface exploration and production

Three beacon programs have been set up to address subsurface data.

- Geological Assistant. The aim of the program has been to develop a tool-supported method for exploration geologists to better assess and evaluate exploration prospects by applying established techniques from the analysis of complex systems research program and knowledge representation through the ontology engineering research program.
- Subsurface Data Access and Analytics. Building on the Optique platform for ontology-based data access, which is the at the core of the semantic integration research program, the aim of the program has been to demonstrate how repositories like DISKOS can be developed into digital platforms for exploration, research, and innovation. Once this data is accessed, it needs to be analyzed. Hence the program had also been occupied with image analysis, data science and natural language applications in sub-surface data management.

[6] https://opm-project.org

- Digital Field and Reservoir Management. Production facilities and reservoirs interact with each other. The focus of this beacon is to demonstrate how methods from high-performance computing can be used to improve the performance of open-source reservoir simulators. In addition, data science and digital twins proved of interest in field management and petroleum technology. SIRIUS had therefore worked with Equinor, Petrobras and the Federal University of Rio Grande do Sul (Brazil) to develop research-based best practices for implementing digital twins for field management.

5.3.2 Facilities engineering and operations

Two beacon programs have been set up to address engineering data:

- Digital Field Development. This program has demonstrated the application of ontology engineering methods to structure requirements and technical information produced during a field development project.
- Digital Twins. The digital twin concept reached the top of Gartner Group's well-known hype curve in 2018. "Everybody" is building a digital twin of their process, plant, or product. Building sustainable and usable digital twins requires high-quality data science and knowledge representation. The program addresses application of methods from the analysis of complex system, domain adapted data science, semantic integration, and ontology engineering programs to link facility models to simulation applications and to develop an architecture for scalable digital twins.

One beacon program has been set up to address operational data:

- Integrated Digital Planning. SIRIUS' planning beacon addressed a case study that looks at vessel movements and cargo transport in the North Sea. The goal has been to improve the workflow of planners at Equinor by providing a better overview of the bottlenecks that could delay overall progress, the load on different vessels, and the quality of their logistics operations. It is especially deploying methods from the analysis of complex systems program.

5.3.3 Cross-domain application

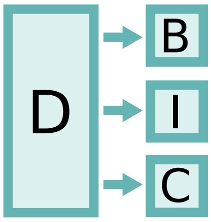
The objective of cross-domain applications has been to demonstrate how methods and tools created by SIRIUS' researchers obtained from working in the oil & gas domain transfer to other areas in industry, biomedicine, and environmental applications. There were three primary areas of focus: Healthcare, Earth Science, and Biodiversity.

6 Research achievements

6.1 Solving real-world industry problems

SIRIUS researchers have developed methods, languages, and computer implementations that enable users to lift information that currently resides in data repositories and technical documents, [**D**] in the figure below, into computable information structures. The computable information structures are in nature actionable, i.e., they are structures that can support and underpin data driven decision making and transformed work processes.

SIRIUS has targeted three types of computational information structures:



[**B**] Models of system behaviour, including models expressed in terms of differential equations and agent-based models. These models can be used to analyse scenarios descriptively (what happened?), prescriptively (what-if analyses) and reactively (automated decision making);

[**I**] Models of semantic information, including knowledge graphs that interplay with background knowledge and contextual information expressed in terms of ontologies. These models are designed to facilitate model integration and designed to be knowledge resources that can be queried;

[**C**] Computable models, including methods for optimising computer programs that exploit high performance computing and computing resources in the cloud.

SIRIUS has addressed real-world problems in industry. Such problems tend to be many-faceted in the sense that they seldom fall nicely within the boundary of a single research community. A combination of techniques and approaches must be used. The research achievements in SIRIUS are therefore in most cases a result of applying different techniques, or combination of techniques, in new ways.

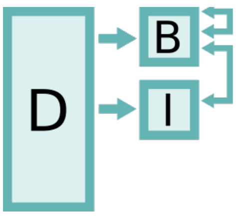
Developing new methods and technologies [B, I, C] to lift information that residing in data repositories and technical documentation [D] is one thing. Making the transition to data-driven forms of decision-making and new ways of working requires that companies transform. SIRIUS has also addressed this aspect of real-world problems in industry. The broad-based collaboration in SIRIUS between research groups and partners across the value chain has made this research possible.

6.2 Achievements in Research Programs

The survey of research achievements in this section makes repeated use of the figure in the previous section by emphasising which computational structure that data has been lifted into and which interrelationships that, for each achievement, have been established by new knowledge produced by SIRIUS researchers.

6.2.1 Analysis of Complex Systems

The research program has improved and developed methods and tools for the modelling and analysis of complex systems. It has results in two areas: Agent-Based Simulation and Integration of Semantic Data and Simulation.



Agent-Based Simulation

This part of the program focused on connecting agent-based simulations with structured data (I → B), among others to achieve optimal deployment decisions in cloud applications through analyses (B → B). Which advanced the field beyond raw data access (D → B) using ad hoc mechanisms. To use synergies and build on existing expertise, most work focused on the ABS tool suite.

ABS (Abstract Behavioural Specification) is a method and language for modelling, analysing, and simulating distributed timed, resource-aware systems. In addition to supporting the modelling of functional behaviour and distributed algorithms and systems, ABS supports the modelling of resource restrictions and resource management. It combines implementation-level specifications with verifiability, high-level design with executability, and formal semantics with practical usability. It is an open-source research project that is used in teaching and research, including industrial innovation research in SIRIUS. Among smaller advances, the following results were achieved:

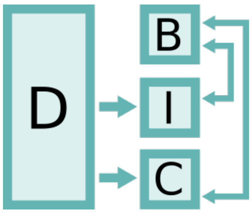
Schlatte and colleagues connected the existing ABS tool suite to external, non-semantic, but structured data sources and successfully applied it to the simulation of vessels to plan their routes. This data was provided by industry partners [1].

Gianluca Turin and colleagues successfully developed a model in ABS to predict optimal deployment decision in industrial cloud systems [2] and provide a tool for Microsoft Kubernetes [3] that is now used in industry.

Schlatte and colleagues vastly improved efficiency and reliability of the ABS tool suite [4], which is used in further, on-going and starting, projects at the University of Oslo and is the basis for research at other universities.

Johnsen and colleagues developed a novel analysis for agent-based systems based on the combination of two different techniques: Partial Order Reduction and Symbolic Execution. This combination vastly improves performance of concurrent models [5].

Kamburjan and colleagues improved the variability modelling in ABS, and developed a novel variability mechanism that is based on compositional and interoperable variability modules [6]. This extension, and a similar extension for variability in functional programming in ABS [7] advanced state-of-the-art in product lines beyond its classical application areas.



Integration of Semantic Data and Simulation

This part of the program focused on integrating semantic data in programming languages (I → B), together with connections to co-simulation units (C → B). Thus, the programmer has a well-defined, standardized interface to non-semantic data (D → I, D → C), which simplifies training and enables us to holistically model data and computations through semantic technologies. To investigate this approach, and provide tool support, the Semantic Micro Object Language (SMOL) was developed.

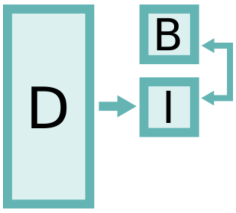
SMOL is an imperative, object-oriented language that uses language-based integration of semantic web technologies [8] and numerical simulation blocks (based on the FMI industrial standard for co-simulation units) into object-oriented programs [9]. SMOL programs can contain queries to external knowledge graphs that contain, e.g., domain knowledge about an application domain. SMOL further proposes semantic reflection of programs into knowledge graphs by lifting the runtime state of the program into an associated knowledge graph, which enables programs to directly query this semantic representation of itself at runtime. This way, programs can make use of domain knowledge directly. The following results were achieved:

Kamburjan and colleagues developed a new way to ensure type safety of programs working with semantic data, which is implemented in SMOL [10] and further developed it to a tool that connects ontological and computational class models [11], thus enabling a safe handling and integration of knowledge graphs into software.

Kamburjan and colleagues connected SMOL to asset models, such as the IMF system developed in SIRIUS, to model and develop Digital Twins [12]. We investigated the automatic adaptation of the SMOL digital twin model, which contains FMU simulators and knowledge graphs, to changes in the twinned physical system.

Qu and colleagues validated SMOL by simulating geological processes and connecting it to an externally developed ontology [12]. This application shows that SMOL is indeed able to model the scenarios it aims for.

6.2.2 Ontology Engineering



This research program has developed methods, languages and tools that lower the barrier and increase the scalability of information model construction and maintenance and use for industrial applications. This targets the process of lifting data to information and creating read and write interfaces between information models and behaviour models.

Reasonable Ontology Templates (OTTR), developed by Skjæveland and colleagues [13][14][15][16], is a language and framework for representing and instantiating recurring patterns for the engineering of ontologies. This allows building and interfacing with the ontology at a higher level of abstraction than what is possible using the current standard ontology language OWL, including:

- building ontologies and knowledge bases by instantiating templates;
- presenting, transferring, and visualising the knowledge base as a set of template instances at various levels of abstraction; and
- securing and improving the quality and sustainability of the knowledge base via structural and semantic analysis of the templates used to construct the knowledge base.

OTTR has had significant impact both in academia and industry. The open-source tooling developed by the project is in active use by several companies including DNV, Grundfos and CapGemini.

Lupp and colleagues developed a methodology for aiding domain experts and ontology engineers in constructing and maintaining industry-viable ontologies using a template-based approach for ontology modelling and instantiation [17]. Using the OTTR framework, the structure of the input formats and the semantics of the target domain are modelled and maintained in separate modularized template libraries.

The Information Modelling Framework (IMF), edited by Waaler and Skjæveland, targets the need in the industry for developing a more precise structuring of asset information, moving from "documents to data" towards a more data-driven industry. The IMF project had delivered methods and resources that enable the design of:

- models of asset information so that questions that today can only be answered by discipline experts, can instead be answered by querying a computer,
- industry commons resources, such as properties, types, and classes, can be shared and used by all parties in the value chain,
- machine to machine sharing through publishing so that pieces of asset information can be seamlessly reused in a «single source of truth» manner,
- protocols for exchange of information and for dynamically allocating authoring rights in compliance with the needs of companies in the value chain.

IMF has had significant industrial impact. It is at the core of an ongoing joint industry initiative with Equinor, AkerBP, DNV and the POSC Caesar organisation. On the roadmap for the project is to align with Asset Administration Shell developed in the Industry 4.0 initiative and the recent ISO developments on Industrial Data Ontology (IDO).

Rustam et al has proposed a classification of identifiers needed for entifying assets on an industrial scale and proposed an approach to digital transformation to address the problem of creating and maintaining machine-readable mappings between the various ways of identifying industrial assets across IT applications, domains, and actors [18]. This is done by building upon a model-based approach that has been gaining popularity in recent years. The approach is applied to a real use case emerged from the Information Modelling Framework project.

Vidar Klungre and colleagues have developed techniques and tools to increase the productivity of end-users with specific information needs [19]. More specifically, they have developed methods for ontology-based query formulation systems that allow the systems to use both the domain ontology and the underlying data to efficiently eliminate query extensions that leads to no results, which allows the end-users to quickly find the information they are seeking.

Jieying and co-authors expanded module extraction to include description logic ALC ontologies [20]. This underlines the evolving and versatile nature of ontology management in complex data environments, displaying the potential of these methodologies in advancing the field of AI and data management.

Jieying also worked with colleagues together with EPC contractor Aibel to tackle the challenge of efficiently managing the Material Master Data (MMD) ontology, vital for product classification for piping bulk materials, using ontology modularity to focus on smaller, relevant ontology subsets for reasoning tasks [21]. This method significantly speeds up the process without sacrificing accuracy. The approach demonstrates considerable improvements in handling large ontologies like the MMD, suggesting potential for broader applications in similar contexts.

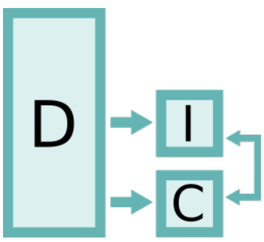
Jens Otten has developed full versions of connection provers for first-order classical logic, first-order intuitionistic logic and for several first-order multimodal logics. Enhancements improve performance and usability, such as a strategy scheduling and the output of a detailed non-clausal connection proof for all covered logics.

Daniel P. Lupp developed in his PhD work interfaces to ontologies and ontology-based data access systems that allow for users to see the big picture rather than needing to understand complex logical constructions. It provides a solid theoretical basis for sophisticated ontology design and maintenance, supporting the encoding of design choices that previously were left implicit as well as algorithms for the detection and removal of unwanted redundancies.

In his PhD, Ratan Thapa has worked on generating SHACL descriptions of RDF originating from relational sources [22], [23] and the use of SHACL constraints for optimizing SPARQL queries [24].

Karlsen, supervised by Giese, wrote his PhD-thesis [25] on efficient query answering over spatial data. He made a novel index structure for efficiently answering queries containing qualitative spatial relationships over many geometrical objects. The developed index structure improved the efficiency of answering such queries compared to the state-of-the-art methods. The work may be used to improve the efficiency of tasks involving large spatial databases, such as map applications, areal planning, and computer-aided design.

6.2.3 Semantic Integration



Error! Reference source not found. shows the conceptual framework of Semantic Integration, also known as ontology-based data access (OBDA). At the bottom of this figure, in this project, we are working on integrating various kinds of data sources, which are typically legacy systems and might come in different forms, such as relational databases (DBs), or as files. The objective is to semantically integrate these data sources into a Knowledge Graph consisting of a set of data assertions that use the vocabulary of classes and properties provided in the ontology. The data assertions in the KG are often obtained by mapping the data stored in various data sources to the terms of the ontology vocabulary. This can be realized either as virtual or materialized knowledge graphs [26][27].

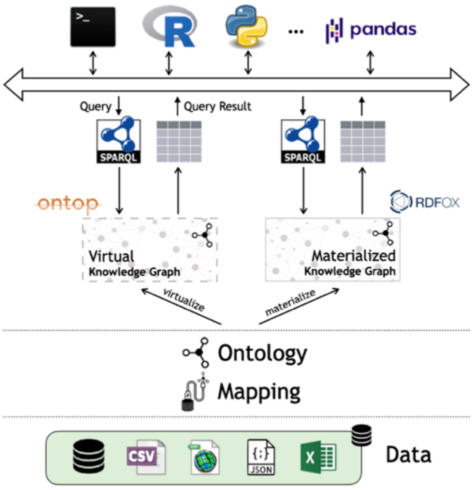


Figure 2. Conceptual framework of Sementic Integration

- **Virtual Knowledge Graphs (VKGs)**. In the virtual approach, the data assertions are not materialized in a separate data store, but their presence in the KG is only virtual. Systems operating on VKGs can retrieve the data directly from the data sources only when it is required for a particular user query. In fact, query processing is delegated to the data sources. This is achieved by unfolding the mappings, thus translating user queries into queries over the data sources, whilst also considering the ontology background knowledge through a so-called query rewriting step. The advantage of VKGs is that information is always fresh and up to date with the data sources.
- **Materialized Knowledge Graphs (MKGs)**. Despite the advantages of the virtual approach, it is sometimes convenient to materialize the data assertions. In such a case, we talk about Materialized Knowledge Graphs (MKGs). The main advantage of MKGs over VKGs is that usually a better performance in query answering can be achieved, especially in those situations where mappings are very complex and thus the unfolding of the virtual approach would give rise to complex queries over the data sources. However, this comes at the cost of maintaining a potentially very large MKG.

Reasoning Techniques for Semantic Integration.
Xiao and the colleagues have further developed the rewriting techniques to support larger fragments of the SPARQL query language in the VKG approach. They studied how to support the OPTIONAL operator [28], the aggregate operators under the bag semantics [29], and the GeoSPARQL stand for accessing geospatial data [30] [31].
Hu and colleagues have developed efficient materialization algorithms for materializing the results of reasoning. They have explored ways of improving the performance of materialisation and incremental updates by handling specific Datalog rules using specialised algorithms [32] [33]. They developed a framework for materialisation and incremental updates that integrates specialised algorithms with the semi naïve evaluation in a modular way [34].
Igne and colleagues have worked on CQ answering for expressive ontologies (in the materialized approach). They have developed ACQuA as a hybrid query answering framework that combines black-box services to provide a CQ answering service for OWL. Specifically, it combines scalable CQ answering services for tractable languages with a CQ answering service for a more expressive language approaching the full OWL 2 [35].
Systems. Several results have been implemented in the renowned software systems in the context of this project.

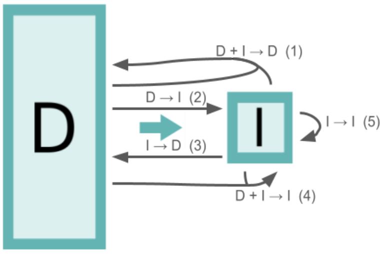
Ontop [3] is the state-of-the-art open-source Virtual Knowledge Graph engine. The Ontop project is hosted by the Free University of Bolzano and is also commercially supported by the company Ontopic.

[RDFox](#) [36] is a high-performance in-memory commercial knowledge graph and semantic reasoner, optimised for speed and efficiency, initially developed by University of Oxford, and currently by Oxford Semantic Technologies.

[Ontopic Studio](#) is a commercial environment for building Knowledge Graphs from relational data. It provides an intuitive no code environment that enables easy onboarding and collaboration.

Use Cases.
Xiao and colleagues have demonstrated the usefulness of the semantic integration in accessing manufacturing data [37], gene expressions [38], and clinical data [39]. Germano and colleagues have applied the semantic integration to the Material/energy flow analysis [40].

6.2.4 Domain Adapted Data Science



We understand D as unstructured or structured but non-semantic data and I as structured semantic data. Within the domain adapted data science research program, we developed approaches along the possible combinations of kinds of input data and output data, if semantic data is involved. For example, we developed approaches that create structured semantic data from unstructured non-semantic data (D → I), and we created approaches that create unstructured non-semantic data from a combination of unstructured non-semantic data and structured semantic data (D + I → D). In detail, we achieved the following results:

D + I → D: Obtain non-semantic data from non-semantic data + semantic data

The accuracy of predictions can be improved when structured semantic domain knowledge is combined with unstructured non-semantic data in the prediction model, as Erik Bryhn Myklebust, Ernesto Jimenez-Ruiz, Jiaoyan Chen, and colleagues have demonstrated in the context of ecotoxicological effect prediction [41].

Likewise, a similarity measure based on the combination of structured semantic domain knowledge (in the form of a taxonomy) with classical frequency-based features leads to significantly better results, as Summaya Mumtaz and Martin Giese have demonstrated in the context of reservoir analogue identification, a task relevant for the oil and gas industry [42].

For a Natural Language Processing (NLP) task (i.e., relation extraction from scientific text), the model by Farhad Nooralahzadeh and colleagues, based on convolutional neural networks, semi-supervised learning, and structured semantic domain knowledge, has shown top performance in an international shared task [43].

Making models' behaviour understandable by humans was also focused by Peyman Rasouli and Ingrid Chieh Yu. They developed a model-agnostic framework that combines user/domain-level semantic knowledge with model/data-level information to create plausible actionable recourses, i.e., feasible changes to the input to obtain the desired outcome [44].

In the context of classification, based on a use case that is relevant to the oil and gas industry, namely that of excess inventory reduction, Daniel Bakkelund has developed theory and methodology for improved classification of interchangeable equipment, by integrating equipment structure awareness into classical methods for unsupervised machine learning [45], thus combining structured semantic data with structured non-semantic data.

Baifan Zhou, Evgeny Kharlamov, and colleagues showed how to facilitate development of machine learning models using semantic technologies [46]. They developed an approach that creates machine learning approaches for unstructured data that create non-semantic data based on structured semantic data.

Basil Ell and colleagues developed an approach that aligns unstructured data (text) and structured data (a knowledge graph) and mines association rules that help to bridge not only from structured data to unstructured data (e.g., relevant in the context of data verbalization), but also from unstructured data to structured data (e.g., relevant in the context of information extraction from text). The authors received the best paper award at the LDK21 conference [47].

D → I: Obtain semantic data from non-semantic data.

Roxana Pop investigated how to extract logical rules from trained neural networks so that humans can better understand these network's behaviour. Thus, her approach creates semantic structured data from a neural network, where the network can be seen as non-semantic data.

Egor V. Kostylev and colleagues studied theoretical and practical connections between graph neural networks (GNNs) and logic-based knowledge representation formalisms. They designed a family of monotonic GNNs that allow for an efficient translation to Datalog logic-based language [48], [49].

Jiaoyan Chen, Ernesto Jimenez-Ruiz, Ian Horrocks, and colleagues evaluated to which extent pretrained language models can function as knowledge bases and capture the class subsumptions present in state-of-the-art ontologies [50].

I → D: Obtain non-semantic data from semantic data.

Symbolic knowledge can be embedded into a vector space, thus transformed into vector-based representations, which enables this data to be processed by machine learning approaches. Jiaoyan Chen, Ernesto Jiménez-Ruiz, Ole Magnus Holter, and colleagues have developed the OWL2Vec* framework which embeds OWL ontologies [51]. BERTSubs, an extension of that work, exploits the pre-trained language model BERT to compute contextual semantic embeddings of an ontology class and its context [52].

D + I → I: Obtain semantic data from non-semantic + semantic data

Ole Magnus Holter and Basil Ell found that large language models (LLMs) can be employed for human-machine collaborative annotation to efficiently create high-quality and complex training data for machine learning approaches in a complex domain, while saving a significant amount of time. Thus, the LLM-based approach generates semantic data that can be used to train, e.g., neural approaches to extract semantic data from unstructured non-semantic data (e.g., natural language text) [53].

Gong Cheng, Evgeny Kharlamov, and colleagues investigated keyword-based exploration of knowledge graphs [54], [55]. These approaches match non-semantic data on semantic data to select/rank semantic data (i.e., knowledge graphs).

Basil Ell and colleagues investigated the benefits of considering literals (i.e., unstructured data) for the prediction of links in knowledge graphs [56], thus combining semantic data and unstructured data to predict semantic data.

I → I: Obtain semantic data from semantic data

Roxana Pop investigated how to employ graph neural networks for temporal prediction on structured data. These predictions can be used to enrich semantic data with further semantic data.

Basil Ell developed statistical approaches that are applied to symbolic data (KGs) for the purpose of identifying regularities and anomalies, for the prediction of missing facts, and for the evaluation of the structural plausibility of facts.

6.2.5 Industrial Digital Transformation

Developing new methods and technologies [B, I, C] to lift information that residing in data repositories and technical documentation [D] is one thing. Making the transition to data-driven forms of decision-making and new ways of working requires that companies transform. The achievements of the research program on Industrial Digital Transformation emphasized this aspect of the D, B, I, C cycle. With basis in the research program's complementary expertise compared to SIRIUS' other, more technically oriented research programs, our achievements focus on what was required of organizations and new technologies to realize the benefits of new computational information structures.

The achievements of the research program are three-fold: impact on industry, straddling the gap of scientific excellence/practical relevance, and setting the direction for a research strand within SIRIUS.

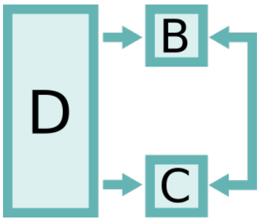
Impact on industry. Extending on our engagement with digitalization initiatives in the offshore engineering sector [57], [58], [59], participants in the research program have been central in developing the national strategy for digitalizing LCI exchange, adopted by NORSOK's sector board in 2022. The strategy was intended to address recurring problems developing digital standards for the offshore engineering industry. Built around a new and innovative standardization strategy for managing complexity in standardization efforts, this strategy is grounded in the insight that a combination of internal and external complexity shapes large-scale standardization processes. Without managing the interaction between internal and external complexity, the total complexity becomes unmanageable leading to scope creep and drift in objectives which increases the risk of failure of the standardization effort. Whereas internal complexity can be handled through the ordering, scope, and dependencies between standardization activities, external complexity stems from environmental volatility that is largely beyond the control of the standardization initiative. The strategy offers practical approach to aligning the planning of activities to handle internal complexity with a proactive approach for handling external complexity.

Scientific excellence, practical relevance. Participants from the research program have developed award winning insights into the new professions and disciplines that emerges as companies become information- and data-driven [60]. These results have both theoretical importance, and practical relevance. They are theoretically important in that they problematize the premise of much research on data-driven decision making and data science: that data can be understood as self-contained and -evident objects to be more or less unproblematically used for analysis. Through an investigation of new types of professions and the criticality of the invisible backroom work they perform to prepare and curate data so it can be unproblematically used for analysis. The practical implication of this research is to increase companies' awareness of the presence of these emergent disciplines (such as LCI managers and data managers) and their criticality for realizing the ambitions of data-driven companies.

Setting the direction for research strand within SIRIUS. Participants from the research program developed in close collaboration with Schlumberger and Equinor that foundational insights for and established the Geological Assistant beacon program [61], [62]. The research initiated with the observation that geologists lacked the digital tool support of geophysicists. As part of theory development on the nature and character of digital data use in practice [63], [64], [65], we developed an understanding of the diverse ways of reasoning underpinning these two distinctly different geoscience disciplines. Whereas geophysicists and signal and quantitively oriented, geologist way of working is historical and interpretive. These foundational insights about how geologists reason formed the basis for the contributions made by the multi-disciplinary team in developing tools and methods for supporting such historical reasoning.

6.2.6 Scalable Computing

6.2.6.1 Computational information contributions



The Scalable Computing research strand has looked at the foundations for computing, aiming to better exploit the data about computational tasks at hand and measurements from the running application to better configure the resources used by the application. This comes about as application models used at run time, as reservoir simulation models built from seismic data, and reconfigurable hardware platforms to execute flexibly the applications.

6.2.6.2 Models of system behaviour: Automatic hybrid Cloud application management

Cloud computing is a business model there computing resources can be rented on-demand in remote data centres where the hardware is managed by third parties. Investment in private computing infrastructure and its maintenance is therefore not needed. However, renting resources is more expensive overall, and the most profitable execution model is to run distributed applications mostly on own hardware, and rent additional resources for peak resource demands. The MELODIC[1] project was initiated by the SIRIUS team to develop a platform that automatically could manage the distributed application on behalf of the application's owner. Automation required a model of the application, and we contributed to the definition of a Cloud application modelling language [66]. This model integrates the topological model of the application with a metric model defining the measurements available from the application and the execution platform and an optimisation model to maximise the utility of the deployed distributed application [67]. The MELODIC platform is fully open-source built from open-source components [68].

Modern applications often use machine learning algorithms trained on enormous amounts of data, and it is then useful to scale out using more efficient dedicated hardware accelerators like Graphical Processing Units (GPUs) or Tensor Processing Units (TPUs) for training, and then continue to use the trained models on local premises after training. Furthermore, finding the optimised configuration and reconfiguring the running application takes time, and one should therefore maximise the utility for a future time point. The MORPHEMIC[2] project allowed the SIRIUS researchers to extend the MORPHEMIC platform incorporating hardware accelerators and proactive adaptation [69], [70]. The inclusion of proactive adaptation required a novel take on the autonomic computing feedback loop [71]. A core difficulty is to evaluate the effect of a potential reconfiguration on the application performance, and a conceptual framework for using *Digital Twins* for this purpose has been initiated in collaboration with the SIRIUS research programme on Analysis of Complex Systems [72], [73].

The SIRIUS results on automatic distributed application management are currently taken forward in the NebulOuS[3] project [74]. Applications processing sensor data will be distributed across private computing infrastructure, Cloud, local servers at the network edge, and internet of things (IoT) sensors. The SIRIUS research team will contribute an application component placement optimiser incorporating a digital twin performance module to learn and predict the performance of alternative application deployment configurations.

6.2.6.3 *Computable models: HPC support for reservoir simulation*

Although seismic surveys and production well logs produce copious amounts of data that can contribute to understanding the subsurface, detailed and trustworthy models of oil reservoirs also rely on extensive numerical simulations. Such simulations solve complicated mathematical equations with high resolutions, thus requiring efficient use of parallel computers. Here, scalable simulations mean that using more computing resources should give faster computations. This requires that the underlying numerical strategy should scale with the number of processing units while the software implementation should limit the overhead due to parallelization.

Since subsurface reservoirs are of irregular 3D shapes, unstructured computational meshes must be adopted. Partitioning unstructured meshes for parallelization is a challenging task, with an added difficulty for reservoir simulations being that the involved advanced numerical strategies may require a different goal for partitioning. For example, mesh entities that are strongly coupled numerically should be assigned to the same partition, instead of being divided among multiple partitions. Thus, partitioning reservoir meshes must balance between the standard partitioning criteria and the effectiveness of the parallelized numerical algorithm. SIRIUS researchers from SIMULA and UiO, in collaboration with Equinor staff, have derived new, physics-guided mesh partitioning strategies that give low communication overhead and high numerical scalability. The reservoir simulation software in the open-source OPM**Error! Bookmark not defined.** framework was also substantially enhanced by eliminating non-contributing computations related to parallelization [75]. Moreover, SIRIUS researchers have developed new theoretical models that considerably improve the prediction accuracy of detailed communication overhead, compared with state-of-the-art models [76]. Another research result is an automated tuning strategy that can find improved numerical parameters for reservoir simulations to achieve faster computations [77].

Using an open reservoir-simulation benchmark named Norne, we have shown that physics-based mesh partitioning combined with elimination of non-contributing computations can speed up parallel reservoir simulations by 26% on average [75]. The enhanced scalability also benefited simulations that help with planning storage of CO_2 in depleted reservoirs [78]. Moreover, automated parameter tuning was shown to further speed up the Norne benchmark by more than 20% [77]. The combined consequence is that Equinor has considerably improved its daily reservoir-simulation workflow, while becoming less dependent on proprietary simulation software. The benefits are equally accessible to all companies and research groups, due to the OPM open-access software framework.

6.2.6.4 *Computable models: Advanced Hardware Accelerators and Smart Scalable PCI Express*

To meet the challenge of unused processing and input-output (IO) resources in a compute cluster with servers connected by a PCI Express network, the SIRUS team collaborated with external actors in the Smart Scalable PCI Express project focused on hardware development, with Dolphin designing adapter cards and switches supporting the Gen4 and Gen5 standards of PCI Express. Towards the end of the project, we started to investigate PCI Express Gen6 and the new standard Compute Express Link (CXL), a future standard for connecting IO, accelerators, and memory in servers.

As a result, we have implemented support for the PCI Express network attached IO that enables machines to access remote IO resources and achieve the same performance as if the IO devices were local. We have improved Dolphin's existing SmartIO software technology and solutions to enable the sharing and migration of PCIe devices. We extended the SISCI API[7] to share non-single-root input/output virtualization (SR-IOV) NVMe devices and direct transfers between NVMe and memory specified by users in both main memory and GPU memory [79]. Furthermore, we have completed a full implementation of DIS_NVMe, which is a distributed NVMe driver, validated on the large-scale PCIe Gen4 networks in the eX3 national research infrastructure at SIMULA [80]. The testing had included existing shared disk file systems, and we have started the development of a shared disk and distributed file system optimized for PCI Express and the new Compute Express Link (CXL).

6.3 Achievements in beacon programs

6.3.1 Subsurface exploration and production

Geological Assistant:

Interpretation of the subsurface to find out where hydrocarbons are located was a challenging task for explorationists. They needed to be creative and produce innovative ideas when defining and assessing new prospects, especially nowadays when the easy to find, big fields have already been discovered. The challenges related to prospect assessment were:

1. Geodata is uncertain, intermittent, sparse, multiresolution, and multi-scale, and
2. explorationists often limit themselves to assessing just a few possible scenarios.

Recent advancements in computation, network and storage have led to numerous opportunities to improve these subsurface evaluation workflows. Further, the volatility and uncertainty in the oil and gas industry have forced exploration and production companies to find improved and cost-effective solutions by automating these workflows.

When it comes to digitalization, traditionally, the focus has been on purely data-driven workflows. Although geological reasoning is the most crucial factor that defines exploration success, little attention has been given to exploit digitalization opportunities in reasoning-based evaluation. In geological reasoning workflows, explorationist still rely on ad hoc manual work practices and tools and use pen and paper along with computer drawing and presentation tools to develop and communicate multiple hypothetical geological scenarios of the prospect. This leaves them with little to no efficient means to make the fullest use of state-of-the-art digital technologies to communicate and systematically compare and assess different hypothetical geological scenarios before deciding which scenario to pursue when assessing exploration prospects. A study[8] of 97 wells drilled in the UK sector of the North Sea from 2003 to 2013 showed that some of the major reasons for unsuccessful exploration were the fact that several of the prospects relied too heavily only on data (seismic DHIs and amplitude). Regional play-based work for setting and context was frequently overlooked, and pre-drill analysis often failed to consider the entire spectrum of potential outcomes.

The industry's current trend on moving from a physics-driven world to a purely data-driven world for a complex domain like Geoscience has proved inefficient. We believe that a significant success factor will be to combine geological reasoning-based evaluation with the insights derived from the Geological, Geophysical, and Petrophysical data [61], [62], [65].

[7] http://www.dolphinics.com/products/embedded-sisci-developers-kit.html

[8] https://www.nstauthority.co.uk/media/1578/cns-mf_post_well_analysis_report.pdf

The Geological Assistant was a SIRIUS innovation project between university researchers, Equinor, and Schlumberger. The project's aim was to develop a tool-supported method for exploration geologists to better assess and evaluate exploration prospects by applying established techniques from knowledge representation and formal methods from software verification. The project included researchers from the University of Oslo and NTNU with expertise in implementing and using digital technologies, knowledge representation, formal methods, and geology expertise.

The geological multi-scenario reasoning methodology developed in this project (GeMS) [81], [82], [83] provides a hybrid approach by combining the data-driven seismic interpretation (faults and horizons) with geological reasoning (based on the encoded geological rules). It can significantly help subsurface experts to think out of the box to consider several geological models rather than relying on a single model. Further, it enables Geoscientists to consider a full range of possible scenarios and corresponding outcomes beyond what is possible within human capacity. We have experimented with logic-based techniques for subsurface modeling, with focus on how the inherent complexity in geology such as spatial and temporal aspects can be formally captured and reasoned about using the strength of different formalizations. We demonstrated the use of abstraction and how formal modelling gives a precise and human-readable representation of domain knowledge. Further, we developed a mechanism to bring together the various models in a novel tool-based approach that constructs multi-scenarios to support geologically oriented subsurface evaluation. We combined techniques from knowledge representation with formal methods (mathematical approaches that support the rigorous specification, design, and verification of computer systems) to the exploration domain. This logic-based technology enables explorationists to express interpretive uncertainty as discrete scenarios with branches of potential alternative interpretations. With this approach, common-sense explorationist domain knowledge and rules of thumb are explicitly represented in the tools together with collected O&G data.

Subsurface Data Access and Analytics

Enhanced access to subsurface data is critical as it facilitates diverse research and boosts the progress in subsurface exploration. SIRIUS has gained great achievements in the SIRIUS OBDA Pilot and SIRIUS Subsurface Lab projects.

The SIRIUS OBDA (ontology-based data access) Subsurface Pilot project was driven by Adnan Latif and was primarily focusing on overcoming the bottleneck of data access in subsurface projects, including finding, accessing, integrating, and cleaning data before the analysis can begin. This project is an extension of the Optique project [84], focused on applying OBDA in subsurface applications. It used OTTR templates for the creation and management of mappings and incorporated domain knowledge. The prototype of this project was demonstrated and tested in prestigious data management conferences [85], [86]. Due to the limitations of the Optique database, the project SIRIUS Subsurface Lab established a large in-house relational database [87] using publicly available subsurface datasets, primarily from the Equinor's Volve dataset. This database was utilized in various internal and external research projects for experimentation.

Quick and easy access to relevant data matters when it can be used to gain insights and make decisions. SIRIUS has implemented three Subsurface Data Analytics projects on how to extract and analyse both structured and unstructured data.

Hierarchy-based Similarity Measures and Embeddings is a PhD project (PhD: Summaya Mumtaz) that focuses on structured subsurface data extraction and analysis. Recognizing the limitations in increasing dataset size in the subsurface data, the project adopted semantics technologies to handle categorical variables and domain knowledge. In addition, this project explored the integration of domain knowledge in ML processes, defined semantic similarity for categorical variables, and devised vector embeddings. This project successfully addressed critical challenges, providing valuable insights and methodologies to enhance ML applications in subsurface exploration workflows with highlighted results in:

- A practice based on domain information extracted from a concept hierarchy to compute similarity measure in an unsupervised setting [42].
- A method to calculate semantic similarity based on domain information and a comparative evaluation with existing frequency-based similarity methods [88].
- An approach for encoding high-dimensional categorical variables based on domain knowledge in the form of hierarchies using semantic similarity [89].

Low-Resource Adaptation of Neural Natural Language Processing Models is a PhD project (PhD: Farhad Nooralahzadeh) that focused on unstructured low-resource subsurface documentation data. The aim was to improve natural language processing (NLP) in real-world situations where challenges arise due to varying languages, topics, and styles. The project employed techniques such as distant supervision and transfer learning to optimize NLP for different domains. Specifically, it investigated the impact of domain-specific word embeddings and syntactic dependencies on NLP tasks, emphasizing areas like oil and gas. This project demonstrated increased intelligence and versatility in addressing diverse and resource-constrained contexts. The highlighted results from this project are:

- Demonstrating the benefits of constructing domain-specific word embeddings with limited input data and highlighting the importance of rare words handling in a model [90].
- Introducing a convolutional neural network (CNN) model that uses the shortest dependency paths between entity pairs for effective relation extraction and classification [43].

- Showing the impact of different dependency representations on neural relation classification, comparing three widely used representations and emphasizing that the choice of representation influences downstream processing outcomes in the industry [91].
- Proposes a solution for auto-generated data issues in named entity recognition, using a reinforcement learning module for false positives and an adapted Partial-Conditional Random Fields layer for false negatives [92].
- Introducing an effective use of meta-learning to leverage training data from an auxiliary language, enhancing the performance of state-of-the-art baseline models in zero-shot cross-lingual transfer for natural language understanding tasks [93].

In response to the challenge of efficiently locating geological images in a vast database, in 2019, the SIRIUS Geo-Annotator prototype was developed. As an ontology-based system that creates corresponding geological image knowledge graphs, this tool allows geoscientists to execute complex queries based on embedded geological content, reducing time and effort in image retrieval with a user-friendly interface. Results include a public demo, documentation, and open-source code on Gitlab [94]. The SIRIUSGeoAnnotator marks a significant advancement in subsurface data analytics for geological images. As an ontology-based geological image annotation tool, SIRIUSGeoAnnotator is tested as a validation tool in the work of [95]. According to the users' feedback, the tool is easy to use and response quickly.

Digital Field and Reservoir Management

The first focus area of this beacon program is to use high-performance computing to improve the computational efficiency of open-source reservoir simulators, which are of fundamental importance for the oil & gas sector. The research activities and achievements of SIRIUS in this focus area will be presented in detail in section 7.1, as one of two SIRIUS highlights of scientific results that provide a basis for innovation and industrial activity.

The second focus area concerns data science and digital twins. In collaboration with Equinor, Petrobras, and the Federal University of Rio Grande do Sul (Brazil), SIRIUS has conducted the research-based project PeTwin for exploring the best practices of implementing digital twins for field management. From a subsurface perspective, PeTwin supported a PhD project (PhD: Yuanwei Qu) to explore the potential of using Artificial Intelligence (semantic technologies and machine learning methods) to digitize and represent both static and dynamic geological knowledge and petroleum production. This project offers insights and overcomes challenges associated with diverse and complex geological datasets across disciplines, which suits the practical needs for a petroleum digital twin with subsurface data. To be specific, the PeTwin PhD project:

- demonstrated the benefits of ontological analysis in elucidating the multifaceted concept of faults in geology and provided a formal geological domain ontology in supporting a realistic and reliable framework for interpretating geological fault data [95].
- provided a holistic understanding of geological terms by means of a term-frequency evaluation of fault-related literature coupled with an ontological analysis, undertaken collaboratively with domain experts and knowledge engineers [95], [96].
- introduced a novel approach linking geological domain knowledge to a process simulation program, enabling geologists to model and simulate geological processes based on their knowledge and specified conditions [97], [98].
- followed the work of SIRIUSGeoAnnotator and outlined a framework on creating an industrially applicable information capture method in structural geology [99], [100].

- applied ontologies and knowledge graphs for data integrity verification, with an exploration of ensuring high-quality data for reliable implementation of data-driven methods in the energy industry [101].
- proposed machine learning approaches, including random forests and temporal convolutional networks, for real-time detection of undesired events during petroleum production [102].

6.3.2 Facilities engineering & Operations

The business value of the facilities engineering & operations beacon lies in using information to make optimal design and operational decisions. We believe that the digital twin is a powerful pattern for achieving this. Digital twin is a hyped concept, with a massive literature and many contradictory definitions. SIRIUS has worked with a simple and pragmatic model for digital twins, presented by Cameron et al. 2018 [103]. This model, the "three-legged stool" identifies five elements in a digital twin used to support decisions about the design or operation of a complex system. The twin builds on a foundation of (1) information about the structure and attributes of the system, (2) simulations and analyses that allow us to mirror and predict the behaviour of the system and (3) measurements and observations of the state and behaviour of the system. The digital twin integrates this information and provides a basis for analyses and artificial intelligence that support decisions. The results of these analyses must then be presented to decision makers in simple and effective ways.

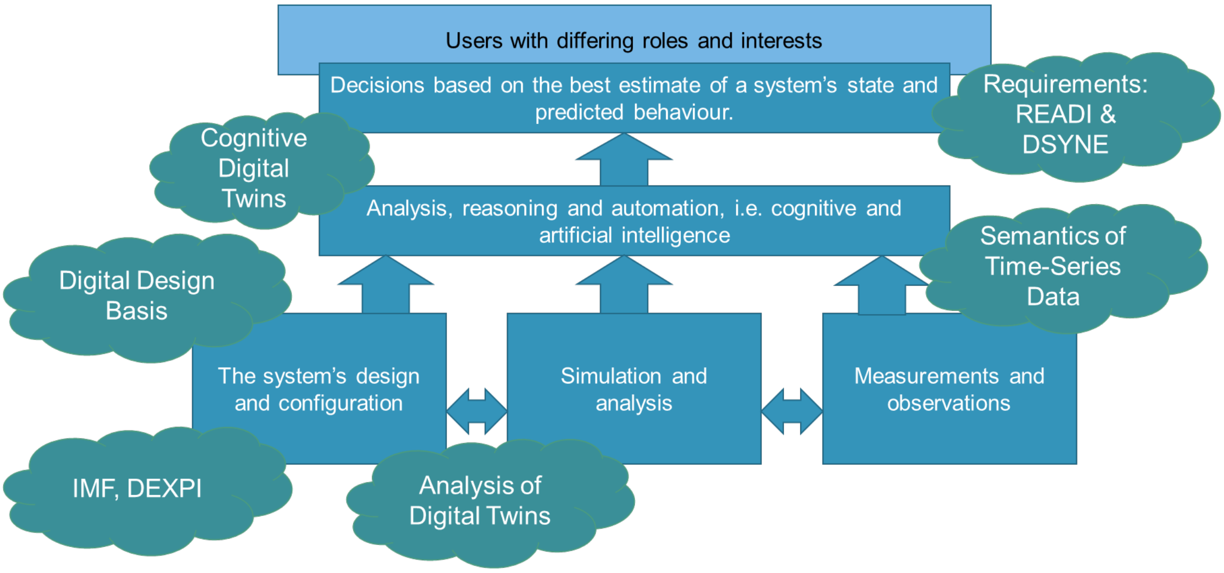


Figure 3. Alignment of projects with the SIRIUS model of a Digital Twin

Digital Requirements

The quality of the decisions we make in engineering and operations is determined by our ability to optimize the system's compliance with requirements. Unfortunately, most of these requirements are defined as documents or unstructured data. The READI joint industry project (https://readi-jip.org), which started as the NORSOK Z-TI project and ended in May 2022, created a model for representing requirements as digital statements, managing and structuring them. This resulted in the development of the Scope-Condition-Demand (SCD) model for requirements, where a requirement or specification can be represented by a data triple. SIRIUS researchers worked with DNV, Aker Solutions, TechnipFMC, Computas, Equinor to define this standard. Based on this work, SIRIUS established an INTPART-financed thematic network called DSYNE. This network linked the University of Oslo with the leading Systems

Engineering group at University of South-Eastern Norway. It built a cluster with two American Universities: Stevens Institute of Technology and University of Houston and two Brazilian institutions: Federal University of Rio Grande do Sul and Federal University of Espirito Santo. The network also had industrial support from Equinor, TechnipFMC and Petrobras. Its aim is to develop teaching material that supports the adoption of digital requirements in engineering projects

Cognitive Digital Twins

Dimitris Kiritsis, Evgeny Kharlamov and Foivos Psarommatis have worked on developing the concept of a cognitive digital twin in manufacturing applications. The cognitive twin is dependent on access to a knowledge model that supports the analyses necessary for effective decision support. The IMF work described below provides this semantic foundation. This concept has been developed through a series of European Union projects. The linkage between IMF and the cognitive concept is described in Cameron et al. 2022 [104].

Standardization of Digital Twins

Foivos Psarommatis developed a standardised design methodology to guide researchers and practitioners in their efforts to develop DTs regardless of the domain. After examination and interpretation of the literature, we also present the results of our state-of-the-art analysis, discuss the current state and limitations of research and practice, and provide useful insights on this important and complex topic. The design methodology proposed in our study will benefit both practitioners and academicians by covering the essential elements to be considered when developing DTs [105]. For this paper was recognised as top cited and highly influencing papers for 2023 from International Journal of Production Research.

Semantic Support for Time-Series Data and Machine Learning

Bosch, OSISoft, Computas and DNV worked on a SIRIUS innovation project that addressed the challenges of using time-series data from industrial processes for machine learning. The project examined the use semantic models to organize the data, support efficient pipelines, and work processes for machine learning. It has been followed up by work with both Bosch and Equinor [46].

Information Modelling Framework (IMF): Organizing Data in the Digital Twin and Contextualizing Requirements

The work done on requirements in READI identified a question that has to be answered if digital requirements are to work: how can the requirement be linked to the process design? In other words, how can we unambiguously define the scope of a requirement? This resulted in the project adopting a system engineering approach, built on the ISO/IEC81346 standard for structuring the information in a digital twin. This provided a way of breaking complex systems into subsystems in a way that allowed requirements to be applied in an unambiguous and clear way. This breakdown needs to be supported by semantic data model. This was provided by the Information Modelling Framework. The IMF provides a bridge between today’s design practices, system engineering and semantic modelling. The READI project developed a reference designation system, a standard set of system definitions, for the oil & gas domain. See section 7.2 for more details.

Digital Design Basis: Digitizing Requirements and Design Information in Early-Phase Field Development

The ideas developed in READI were piloted in a joint industry project that was organized as a SIRIUS innovation project. This project brought together three operator companies: Lundin, AkerBP and Equinor, with three engineering vendors: Aker Solutions, Aibel and TechnipFMC.

The aim of the project was to demonstrate the use of semantic technologies to represent the requirements and conceptual design data in the early phase of an oil field development. The work is summarized in Cameron et al. 2022 [106].

NOAKA, DISC and DEXPI: Models in the Chemical Engineering Domain for IMF

Work on digital twins and digital field development merged around the NOAKA (now Yggdrasil) field development project, which was a collaboration between Equinor, Aibel, Aker Solutions and AkerBP. This initiative aimed to try out Industry 4.0 and interoperability methods in actual project delivery of the FEED for a complex, multi-company field development in the North Sea. This project has been fruitful for SIRIUS, as the engagement with actual engineering practice has resulted in:

- Development of a new modelling tool for engineering systems in Equinor.
- Validation and use of the O&G Reference Designation System developed in the READI project.
- Extensive further development and refinement of the READI Information Modelling Framework (IMF).
- Publication of an example of applying IMF to a common academic process example, the Tennessee-Eastman process. This publication is supported by open models and a website.
- Participation in Scandinavian forums for interoperability of engineering data.
- Authorship of a new DEXPI standard for modelling process designs and their supporting documents. See Cameron et al. 2024 [107].
- A key role in the development of new Industrial Data Ontology.

SIRIUS has also participated in the Industrial Digital Twin Association, DEXPI and AutomationML. This positions us as a supplier of technology and experience for the further development of the Industry 4.0 standards in Europe and the Asset Administration Shell.

6.3.3 Cross-domain applications

The objective of cross-domain applications has been to demonstrate how methods and tools created by SIRIUS' researchers obtained from working in the oil & gas domain transfer to other areas in industry, biomedicine, and environmental applications. There were three primary areas of focus: Healthcare, Earth Science, and Biodiversity.

In healthcare, the semantic integration and ontology engineering research teams applied technologies to the area of personalised medicine (PM). Personalized Medicine (PM) is an approach to medicine that considers individual variability in genes, environment, and lifestyle. The goal of PM was to improve treatment outcomes and reduce adverse events.

The BIGMED Beacon Project funded work to explore use of semantic technologies to capture patient characteristics using the Human Phenotype Ontology (HPO) in a new suggestion service pointing physicians to further needed tests and diagnostics for newborns with suspected rare diseases. This work was completed in cooperation with paediatricians at Oslo University Hospital.

The semantic integration team implemented consistency checking using the Sequoia Reasoner, a consequence-based ontology reasoner from the Oxford group. Through collaboration with DIPS AS, a leading supplier of eHealth systems to Norwegian hospitals, we have contributed to the design of the user interface that implements the suggestion service as part of their genetic test requisition tool.

The ontology engineering team applied the use of the Reasonable Ontology Templates (OTTR) framework and created templates for the management of Norwegian health registry data. Work was done towards a demonstrator to illustrate the patterns and reuse potential in health registry related ontologies, to show how templates can improve the quality and sustainability of health registry data in a searchable knowledge base.

Other projects within healthcare involved scoping work in support of data-driven healthcare that resulted in two EU applications. These provided networking opportunities with key healthcare organisations in Norway as well as linking to EU collaborators from research and potential European industry partners. Much of the work laid the foundations necessary to apply digital twin technologies to healthcare.

Within Earth Science, a project was run by the Execution Modelling and Analysis group on cloud computing. The project developed distributed deep learning techniques for the analysis of satellite images, focussing on the detection of sea ice. The project was run by the CIRFA SFI in Tromsø, with Einar Broch Johnsen as part of the supervision team.

In the area of Biodiversity, SIRIUS researchers participated in a project with the Norwegian Biodiversity Information Centre (Artsdatabanken) in a project related to ontology engineering research (OTTR and modeling) and ODBI. The project focused on the design and development of the Norwegian Trait Bank. This is a knowledge source for describing, connecting, and displaying data on species and nature type traits. Species' trait data is used for knowledge-based conservation and research. The project was also a catalyst for biodiversity digital twin project scoping activities.

6.4 Awards

6.4.1 Prizes

Ian Horrocks won the BCS Lovelace Medal in 2020 (see https://www.bcs.org/articles-opinion-and-research/bcs-lovelace-medal-2020-reasoning-systems/)

Ian Horrocks was announced to be honorary doctor at the University of Oslo, Faculty of Mathematics and Natural Sciences, at the honorary award ceremony of University of Oslo in 2017 https://www.cs.ox.ac.uk/news/1369-full.html

6.4.2 Best paper awards

Eduard Kamburjan, Vidar Norstein Klungre, Martin Giese: Never Mind the Semantic Gap: Modular, Lazy and Safe Loading of RDF Data. ESWC 2022 [11].

Paul Kobialka, Felix Mannhardt, Silvia Lizeth Tapia Tarifa, Einar Broch Johnsen: Building User Journey Games from Multi-party Event Logs. EdbA 2022 [108].

Paul Kobialka, Silvia Lizeth Tapia Tarifa, Gunnar Rye Bergersen, Einar Broch Johnsen: Weighted Games for User Journeys. SEFM 2022 [109].

Kiko Fernandez-Reyes, Dave Clarke, Ludovic Henrio, Einar Broch Johnsen, Tobias Wrigstad: Godot: All the Benefits of Implicit and Explicit Futures, ECOOP 2019 (distinguished artefact award) [110].

2023 AIS Senior Scholar's Award for Best Information Systems Publication: In the Backrooms of Data Science by Elena Parmiggiani, Thomas Østerlie, and Petter Almklov

2022 Journal of the Association of IS Best Paper Award: In the Backrooms of Data Science by Elena Parmiggiani, Thomas Østerlie, and Petter Almklov

2019 Best Paper Award at The XIII Mediterranean Conference on Information Systems (MCIS201): Coordinating Innovation in Digital Infrastructure: The Case of Transforming Offshore Project Delivery by Mina Haghshenas and Thomas Østerlie [59].

Best paper: Crystal Chang Din, Leif Harald Karlsen, Irina Pene, Oliver Stahl, Ingrid Chieh Yu, and Thomas Østerlie. Geological multi-scenario reasoning. NIK: Norsk Informatikkonferanse (2019) [83].

Research papers on OTTR was recognised with best research paper nomination at the International Semantic Web Conference 2018 [13] and with best paper award at the Description Logic workshop [14].

Basil Ell won the best paper award at the LDK 2021 conference [47].

6.4.3 Keynotes

Keynote at FormaliSE 2022. Digital Twins: An Emerging Paradigm for Model-Centric Engineering. Einar Broch Johnsen. https://conf.researchr.org/home/icse-2022/Formalise-2022#program [111].

Thomas Østerlie gave keynote at Standard Norway's Annual NORSOK Expert Group Leader meeting on the topic "Digital Twins: A research-based perspective."

Ernesto Jimenez-Ruiz gave a keynote at the Description Logics workshop and is co-organizing the Interest Group on Knowledge Graphs at The Alan Turing Institute [112].

6.4.4 Other recognitions

The relation extraction from scientific text approach developed by Farhad Nooralahzadeh and colleagues was a top performer in SemEval international shared task 2018. The system ranked third out of 28 participants.

Foivos Psarommatis received an award as an outstanding reviewer for 2022 from Journal of Manufacturing systems https://www.sciencedirect.com/journal/journal-of-manufacturing-systems

Foivos Psarommatis received an award as the best reviewer in ISM conference 2023 Linz, Austria.

Foivos Psarommatis received an award as the top 2% reviewers in 2023 for International Journal of Production research.

Foivos Psarommatis received the award of top cited and highly influencing paper for 2023 from the International Journal of Production Research [105].

Ernesto Jimenez-Ruiz, Evgeny Kharlamov and Ian Horrocks are ranked amongst the top-10 scholars in the Knowledge Engineering field in their AI 2000 scholars ranking of 2023 https://www.aminer.cn/ai2000?domain_ids=5dc122672ebaa6faa962c073.

7 Highlights of scientific results

SIRIUS has in many ways created impact, both scientifically, for partners, and for the industry. Two highlights that provide a basis for innovation and industrial activity are within the areas of reservoir simulation and semantic asset modelling.

7.1 Reservoir simulation

Under the auspices of SIRIUS, research on advancing the understanding of the subsurface has led to both a new modelling methodology that quantifies heterogeneity and contention in MPI-based parallel reservoir simulations, and a more scalable implementation of the OPM (Open Porous Media) open-source framework (https://opm-project.org/). This has put Equinor, SIRIUS' leading industrial partner, in a position to achieve more efficient and faster reservoir simulations and being able to migrate from using very costly commercial reservoir simulation software, which altogether will have a tremendous impact on Equinor's reservoir business.

The research activities of SIRIUS on enabling scalable industry-scale reservoir simulations were initiated in autumn 2017, because the reservoir simulator from the OPM open-source framework had severe inefficiencies in the numerical algorithm and software implementation. To overcome the inefficiencies, a SIRIUS team that involved staff from UiO, Simula and Equinor first studied how to partition a reservoir's computational mesh for parallelization. At that time, the state-of-the-art partitioning strategies only considered the geometric information, but ignored the impact of mesh partitioning on the parallel computation. The SIRIUS team derived and implemented new measures, by combining geological properties with geometric properties, to quantify the numerical connectivity between the mesh entities. Specifically, scaled transmissibility values led to a physics-guided mesh partitioner that achieved both low communication overhead and high computational efficiency.

The second research topic focused on the wasteful computations that can arise in a parallel simulator, where the data structure of each partition accommodates so-called "ghost" points that are needed to facilitate communication but whose values should be computed by another partition. The SIRIUS team developed new data structures to re-arrange the ghost points as a contiguous part separated from the non-ghost points. Together with adapted implementations of the computational kernels, non-contributing computations on the ghost points were eliminated. The saved computing time can be substantial because the percentage of ghost points quickly increases with the number of partitions.

The third research topic was modeling of the communication overhead associated with parallel simulators. The standard performance models could not handle realistic interconnects where diverse levels of bandwidth and latency co-exist. The SIRIUS team proposed new formulas to quantify various situations of communication contention and derived new performance models to pinpoint the communication overhead of each process. The obtained new insights are not only important for resource-efficiently placing heterogeneous processes on a heterogeneous interconnect, but also form the basis of next-generation topology-aware mesh partitioners.

The SIRIUS team involved PhD student Andreas Thune (Simula & UiO), PhD student Erik Sæternes (Simula & UiO, joined in August 2020), Prof. Xing Cai (Simula & UiO), Prof. Tor Skeie (UiO & Simula), and Dr. Alf-Birger Rustad (Equinor).

Thanks to the above-mentioned research activities on enhancing the scalability of parallel reservoir simulations, the *Flow* simulator from the OPM open-source framework saw substantial performance improvements in late 2019 and early 2020, when the research induced software enhancements were gradually incorporated into the official software release of *Flow*. As a specific test case, the Norne black-oil open benchmark was run using two versions of the *Flow* simulator, one based on the 2018.10 release of *Flow* (the original version prior to the enhancements), the other including all the research induced enhancements. Both simulators used between 2 and 64 Intel Xeon E5-2670 processor cores, where the average saving of the simulation time was measured as 26% (see below for a plot of the time measurements). More importantly, the saving factor increases as the number of processors used, meaning that the enhanced *Flow* simulator can more effectively use larger parallel computers. The speedup and improved scalability mean that reservoir engineers at Equinor, as well as in other companies (due to the open-source software of OPM), can have a much-improved workflow in operating the production from oil reservoirs or planning the storage of CO2 in depleted reservoirs. The Equinor partner confirmed that multiple of their assets had benefited from the enhanced open-source simulator, while the enhancements had prompted a broader adoption of OPM software within the company.

Another clear benefit of an enhanced open-source reservoir simulator is that oil & gas companies can become less dependent on proprietary simulation software, leading to considerable cost reductions. As a performance comparison, the enhanced *Flow* simulator has competed head-to-head with two industry-standard proprietary reservoir simulators: *Eclipse* (version 2018.2) and *Intersect* (version 2019.1). Specifically, all the three simulators ran a higher-resolution version of the standard Norne benchmark, using up to 16 Intel E5-2687W processor cores. While the speed of *Flow* is between *Eclipse* and *Intersect* when using 1 and 2 processor cores, the open-source simulator is the fastest when using 4,8,16 processor cores (see below for a plot of the time measurements). More details of *Flow*'s scalability measurements and the performance comparison against *Eclipse* and *Intersect* can be found in Thune et al. 2021 [75]. The usage of the enhanced *Flow* simulator for CO2 storage simulations is reported in Sandve et al. 2022 [78].

The impact of the scalability research results extends beyond the oil & gas sector. This is because physics-guided mesh partitioners and the elimination of wasteful computation during parallelization are applicable to other scenarios of physics-based parallel simulations. Moreover, the proposed new performance models of communication overhead, as described in Thune et al. 2023 [113], have shown to greatly improve the accuracy of state-of-the-art models. For example, extensive measurements of 8192-process communication overhead were carried out on the Betzy supercomputer, and the measurements showed that the new theoretical performance models can achieve 84% accuracy, which is an unprecedented level for the existing performance models.

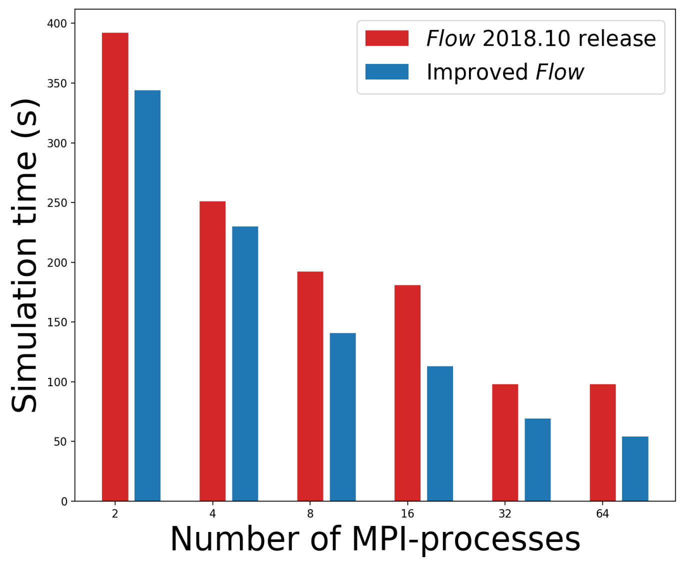


Figure 4. The computing speed of the open-source Flow simulator has improved due to the research activities at SIRIUS.

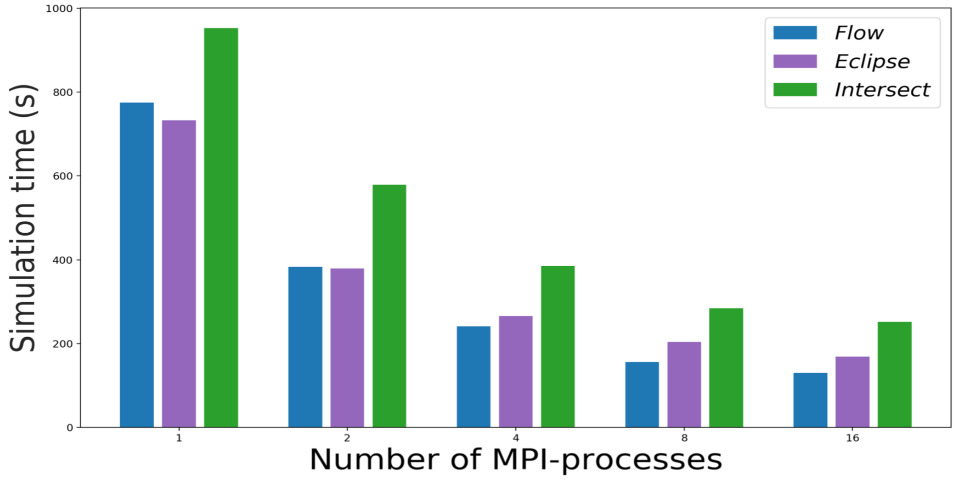


Figure 5. The enhanced Flow simulator has a comparable speed to two proprietary industry-scale simulators.

7.2 Knowledge-Driven Transformation of Engineering and Operations in Capital-Intensive Energy Facilities

The KONKRAFT assessment of competitiveness of the Norwegian Energy Sector[9] identified manual and document-based processes as being driver of costs and a barrier to digital transformation and future competitiveness. These inefficient processes increase cost, in some areas by 20%, and reduce the performance of the built facility. Semantic asset modelling provides a theoretical and practical basis for moving from existing, document-based processes to data-oriented processes by applying and enhancing knowledge representation techniques. SIRIUS has developed methods and tools that have enabled a productive series of joint industry and collaborative projects in the oil & gas sector that demonstrate how engineering and operational business processes in EPC companies (Aker Solutions, Aibel, TechnipFMC), operating companies (Equinor, AkerBP), and equipment vendors (Siemens, Bosch, Grundfos) can be transformed. The results have gained international attention. They have been anchored through open-source software, a DNV Recommended Practice, a new standard in the DEXPI organization for process design, contributions to IOGP practices, and a new ISO standard on Ontology Based Interoperability.

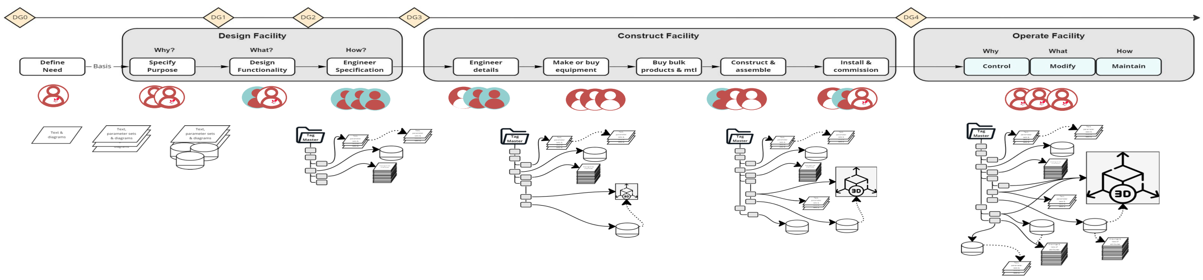


Figure 6. Logical flow of value creation in a facility asset project in the oil and gas industry.

Facility Assets in the energy industry are increasingly complex. The figure above illustrates the logical flow of value creation during an industrial investment and development project.

[9] KonKraft, 'Project Competitiveness – changing tide on the Norwegian continental shelf - Summary and recommendations from the Committee', KonKraft, Oslo, Jan. 2018: https://konkraft.no/wp-content/uploads/2020/03/Summary_and_recommendations.pdf

- When a facility asset is developed, the work begins by defining the overall requirements and functionality (DG0). The result is typically contained in a few documents, which means that at this stage a holistic description is feasible.
- As the work progresses into the design phase of the Facility Asset, more specialized discipline expertise is necessary (DG1 and DG2). The way of working is document-based, and the result is an increasing number of documents. This leads to a fragmentation of information spread across documents, due to the inherent features of their format. Because of this fragmentation, it becomes increasingly difficult to maintain a holistic description of the facility asset. The result is extensive interface coordination between discipline experts.
- When the investment decision is made to execute the construction of the Facility Asset (DG3), the number of documents produced grows exponentially as the supply chain involving both contractors, suppliers, and manufacturers ramp up their deliveries for construction, installation, and commissioning of the facility asset. At this stage, a lot of information in documents is duplicated, resulting in several sources of the same information. The consequence of this is labour-intensive work to prevent quality deviations and HSE incidents.
- When handover to the operator takes place (DG4), information is fragmented and lacks relational information. This often results in a need to 're-engineer' the solution to establish the holistic view necessary to maintain, control and evolve the facility asset. It is worth noting that reduced information quality can reduce the decision quality and is often costly and inefficient to manage.

Our research has focused on the design of engineering-specific knowledge representation languages and associated methods. The languages and methods exploit, in a coherent framework, opportunities that come from semantic web technologies to create interoperable knowledge graphs that can be queried, and logic-based languages that provide a precise declarative semantics. Together, they enable the use of automated reasoning to check the integrity and correctness of information.

The research has built on the translational ideas developed in the Optique EU project, where ontology-based data access was demonstrated in use for subsurface and operations data. Our work here can be classified into three categories, cf. **Error! Reference source not found.**. We build on a foundation of fundamental results with a set of translational methods. These then support application and demonstration within the engineering domain.

Fundamental ICT research	Translational research	Application and demonstration
Reasonable ontology templates (OTTR). IDO – a foundational ontology for engineering data. High-performance graph databases and query tools.	Reference architecture and best practice for digital twins. Information Modelling Framework (IMF). Semantic representation of requirements. Semantic management of identifiers in engineering data.	READI joint industry project: Reference Designation System for Oil & Gas and IMF concept. Digital Design Basis JIP. DISC JIP: DEXPI standardization, integration of IMF with Industrie 4.0 standards, industry implementation of IMF.

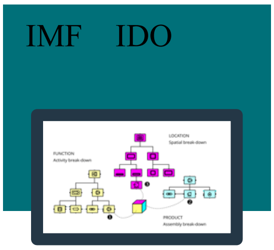
Figure 7. SIRIUS research on semantic asset modelling spans fundamental research, translational research, and application and demonstration.

Reasonable Ontology Templates (OTTR) (https://www.ottr.xyz) is a language developed by SIRIUS researchers that simplifies the development and maintenance of knowledge models by engineers who are not experts in semantic technology.

The **Industrial Data Ontology** is a vocabulary of relevant entities of the domain of interest with relationships that helps users build consistent models, build hierarchies of reference data, avoid categorical mistakes, and maintain data quality through the assistance of a tool that uses formal logic to check model integrity. IDO is under standardisation as a New Work Item in ISO Technical Committee 184 Sub-Committee 4 Industrial Data.

Implementation of these methods depends on access to **high-performance graph databases and query tools**, as developed in the Optique project [114]. We have worked further with the University of Oxford and Free University of Bolzano and their start-up companies, Oxford Semantic Technologies and Ontopic, to advance their methods and the RDFox and ONTOP software tools.

Translation to industrial application is done using **digital twins** as an implementation pattern. We have developed a simple but effective conceptual model of twins that aims to develop a best practice for digital twins for oil & gas.



The **Information Modelling Framework** language **(IMF)** is a language that allows the construction of well-structured information models of engineered systems. It provides a way of moving from document-based engineering to data-based engineering in a way that is relevant to engineering practitioners. IMF makes use of the OTTR and IDO languages. The key feature of IMF is the capability to express and separate four different chains through a body of technical information: requirement/solution, abstraction, topology connectivity, and type/class hierarchies. SIRIUS researchers and partners have worked to unravel and express these chains through asset information in a simple, yet precise way, thereby facilitating navigation through information in different and disparate sources and definition of user defined view to create and access information. These digital models have the potential to transform work processes compared to today's way of working.

IMF also supports different modalities that can be used to capture the different contexts that arise through the project lifecycle. IMF provides a bridge between knowledge representation technologies and systems engineering approaches.

This work was supplemented by work that provided simple semantic **representation of requirements** [115] and the selection and mapping of **identifiers** in engineering information systems.

The **application and demonstration** work took these methods and generated industrial results in collaboration with partner companies. The RDS for Oil & Gas, Digital Design Basis JIP and DISC project with DEXPI participation are described in the impact section 15 below.

Note that we have adopted a dual publication strategy. The fundamental research is published in the semantic technologies literature [16], [15], [116], whereas the translational and application work has been published in the relevant manufacturing [106] or chemical engineering literature [104], [107]. We also present at trade conferences, such as the annual NFEA Digitalization conferences.

The SIRIUS team involved Dr. Martin Skjæveland (UiO), Dr. Baifan Zhou (UiO), Prof. Arild Waaler (UiO), Dr. David Cameron (UiO), Dr Dag Hovland (UiO, then Bouvet), Dr. Johan W. Kluwer (DNV), Dr. Foivos Psarommatis (UiO), Rustam Mehmandarov (UiO and Computas), Prof. Dimitris Kiritsis (UiO), Dr Evgeny Kharmalov (Bosch and UiO), Prof. Ian Horrocks (Oxford), and participants from SIRIUS partners Equinor, Bosch, DNV, Computas, Bouvet, Envester, and Aibel. We have collaborated with Aker BP, Aker Solutions, TechnipFMC, ConocoPhillips, Petrobras, Siemens AG, Siemens Energy, Grundfos, Standards Norway, NTNU, University of Western Australia, Federal University of Rio Grande do Sul and Federal University of Espirito Santo.

8 International cooperation

SIRIUS has been actively involved in various international collaborations, notably with Brazil, the United Kingdom, and with European Union.

8.1 Brazil

Our collaborations in Brazil have been highly productive and substantial. We have consistently played a pivotal role in SINOS, representing Norway's collective academic engagement with Brazil's oil and gas sector.

Collaboration with Brazilian entities includes our ongoing partnership with the Federal University of Rio Grande do Sul (UFRGS) in Porto Alegre, as part of a project within Digital Geosciences, funded partly by DIKU and DIKU/CAPES. The PETROMAKS/FINEP project, PeTWIN, stands as a testament to our fruitful partnership in this region.

Moreover, our continuous participation in the SINOS collaboration with Brazil, along with the coordination of the DSYNE INTPART network with partners in Brazil and the USA, marks our commitment to fostering international relations.

Our engagement with the Brazilian sector has allowed us to forge valuable partnerships and supplement our WP1 (exploration) beacon projects, giving us access to a prominent group in petroleum informatics.

International Workshops: We continue to encourage knowledge exchange among our partners. An example is a workshop in Rio de Janeiro that provided a platform for discussing and refining project objectives.

Collaboration with the Federal University of Espírito Santo: Rodrigo Calhau has worked at UIO and USN since September 2022, focusing on semantic system modelling.

8.2 Alan Turing Institute, UK

Our relationship with institutions in the UK, specifically the Alan Turing Institute, has been strengthening and highly beneficial. We are active participants in the Institute through the University of Oxford's partnership and through the participation of SIRIUS researchers in the centre, including Ernesto Jiménez-Ruiz from the City University London.

We have also maintained a constant presence in the ontology-based data access work around petroleum databases, thanks to the continued participation of researchers from Birkbeck, University of London. In 2018, two of our researchers were visiting fellows at ATI, furthering our collaboration and mutual knowledge exchange.

8.3 University of Oxford, UK

University of Oxford has been a highly active academic partner in SIRIUS. This partnership ensures we are at the heart of the academic and innovative activities in centre on shaping the future of data-driven research and application within the Oil and Gas industry.

8.4 European Projects

Our commitment to the European research landscape is deeply reflected in our active involvement with various projects and institutions, including the centre of the University of Oxford. SIRIUS' research and innovation program builds on the foundation laid by three EU projects that concluded in 2016 or 2017: Optique, Envisage, and HyVar.

Expansion of H2020 Projects: We have successfully expanded our H2020 project, Melodic (731664), including Morphemic (871643).

SIRIUS in REMARO: Through Einar Broch Johnsen, SIRIUS has also partnered in REMARO, a Marie Curie project focusing on applying formal methods to ensure the safety and reliability of autonomous robotics.

Research Proposals and Acceptance: SIRIUS submitted in total 35 research proposals for H2020, several of which were accepted and currently in execution. An example of such projects is the project Plooto, which is designed to deliver a Circular and Resilient Information System (CRIS) that assists manufacturers in their green, digital, and circular transition.

EU Project RE4DY: Initiated in 2022, this project aims at constructing data-driven digital value networks 4.0 to maintain competitive advantage through digital continuity and superior data spaces across all product and process lifecycle phases.

Leadership in ONTOCOMMONS: SIRIUS is a partner and Work Package leader in ONTOCOMMONS, an H2020 Coordination and Support Action advocating the use of semantics in materials technology, design, and manufacturing.

EU Project Eur3ka: As a partner in the H2020-SC1-PHE-CORONAVIRUS-2020-2-NMBP project Eur3ka, SIRIUS contributes to the development of ICT-based flexible responses to pandemics within the industry.

EU Project Plooto: delivers an innovative digital platform and related tools and services that favour establishing collaborative practices and industrial alliances to implement circular value chains.

Membership in BDVA and A.SPIRE PPP: Our positioning work towards the EU is carried out through membership in the Big Data Value Association (BDVA) and the A.SPIRE PPP for process industries.

Nordic Interoperability Cooperation: SIRIUS participated in the Nordic Interoperability Cooperation, collaborating with universities and companies in Sweden (Luleå) and Finland (Tampere) to establish EU projects in this crucial subject area.

Industrial Digital Twin Association, NAMUR, DEXPI and AutomationML. Our work on semantic asset modelling places us in a position where we can contribute to the development and standardization aims of four German standardization initiatives. This has enhanced our research and development network with German universities and companies.

These activities reflect SIRIUS's commitment to strengthening our European cooperation and contributing significantly to the H2020 initiative.

9 Training of researchers

9.1 Setup for researcher training

Training young researchers have been a major focus in SIRIUS. Several initiatives were executed which we believe helps making the centre attractive for recruiting talented national and international doctoral candidates as well as retention of candidates.

9.1.1 Training through the Research programs and within projects

Ph.D. level training is organized by the research programs as each stipend holder are organized within a specific discipline. However, to get necessary domain understanding, the centre offered a one-week residential course on the oil & gas industry.

The course provides as in-kind contribution by Schlumberger. During this hands-on course, the students learned the life cycle of the oil and gas industry, the functions of companies involved throughout the cycle and their roles and responsibilities. An overview of technologies, workflows, and processes as well as risks, rewards, social, environmental, and financial impacts associated with the industry. Other domain specific educational workshops, lectures or field trip studies are organized by demand within research projects that are defined together with centre's partners, such as exploration geology, logistics and planning. Recruitment of master students is also done within individual research projects or research programs. With awards from DIKU, master's students could work on their projects at the Federal University of Rio Grande do Sul. This work is part of the Exploration beacon projects.

9.1.2 Training through the Mentoring Program

The mentoring program is a formal and structured one-on-one program where a mentor facilitates the development of a mentee. The program aims to contribute to the professional and personal development of both mentors and mentees and functions as a vehicle for increasing industry-academia collaboration through forming shared understanding.

It is challenging to create industrial innovation and outstanding research at the same time. By targeting researchers who are at the beginning of their careers, the program was seen as unique within academia in Norway. The overall objectives of the program were:

- Offer individual researchers personal development strategies and to train future research leaders in academia or industry.
- Shape the centre identity by exchanging expertise, values, skills, perspectives, attitudes and through networking.
- Increase mutual understanding between SIRIUS industries and academia to foster collaboration, engagement and build career competences on both sides of the mentoring relationship.
- Promote and harness the full potential of diversity in SIRIUS: cultural, age, gender, and expertise aspects.

Mentors are industry leaders from SIRIUS partners who are motivated to support the career development of a SIRIUS researcher (Ph.D. researchers and Post Doctoral researchers). Each program has one-year duration. In total, the mentoring program enrolled 20 mentor- and mentee pairs. The mentor program is an essential vehicle in the centre for promoting and training future female research leaders, and we try to recruit female role models as mentors from our partner companies.

All junior researchers at the centre could apply for participation. To enrol in the program, the mentees needed to apply with a letter of motivation including their development goals and participate in an interview. Mentors also send applications to participate where they share their motivation for participation, background, and experiences to ensure the best possible link between mentor and mentee. To prepare mentors and mentees for the program, we organized a Mentor Master class and an information meeting for the mentees. In these meetings, we introduced mentoring and the role and responsibilities of an adept/mentor. After the matching, each mentee received their own mentor.

In the twelve-month program, five gatherings were carried out. Each mentor-mentee pair met ten to twelve times between sessions, and mentees also visited the mentor's workplace. At these visits, mentees were introduced to relevant people at the partner companies and gave professional presentations.

Through the programme, the mentees gained and expanded their own strategic network. The mentee group also became a source of personal support for each other. They gained an increased understanding of industrial innovation, which fulfilled one of the main aims of the programme. In addition, all parties feel that the program has strengthened the partnership between the company and SIRIUS.

researchers. An enabler for personal development and innovation, University-Industry Innovation Conference, 2020

The SIRIUS centre's managers, who interacted with the mentees daily, experienced that the mentees matured during the years of the programme. They observed that the mentees became better at communicating and communicating their research with those who were not experts in their subject specialisation. They acted with greater self-awareness and assertiveness and interacted more closely with colleagues. The group of mentees also actively contribute to other activities in the centre such as Onboarding program of new employees, the Researcher Gatherings, and the General Assembly. They take more ownership in the centre. All participants were strengthened through a social and developing collaboration.

9.1.3 Training through Onboarding

The SIRIUS onboarding is designed to help new employees to adjust to the centre's culture and work environment. The practice is structured with a written onboarding plan that is consistently implemented. All new employees will be assigned a buddy, typically a post doc or a Ph.D. student. The role of the buddy is to help the new employee during his/her first 3 months of employment and offers guidance and support regarding the day-to-day aspects of working at the centre. This includes culture, organizational structure, the department, mentoring and educational programs, introducing co-workers and (industry) partners and other information sources. We believe that a good onboarding process will help new researchers to be well adjusted and that they experience an inclusive working environment. Our buddies take on a leadership role and this strengthens and contributes positively to the centre culture.

9.1.4 Candidates' reflection of their time in SIRIUS

"I joined the SIRIUS research center in September 2017 when I got accepted for a PhD position at the Norwegian University of Science and Technology (NTNU) in Trondheim. This position was funded by SIRIUS through their collaboration with NTNU. One of the primary reasons I chose to apply for this position and become part of the research center was the evident emphasis on collaboration with industry and employing cutting-edge technologies to address industrial challenges in SIRIUS.

Throughout my four-year PhD journey, SIRIUS played a crucial role in supporting me. I had the privilege to be involved in a joint industry-academic project, fostering close connections with industrial stakeholders. My PhD specific project was based in Oslo, and I received full financial support from SIRIUS for essential travel during the data collection phases as part of the PhD funding. This involvement allowed me to expand my professional network significantly. Beyond financial support, SIRIUS also organized a mentorship program focused on personal development. Selected PhDs and postdocs were paired with industrial mentors based on their individual needs and development plans. The year-long mentorship was invaluable, offering opportunities to enhance non-technical skills such as presentation, feedback exchange, effective communication, and more. That mentorship program equipped me with the skills needed to effectively communicate and leverage my competences, ultimately contributing to my successful integration into the industry. Even years later, I maintain contact with my mentor.

Upon completing my degree, I secured a position at Equinor, one of the key companies collaborating with SIRIUS on various projects. The skills honed during the mentorship program, coupled with my competences and the help of network provided by SIRIUS, played a pivotal role in getting that position." - Mina Haghshenas (now working at Equinor).

"My decision to join SIRIUS, a renowned center for research-driven innovation in the oil & gas industry, was driven by a keen interest in delving into the real-world challenges of AI in an industrial setting. The center provided a unique opportunity to access extensive industry data and models, offering a practical dimension to my theoretical knowledge. At SIRIUS, I was not only part of a collaborative environment with leading industrial partners like Equinor, Schlumberger, and IBM but also benefitted immensely from direct mentorship. I was fortunate to have a mentor from IBM for a year, who played a pivotal role in familiarizing me with the working culture, intrinsic challenges, and the often-unspoken rules of the industry. This mentorship, coupled with SIRIUS's interdisciplinary approach and engagement with top-tier academic institutions like Oxford and NTNU, significantly enriched my understanding and application of AI. My time at the center was marked by substantial contributions to the field, as evidenced by six publications in prestigious AI and data science venues. Post-PhD, as a Senior Data Scientist at Sopra Steria Oslo, I now apply the insights and skills acquired at SIRIUS to make AI models in the oil and gas and energy sectors more understandable and transparent. The exposure and experiences gained at SIRIUS have been instrumental in shaping my approach to AI, ensuring that its advancement is not only innovative but also aligned with the practical and ethical demands of the industry." - Peyman Rasouli (now working at Sopra Steria).

"I joined the SIRIUS centre in 2019 for the interdisciplinary GeoAssistant project. Within the project, I got to collaborate with geologists, people with different computer science backgrounds, and people from Schlumberger and Equinor. This cross-domain working experience was extremely valuable for me. It strengthened not only my technical skills but also my soft skills. I also participated in the SIRIUS mentoring program. My mentor and I set up regular meetings throughout the year. I received critical career advice from my mentor, who has excellent experiences both within leadership and within his technical expertise. I appreciated the opportunity to be part of the SIRIUS centre and through it I met many excellent researchers, leaders, and engineers. The training and networking I obtained through 2019-2020 at the SIRIUS centre has indeed strengthened my research career and led me to my current position as an associate professor at University of Bergen." - Crystal Din (now associate professor at University of Bergen).

"At SIRIUS, the decision to join was fuelled by the existence of an international environment, providing a rich tapestry of perspectives and a collaborative spirit. The centre's strategic partnerships, notably with industry giants like Equinor, presented a unique opportunity to bridge academic excellence with real-world applications. During my time at SIRIUS, the workplace culture stood out as a breeding ground for innovation. The freedom to explore and push boundaries in research was not just encouraged but celebrated. The supportive ecosystem enabled me to delve into projects that were not only academically stimulating but also held practical significance in the broader industrial landscape. Now, as a senior data scientist at Warner Brothers Discovery post my PhD, I find myself seamlessly applying the skills and knowledge learned at SIRIUS. The center not only equipped me with a robust academic foundation but also instilled a problem-solving mindset crucial for navigating the challenges of the professional realm. My journey with SIRIUS has been transformative, laying the groundwork for a fulfilling career that extends the impact of rigorous research into the pragmatic realms of industry." - Summaya Mumtaz (now working at Warner Brothers Discovery).

"I joined SIRIUS in 2017 through the DataScience@UiO research and innovation cluster, a collaboration between the Department of Informatics and the Department of Mathematics at the University of Oslo.

Having a background in mathematics and data science, being immersed into an environment of semantic technologies and knowledge graphs, was invaluable to me. My research project was on combining formalised knowledge in terms of logical structures with statistical machine learning, and it is difficult to imagine a better place for this, at that time. Nowadays, research on machine learning over knowledge graphs pop up everywhere, but in 2017, DataScience@UiO and SIRIUS was a place for pioneering ideas on the subject matter.

The industrial partners of SIRIUS provided a nice grounding, steering the research towards applications and solving real problems. While, at the same time, not budging on academic excellence, this made for a powerful combination that allowed me to work on, and solve, very hard industry problems.

My time with SIRIUS has placed me at the forefront of the world of graph machine learning, a weight I carry happily, and one I make use of every day in my current role as Machine Learning lead at IndyKite." -Daniel Bakkelund (now working at IndyKite).

"Looking back on my time at SIRIUS, it is hard to overestimate the impact the center has had both on my personal and career development. I joined SIRIUS at the very beginning of the center, during my PhD. As a theoretician, I had always been interested in complex, abstract problems, yet had previously struggled to find a meaningful connection to real-world challenges. SIRIUS provided a unique opportunity to combine my theoretical interest with real-world applications. The close proximity to industry ensured constant cross-fertilization, where fascinating research questions could be motivated and guided by industry needs. This, due to the open and collaborative work environment, has resulted in what I consider some of my most fruitful work. Therefore, I jumped at the chance when I was awarded the opportunity to continue as a post-doc after my PhD.

In addition to providing a meeting ground for industry and academia, SIRIUS also provided mentoring and training which affected more than just my research. Due to the inter-disciplinary nature of the center, we constantly interfaced with others who were not contained in our own academic bubble. This happened both formally, through initiatives such as the mentoring program, and informally in social gatherings and events. Through this I gained a lot of experience in presenting complex theoretical ideas to non-experts, without being able to rely on heavy use of lingo. This was invaluable for my teaching at the university, where I could motivate the curriculum by examples in current research. This proved very successful during my time teaching at the university, and I still benefit greatly from this experience in my work today.

SIRIUS helped provide a solid foundation for me to explore new fields of research and expand my career after leaving the center, first as a Researcher in confidentiality at Statistics Norway, and now as a Senior Data Engineer within AI at the Norwegian Tax Administration." - Daniel Lupp (winner of best teaching prize at the department of Informatics, UiO. Now working at Skatteetaten).

"Researchers at SIRIUS have been crucial in improving our educational programs. They have brought vital insights and developments from their research into our courses. For example, they have introduced new methods, languages, and research findings into the more advanced courses' curriculum, ensuring it stays up to date. Importantly, they have included real-world examples from their work, such as industrial case studies. This makes the material more relatable for students, as they can see firsthand how these concepts are applied in the real world. This unique integration of research and education makes our courses current and adds a practical dimension to learning.

The close tie with our industrial partners is helpful in getting guest lecturers on board, making the courses even more engaging and relevant. Furthermore, PhDs from partner industries also take up these courses and provide valuable feedback for improvement. Their input helps in keeping the study material current and relevant to industry needs. This makes our courses useful not just on a theoretical level, but also gives students a clear idea of their practical applications." - Leif Harald Karlsen (winner of best teaching prize at the department of Informatics, UiO. Now Senior Lecturer in UiO).

9.2 Gender perspective.

The centre has had Ph. D.s, postdoctoral, and researchers from over 20 nationalities. Throughout its lifetime until its end date of 31 October 2023, the centre successfully cultivated an environment that embraced diversity in all dimensions. It aimed to create an inclusive atmosphere where everyone, regardless of gender or nationality, felt valued, could contribute their best, and could thrive professionally approximately 35% women and 65% men. For the mentoring programme 2017-2018, we had 20% female mentors and 40% female mentees. For 2019-2020, we had 30% female mentors and 20% female mentees.

9.3 Employment of PhD candidates

Employment of PhD candidates (number)							
By centre company	By other companies	By public organisations	By university	By research institute	Outside Norway	Other	Total
	6		2		7	2	16

Table 2. Employment of PhD candidates (numbers)

10 Communication / Popular dissemination of knowledge

SIRIUS's primary communication channel has been its website (https://sirius-labs.no). This provided the public-facing communication for the centre. This site was supported by a LinkedIn group SIRIUS Centre for Research-driven Innovation, with 159 followers.

The annual report was a key document for communication to the wider community, especially in the start-up of the centre. As social media and digitalization of communication advanced, the role of the annual report was taken over by the website.

Our communication and popular dissemination work has focused on operating and energy companies in the energy sector. This has been supported by the following activities:

- SIRIUS has financed the University of Oslo's membership of **NORWEP**. This membership was used early in the centre's life to position and align SIRIUS's innovation agenda. Presentations on SIRIUS were held at NORWEP conferences and seminars in Paris and Aberdeen.
- SIRIUS workers have regularly participated in the annual **ECIM conference** for data managers in the oil & gas industry.
- Further education modules on industrial digitalization and digital twins have been developed at have been taught at University of South-Eastern Norway and the University of Oslo. These courses were developed as a response to the COVID-19 crises as a tool for developing new digital skills.
- SIRIUS workers participated in SPE conferences in Aberdeen and Houston. Keith Lewis and David Cameron travelled to Houston as part of a Norwegian Delegation to the OTC conference in 2019. This resulted in a series of briefing seminars and meetings with engineering and operating companies in the United States.
- The annual November Conference in Rio de Janeiro has been used to profile the centre and develop its contacts in the Brazilian energy industries.
- SIRIUS has provided content and resources to Ontocommons EU project's dissemination and policy-shaping rounds

This targeted communication has resulted in the centre developing a reputation as a centre for informatics research in the energy and manufacturing industries in Europe (France, United Kingdom, and Germany), the United States and Brazil.

11 Effects of centre for the host institution and research partners

11.1 University of Oslo

The SIRIUS SFI has been very important for The University of Oslo (UiO).

Firstly, SIRIUS has strengthened core computer science at the Department of informatics and in particular built strong research activities with logic, information modelling and digital twin technologies. In addition, strong relations are built to complementary research groups, both locally at UiO, nationally and internationally. An example of these types of connections are that core researchers in SIRIUS participate in Integreat – Center for knowledge-driven machine learning funded through the CoE-mechanism at the Research Council of Norway.

Secondly, SIRIUS has strengthened UiO's collaboration with industry, both by bringing state of the art research-based knowledge into product, industrial solutions, and processes and through long term collaboration with R&D-personnel in industry. These achievements have been and are used when building new project activities with industry and public sector.

Thirdly, SIRIUS has made an important contribution to how UiO should organize projects and interdisciplinary actions across departments and faculties and together with external partners. Experiences with SIRIUS were of crucial importance when the Centre for Computational and Data Science (dScience) was established in 2021, and personnel at SIRIUS have been and are central in the development of dScience, in particular the dScience Partner Program.

11.2 Simula

The SIRIUS SFI has provided Simula with precious opportunities for embracing important, real-life research challenges, which have in turn further developed Simula's general expertise on high-performance computing, as well as expanding Simula's collaboration network. More specifically, Simula established a fruitful research collaboration with Equinor and UiO about scalable reservoir simulations. As detailed in section 7.1, the collaborative research team developed various scalability-enhancing strategies and the corresponding implementation inside the OPM open-source reservoir simulation framework. Moreover, SIRIUS has provided a platform where Simula strengthened existing collaborations with other consortium partners. For example, in the SIRIUS context, Simula worked with Dolphin Interconnect Solutions and UiO on consolidating the SmartIO technology, which is important for cluster computing and distributed applications.

The SIRIUS-generated impact for Simula is also illustrated by additional industrial collaborations that have been established thanks to the achieved results within SIRIUS. A good example is that Equinor has provided Simula with extra funding worth of 55 person months (beyond SIRIUS) for further enhancements of the OPM software framework and new research activities about automated parameter tuning. A new paper about the latter subject, Sæternes et al. 2024 [77], was published in the prestigious Journal of Computational Science. Another example is that AkerBP, another oil & gas company, joined forces with Equinor to fund a four-year industrial PhD student to be co-supervised by Simula and Equinor staff, starting in January 2024. These industrial collaborations are expected to have long-term impacts on Simula's research activities in the wide area of scientific computing.

11.3 NTNU

The SIRIUS SFI has been important for NTNU in that it deepened and strengthened our existing research activities within digitalization in oil and gas. NTNU, including Department of Computer science, the SFI SIRIUS partner from NTNU, already had a history of research projects within this domain, but SFI SIRIUS allowed these activities to be significantly boosted. Prior to SIRIUS, NTNU's focus had been dominated by geoscience concerns, with only modest attention to the digitalization aspects. SFI SIRIUS has shifted this emphasis.

More specifically, NTNU's participation in SFI SIRIUS promoted a new portfolio of research activities, with novel problem owners and with a new set of research partners. As such, SIRIUS has contributed to forging stronger research ties between NTNU's Computer science and University of Oslo's Informatics departments.

SIRIUS funded only one PhD and one researcher at NTNU. The significance of SIRIUS for recruitment at NTNU was more importantly that SIRIUS funded a handful of faculty members who invested time and efforts into research activities and operations, including recruiting master students to do projects within SIRIUS.

In sum, SFI SIRIUS has contributed at NTNU to a stronger visibility of digitalization as crucial to the transformation of oil and gas in ways not previously evident.

11.4 Oxford

SFI SIRIUS made a significant contribution to research in the Data and Knowledge group at the University of Oxford. Specifically, SIRIUS encouraged and supported engagement with stakeholders in the Norwegian Oil and Gas industry, which was important for both directing and evaluating our research, and collaboration with academic and industry partners in Norway, which helped to broaden our range of skills and our impact on real-world applications.

An example of such a collaboration has been work focussed on large-scale infrastructure design with partners from Aibel, DNV and UiO. In this work Aibel contributed motivating use-cases and deep domain expertise, DNV contributed conceptual modelling expertise, and Oxford and UiO provided expertise on knowledge representation and reasoning systems. The combination of these skills promoted not only the development of reasoning systems, but also their evaluation and deployment in realistic demonstration applications.

SIRIUS funded several PhD students and one postdoctoral researcher at Oxford. They all deeply appreciated and benefited from the international collaboration and the deep connections to motivating use cases. The PhD students also appreciated the SIRIUS mentoring scheme, which helped them to navigate their PhD and to develop a diverse network.

It is worth noting that the strong collaboration between Oxford and UiO has continued beyond SIRIUS. For example, Oxford is now engaged with the Integreat Center for knowledge-driven machine learning, and we continue to support jointly supervised PhD students.

12 Effects of centre for the company partners, public partners, and society at large

12.1 Alignment with Partners

The SIRIUS centre has worked hard at aligning its research and innovation agenda with the aims of each partner. Every partner has held a partnership strategy meeting, using a Partnership Canvas, with the centre management and key researchers. This has allowed us to determine the objectives of each partner. The results of the meetings before the mid-term review are summarized by Cameron et al. 2019 [117], from which the following material is taken. All partners joining after the review had a meeting when they joined.

With twenty partners, there were many goals behind participation in the centre. However, we saw several common features:

- Vendors want to use the centre to gain access to end user's problems and thereby expose, benchmark, and improve their hardware, software, and services.

- All partners wanted to use SIRIUS as a forum for building collaboration between companies around research problems in the centre. Several partners talked of a “forum” or a “community vision.”
- Partners see the centre as a means to build the digital competence of their personnel and influence internal R&D work.
- Participation in the centre was built, for core initial participants, around existing relationships in European research projects.

From the academic side, we emphasized our need to work with real industrial problems and real data sets, engage with end-users of technology and prototype our technologies in our partner’s products and systems.

The formats for collaboration identified varied from company to company, but included the following mechanisms:

- Many partners see SIRIUS as a forum for gaining and sharing knowledge. Our activities that create places to meet and share research ideas and results were encouraged.
- A laboratory for software and hardware is a necessary part of the centre. We responded to this by employing a laboratory manager and creating the necessary repositories and services.
- Innovation projects, with several companies and research groups are seen to be essential to generating value. These need to be funded, so we need to be pursuing money from the Research Council, European Union, and Joint Industry Projects.
- SMEs and service companies depend on external funding or payment from operating companies to participate in innovation projects. This was a barrier to involvement.
- Placement of researchers in companies is possible and desirable.
- Seminars and workshops are vital for building collaboration networks and shared understanding.
- SIRIUS’ mentoring program is a valuable way of building relationships.
- There was a strong willingness to host interns, M.Sc. projects, and summer students. This willingness needs to be met with the recruitment of suitable students and changes to curricula that support this exchange.

The meetings also developed a set of success criteria and KPIs for the collaboration.

- Milestones and deliverables
    - Compelling demonstration of a prototype or pilot at a corporate customer or end-user conference.
    - Innovation projects initiated and run successfully.
    - Number of workshops or knowledge exchange events held.
    - Changes made to work processes, products, or systems in the company.
    - Exchanges of personnel, internships, and M.Sc. projects.
    - Joint publications.
    - Recruitment of students and graduating centre personnel.
- Qualitative criteria
    - Qualitative description of value of collaboration.
    - Competence transfer and increases in organization.

The centre grew in number of partners during its period. We saw two periods of growth: first in 2018 when READI (Joint Industry Project) partners Aker Solutions, TechnipFMC and Aibel joined, together with SINTEF. They were already active in Joint Industry Projects and saw the potential for immediate benefits for development of software, building of skills and transformation of engineering practices through engagement with SIRIUS researchers. The second wave of new partners was an attempt to engage relevant SMEs with the research agenda of the centre. This was less successful, as they were not able to allocate the necessary resources to align their product or service development with our beacon programs. We were also limited by the COVID lock-down and could not conduct the necessary networking activities to activate these companies. To achieve this alignment, we see the need to obtain direct funding of the SME's involvement from end-users and innovation funding. We also saw that the acquisition of smaller companies by larger companies: fluidOperations by Veritas Technologies, OSIsoft by Aveva and Prediktor by TGS, terminated their commitment to the centre.

However, an employee of one of the smaller companies is central to a recent start-up Data Treehouse AS. This company uses OTTR as a core component in their software and systems. They are also users of the standardization results delivered by DEXPI Process.

12.2 Policy and Sustainable Development Goals

David Cameron has represented the University of Oslo on Offshore Norway's reference group for research and education. This has resulted in development of further education modules at M.Sc. level on industrial digitalization and digital twins. We believe that the alignment of our research with education and training can be essential in generating impact from our work.

The SIRIUS annual report in 2018 aligned the strategy and deliverables for the centre with the UN Sustainable Development Goals. We were able to document contributions to the following goals:

- Good health and well-being – through our personalized healthcare work.
- Quality education through our work on digital geosciences and industrial digitalization.
- Clean water and sanitation through our collaboration with NIVA.
- Affordable and clean energy through our operations beacon projects.
- Decent work and economic growth through our rationalization of tedious, document-driven work processes.
- Sustainable cities and communities, through the application of IMF to modelling and digital twins.
- Climate action through our collaboration with the CIRFA remote sensing SFI in Tromsø.
- Life beneath water through our use of knowledge representation in building and monitoring sound and safe subsea production systems.
- Partnership for the goals, through an extensive collaboration with Brazil and the EU.

12.3 Impact: Reservoir simulation

In section 7,1, we provide details about the joint SIRIUS research activities, between Equinor, Simula and UiO, on scalable reservoir simulations. Specifically, various new scalability-enhancing strategies have led to substantially improved computing speed of the OPM open-source reservoir simulation software. A standard benchmark has shown that the speedup obtained is at least 25%, with a higher potential gain on larger computing systems. The expected long-term benefits, due to the SIRIUS research activities and the new follow-up activities, include the following aspects:

- The daily workflow of reservoir engineers at Equinor and other oil & gas companies will be improved, due to faster reservoir simulations.
- The reliability of reservoir operation/management will be noticeably improved, due to the possibility of running more simulations for better uncertainty analysis.

- The reservoir simulations will become more energy-friendly, due to the improved parallel efficiency of reservoir simulators (i.e., less time used combined with higher energy efficiency).
- Oil & gas companies can greatly reduce their operation costs, due to the competitiveness of the enhanced OPM open-source software, against costly proprietary software.
- The entire research community for subsurface modeling will benefit from the enhanced OPM software framework, because faster and more-detailed simulations are achievable.

12.4 Impact: Knowledge-driven transformation for engineering and operations in capital-intensive facilities

A major impact of SIRUS has been the advancement of knowledge representation as a tool for transformation in industry.

In section 7.2 we describe the main achievements of our coherent program of fundamental, translational, and applied research and innovation work addressing the use of knowledge representation to transform engineering design and operations. Here we describe the impact of this work and how it was achieved.

The work built on the impact and industrial network established by the **Optique EU project** (2014-2016). The core network in Optique became central to the SIRIUS Centre for Research-Driven Innovation in 2015. Early in the life of the centre, it became clear that effort would be needed to ensure that fundamental IT research answered genuine business challenges of partner companies. SIRIUS thus established a **beacon program** on digital twins and digital field development [118]. This created a portfolio of projects with the explicit purpose of deriving impact from SIRIUS' research agenda for knowledge representation and graph databases.

The agenda for this work was set by workshops with SIRIUS partners (Equinor, DNV, SLB, IBM, SAP, OSISoft) and other companies (Siemens, TotalEnergies, Shell, Aibel, Aker Solutions, TechnipFMC). We pursued a dissemination strategy that involved business-oriented presentations at events organized by NORWEP, EU PPPs (BDVA and SPIRE) and workshops in Rio de Janeiro and Houston. This resulted in PeTWIN, a collaboration with Petrobras, Shell, Equinor and UFRGS, financed by the RCN and FINEP.

Collaboration with DNV and Equinor resulted in engagement with the **NORSOK Z-TI** project and its successor, the **READI Joint Industry project**. **The economic driver here was the potential to reduce procurement costs in field development by up to 20%.** Here the SIRIUS research team was a key provider of tools and ideas behind the implementation of the project. READI resulted in four deliverables: the ISO/IEC81346 RDS for oil & gas, the IMF concept paper, a semantic representation of requirements, and the Industrial Data Ontology (IDO). The work on requirements is being developed as a course program, staff exchanges and workshops with dissemination in Brazil and the US, through the DSYNE INPART network (https://dsyne.no).

The READI JIP identified the need for **IMF** as a tool to link the RDS for oil & gas to engineering data and requirements in a way that exploits the power of semantic technology and logic-based knowledge representation methods. IMF provides a rich information model that supports structuring of engineering data in an effective way that also supports reasoning about requirements. At the same time, 2018, participants in READI, Aibel, Aker Solutions and TechnipFMC, became partners in SIRIUS.

This provided an opportunity for a further **Digital Design Basis JIP**, organized within SIRIUS, that attempted to model design bases from three operating companies (Equinor, Lundin and

AkerBP) as semantic data, so that it could be used by three vendors (Aker Solutions, TechnipFMC and Aibel). This prototyping work informed software development by Aize AS, TechnipFMC, Equinor and Aibel. **Aker Solutions' business case for the project identified cost savings of at least NOK 1.6 billion a year across the Norwegian Continental Shelf just in early phase design.**

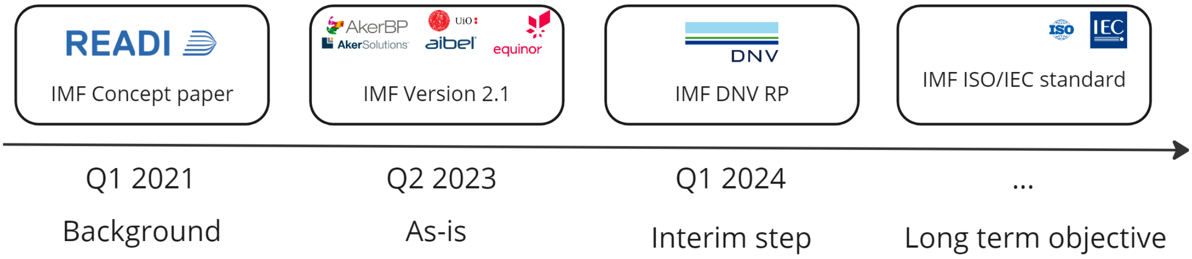
This work was followed up further by the **DISC initiative in the Yggdrasil field development**. This initiative is a collaboration between Equinor, AkerBP, Aker Solutions and Aibel, where operators and vendors agree to pilot new ways of transferring engineering data during a field development project, with the aim of moving away from document-based work processes. This initiative has validated the IMF, the RDS for oil & gas, and IDO. In addition, the project has been a leading implementer of **Industry 4.0 standards** such as AutomationML, NAMUR, Asset Administration Shell and DEXPI. This has resulted in SIRIUS establishing new collaborations with German academia and industry, notably through the publication of an IMF-inspired DEXPI standard for process design data. We have also developed a library or IMF types for design of facilities. A new working group in IDTA has been set up to address how to enhance Industry 4.0 based on IMF.

OTTR has also been adopted as a **tool by third parties**. Aibel, DNV, and Grundfos use OTTR in their development. A recent start-up, Data Treehouse AS (https://www.data-treehouse.com), uses OTTR as a core technology in their products. The group of Prof. Melinda Hodkiewicz at the University of Western Australia uses the tool to manage ontologies of maintenance systems for mining companies (BHP and RioTinto) [15] and is active in the IDO work.

SIRIUS is among the founding members of the recently created Knowledge Graph Alliance (https://www.kg-alliance.org/), one of the results of the OntoCommons EU project (https://ontocommons.eu/). **IMF** principles have been used in the development of the OntoCommons EcoSystem (OCES) and partially demonstrated in the project's demonstrators. SIRIUS developed collaborations with Industrial Ontology Foundry (https://oagi.org/pages/industrial-ontologies) and organised, together with DNV, the first open workshop of IOF in Oslo in 2019 with about 120 participants.

SIRIUS methods are being applied and further developed in four ongoing Horizon Europe projects in the manufacturing sector with UiO as partner: Re4Dy (https://re4dy.eu), Plooto (https://www.plooto-project.eu), Tec4MaaSEs (https://tec4maases.eu), and Sm4rtenance (https://sm4rtenance.eu).

Initiatives ongoing to realize the full potential of this transformation include: (1) publication of IMF as a DNV Recommended Practice; (2) communication through the IOGP digital initiative https://www.iogp.org/workstreams/engineering/standards/digitalization/ and CFIHOS https://www.jip36-cfihos.org; (3) collaboration with a revitalized POSC Caesar Association, who is developing IDO and also collaborating in the fPVN – Arrowhead EU project https://fpvn.arrowhead.eu/fpvn-arrowhead/; (4) participation in the new ISO standard ISO/NP 23726 Ontology Based Interoperability. IDO will be part 3 of this standard; (5) use of the DSYNE network to catalyse further work and support adoption in Brazil and the US; support of new and existing software vendors in the development of industrial-strength tooling; (6) contributions to standardization work in the Industrial Digital Twin Association, NAMUR and DEXPI and (7) collaboration with stakeholders in the electrical energy sector including Statnett and Statkraft, and construction sector to prove our methods as a unifying tool for discipline-specific data models, such as CIM and BIM.



12.5 Impact Statements from Partners

12.5.1 Alf Birger Rustad, Equinor

The reservoir simulator *Flow* from the OPM open-source project has been one of the focal points for the SIRIUS project. Being capable of running industry relevant cases has been an invaluable test bed for research on numerical methods and high-performance computing. As demonstrated by multiple scientific articles, the contribution from the SIRIUS project has been instrumental. Today, multiple assets in Equinor are benefiting from these achievements.

12.5.2 Torleif Saltvedt: Equinor

In Equinor the SPINE project has been a major sponsor for advancing in the knowledge about how to do facility asset modelling by use of the Information Modelling Framework.

One of the major learnings in SPINE was the acknowledgement of the need to involve actors in the whole value chain and thinking end to end (design, operation, purchasing, construction, maintenance), while, at the same time, involving experts on IT and semantic WEB technology. Modelling experts and subject matter experts need to be brought together to fully understand the needs and avoid silo thinking.

The achievements on IMF and modelling would not have been possible without the engagement from SIRIUS. SIRIUS provided a wide network and close interactions with stakeholders in academia, industry, and standardization bodies where one of the biggest contributions was the ability to communicate and facilitate exchange of knowledge between Information Technology, Engineering Technology, Information Management, Operations Technology, and modelling.

12.5.3 Hugo Kohmann, Dolphin Interconnect Solutions

The main experience for Dolphin in the SIRIUS project has been good. The main benefit has been improved access to scientific personnel for advanced technology and market discussions. As a result of the learnings, Dolphin has optimized its SmartIO product offering for NVMe sharing. Most of the work on the NVMe driver was done by Jonas Markussen, who received his PhD in 2023. During the project, Dolphin has hosted several maser grade projects which enabled Dolphin to gain further insight into new and challenging problems. Jonas and several of the master grade students are now permanently hired by Dolphin.

Dolphin considers themselves to be the global leader in PCIe clustering technology and have, during the duration of the project, had a significant success in the market. Various SKATTEFunn projects and strong collaboration with the University of Oslo and Simula on master's degree work, eX3 and SIRIUS projects has been fundamental to this success. Future collaboration projects on PCIe 5.0 and 6.0 as well as CXL are foreseen.

12.5.4 Jan Kåre Slettebakk, Aker Solutions

Aker group has identified the following main benefits of SIRUS partnership as being:

- SIRIUS provided the scientific foundation for DISC Joint Industry Project cooperation.
- Corporate wide vision for use of industry standards as base for digital value chain optimization

- Combination of digital twin EPC and Asset Data via systems engineering modeling
- Inhouse information model development process in the Aker Group
- Understanding of RDF semantic web as information framework
- Aker Group's digital investments includes competence gained from SIRIUS
- An Improved semantic competence network

While SIRIUS has been a good arena for us, I see the potential for a deeper focus on the concrete EPC-operator value chain or lifecycle, with a broad focus on handling large amounts of data, semantic methods, and database technologies. This would be a fruitful area for future work.

12.5.5 Thomas B. Pettersen, Computas

Computas has been a SIRIUS partner throughout the centre's lifetime. The company works - along with other engagements - with clients in the oil, gas, and energy business, making the very subject of the SIRIUS centre more than interesting. Our main contribution has been to cofinance an industrial PhD candidate and to serve as a SIRIUS board member as a representative of the IT partners of the centre. Additionally, Computas has been engaged in several industrial projects initiated by SIRIUS industrial partners, although these projects in themselves have had production status rather than research as their primary focus.

The centre participation has led to increased contact with the research community at the University of Oslo as well as the semantics expertise of the University of Oxford.

It is our opinion that collaborating with a dedicated centre like SIRIUS is beneficial both ways - commercial companies get acquainted with the research community, and the research community gets exposed to the business thinking and prioritization required to keep a commercial company profitable and resilient.

It is also worth mentioning the Joint Industry Project READI, headed by DNV, and partnered with many of the same actors as SIRIUS, provided added benefits, as it was running in parallel with SIRIUS over its lifetime.

Computas' main success story is that we are now closer to having one of our senior engineers obtain a PhD degree. Secondarily, knowledge has been gained by other employees within the research and methodology fields of SIRIUS. It will be a shorter way to hook up with the university research community when relevant situations should emerge in the years ahead.

The most important effects of the SIRIUS partnership are, in no particular order:

- Influence on Computas' innovation strategy and R&D activity
- Ideas for development of new or improved services and processes.
- Recruitment of qualified personnel; employer positioning (in the competitive IT business sector)
- Strengthened knowledge base.
- Improved access and relations to research institutions with its competent personnel
- Improved network with partners.

12.5.6 Anders Gjerver, Aibel

Aibel builds and maintains platforms and other critical infrastructure for the energy industry. The company holds a leading position within the European offshore wind industries and electrification of offshore oil and gas installations and onshore processing plants.

Close collaboration with our customers is essential. Therefore, we use integrated teams and utilize modern technology to create effective arenas of collaboration. Aibel has had a semantic technology master data solution in operation since 2015. This solution is ISO 15926 / OWL 2 based.

Aibel has been a long-time partner in SIRIUS. We have been engaged in SIRIUS projects like Digital Design Basis and we have contributed to the EU project Ontocommons in which SIRIUS had a leading role. We have also collaborated with SIRIUS partners and SIRIUS representatives in several joint industry projects. Project participation, along with our participation in SIRIUS arranged conferences and workshops, has been valuable for the Aibel employees involved.

SIRIUS was an exemplary collaboration between academia and industry. Within the SIRIUS Centre and among its partners we met experts in their areas of expertise who promote state of the art tools and methods. The academia and industry collaboration that the SIRIUS Centre provided made it possible for Aibel personnel to directly engage with expertise whose availability is often restricted.

The prospect of introduction of semantic technology-based solutions that would enable collaboration within the industry was our main motivation for joining the SIRIUS Centre. We have seen examples and use cases of solutions that could be beneficial for improved collaboration, but in our project execution we are still experiencing many of the same challenges. It has become obvious that another type of organizing is required if the goal is an industrial solution for application independent exchange of business-critical information.

Being a SIRIUS Centre partner has beneficial for Aibel and we will encourage further industry-academia collaboration. The industry should however take it upon itself to ensure that collaborative solutions are adopted.

12.5.7 Evgeny Kharlamov, BOSCH

SIRIUS has made a significant impact on Bosch in terms of shaping company's research agenda, engagement with SIRIUS partners, participation in international projects funded by the European Commission, development of young talents, joint organisation of international events and joint publications. Indeed, some of the priority AI topics in Bosch are semantic technologies, including semantic digital twins, semantic conceptual modelling, neuro-symbolic solutions, and their applications in smart manufacturing. In SIRIUS we investigated these directions jointly with several partners.

Bosch has been very active in SIRIUS, e.g., Evgeny Kharlamov was the Scientific Coordinator of SIRIUS for 2 years. Bosch and SIRIUS members published dozens of papers together.

In terms of products and services that Bosch transferred from SIRIUS there are several examples that include semantic solutions such as SemML (semantic-based system to make ML pipeline development easier and more accessible to end users), SemCloud (semantics-based system for automatic cloud deployment of machine learning pipelines) and ExeKG (a system for automatic conversion of semantic descriptions into executable ML pipelines).

13 Future prospects

All research groups in SIRIUS have been able to raise funding to continue their research programs after closing of the centre.

SIRUS was key in establishing Integreat, a new Centre of Excellence on knowledge driven machine learning. The Domain Adapted Data Science research program in SIRIUS continues as part of Integreat with significantly strengthened network and funding.

The rest of the SIRIUS team at University of Oslo continues its operation as the *SIRIUS laboratory* located under Dept. of Informatics. All key SIRIUS senior researchers at Dept. of

Informatics are active in SIRIUS laboratory. At the closing of SIRIUS SFI these researchers were involved in seven ongoing European projects organised by the SIRIUS laboratory. SIRIUS laboratory is now an internationally recognized competence group and is regularly invited into European proposal consortia. At the time of writing, 11 proposals to Horizon Europe are in preparation from the SIRIUS laboratory.

SIRIUS has initiated an international workshop series entitled Semantic Industrial Information Modelling (SemIIM) with two successful editions, both collocated with top international conferences on Semantic Technologies, namely ESWC 2022 and ISWC 2023. These will continue with SIRIUS laboratory as key driver.

The dScience Centre at the University of Oslo has established a partner program which will maintain SIRIUS' wide network to the industry and seek opportunities for funding of research-based innovation. Two former employees at the SIRIUS SFI are in full-time positions at dScience at the closing of SIRIUS SFI and one is in a part-time position. The dScience centre is hence properly resourced to maintain and strengthen the industry network that has been established by SIRIUS.

The University of Oslo is committed to safeguard research data, software, models, and databases developed in the centre period, particularly the database developed over the Volve dataset.

Simula has followed up its scientific engagement with Equinor with an extended collaboration on further applying high-performance computing to reservoir simulations. So far, Equinor has provided Simula with additional funding (beyond SIRIUS) worth of 55 person months, which is expected to generate long-term impacts on both sides. Another recent development is that AkerBP and Equinor jointly funded a new four-year industrial PhD position, including scientific supervision by Simula staff, with the aim of adopting the enhanced OPM open-source reservoir simulator for the management and operation of new oil fields.

14 Conclusions

14.1 Securing active participation from researchers and partners

An SFI is a collaboration across two sectors that are different in important respects. Key differences are how resources are mobilized and how carriers are built.

A PhD or postdoc researcher is building their CV and is focused on publications and long-term research perspectives. Industry lacks this patience and stamina that is present everywhere among academic researchers. Industry operates with a different sense of urgency: if it can work, make it work quickly; if it is going to fail, fail quickly. In consequence, resources are often mobilized to accelerate a short-term impact.

To achieve active participation from both researchers and partners, an SFI must find a way so that research and industry can complement each other in fruitful and constructive ways. This has been a key priority in SIRIUS throughout the whole centre period and we implemented several measures including partnership canvas, workshops, seminars, presentations, and on-site visits to partners. The partnership canvas was particularly useful for aligning SIRIUS work with partner priorities.

We were most successful when we managed to link researchers and knowledge from research with already ongoing industry collaborations, primarily within standardization or exchange of information between companies. In some cases, we influenced the scope of joint industry projects fully funded by industry. In these cases, contributions from researchers were aligned with the objectives of participating partners and appreciated by them.

14.2 Research leadership

From the point of view of researchers an SFI comes with extraordinary opportunities for collaboration, but research leadership is necessary shall these opportunities lead to results in research and innovation. A challenge is that the centre researchers in some ways need to work against incentives, in particular when substantial work that cannot easily be published is needed for engaging partners.

It is an important responsibility of centre research leaders to be able to recognize and encourage young talents with the ability to succeed in such research environments and to train them to take initiatives, be outreaching, and seek challenges outside their comfort zone. Younger researchers get increased motivation when they see how an SFI brings new career opportunities. When these opportunities lead to attractive jobs, they become valuable ambassadors for the centre.

The experience from SIRIUS is that a successful SFI needs more focus on research leadership than other project forms we have experience from. SIRIUS implemented measures to build a team of younger research leaders to this end. Our mentoring program was highly successful in preparing researchers to work with partners.

14.3 Managing the centre

We experienced that ownership to the centre from all parties and people involved is essential for engagement and success and that several measures proved important to achieve this.

- Centre building activities. SIRIUS invited all researchers to annual general assemblies where partners were widely present
- Communication across projects and work packages
- Bottom-up process for establishing strategy and annual work plans
- Recruiting younger researchers in centre leadership
- Lightweight management structure

14.4 Conclusions of the SIRIUS Experience Survey

We conducted a full survey at the closing of SIRIUS that involved industry representatives, academics, and PhD students. The conclusions of this survey were shared among all participants and the closing workshop.

Key findings:

- Overall, both researchers and industry partners indicated that SIRIUS was a successful centre supporting academia-industry interactions through events as well as collaborative projects.
- Industrial partners stated that the true value of the industry-academic partnership is in the interaction, and more time needs to be spent introducing the industry people to research areas.
- Projects established as a part of SIRIUS were viewed as positive, with both academics and industry partners working towards shared goals. Both sides have indicated the value of SIRIUS as a meeting place for discussing technology and challenges.

- Projects should be centred around the expertise of the researchers. The challenge is to identify projects that are relevant for both researchers and industry.
- Collaborative projects require well-outlined definitions and planning prior to their start. Most importantly, they need to be well-resourced with commitment from all participants. The project cannot be seen as a less important extra activity that is separate from the main work tasks or research interests. As quoted by one SIRIUS member “I hope that future collaborations can be formed as concrete projects with funding and where the industrial partners can contribute in-kind hours so that the project team is focused on the work to be done in the project and not forced to deal with the project as a side activity to the daily business”
- Participants from the academic side found it difficult to achieve project goals while managing the need to publish and fulfil university requirements.
- Bringing demonstrators to the level of commercialization requires additional partners to fill this role, e.g., scrum master, design, and UX. The industry partners can contribute in-kind towards these roles when possible.

Appendix 1

Funding

Note: Funding and cost summarised for the entire centre period.

Sum funding	**RCN**	**UiO**	**NTNU**	**UOXF**	**SIMULA**	**EQUINOR**	**IBM**	**DNV**	**SCHLUBERG**	**Bouvet**	**OSI-SOFT**	**NUMASCALE**	**TECHNIP FMC**	**EVRY**	**DOLPHIN**	**KADME**	**COMPUTAS**	**SAP**	**AIBEL**	**AS**	**BOSCH**	**OST**	**ONTOPIC**	**Billington**	**Predikto**	**ENVESTER**	**Sum:**
Management	6735	5 717	87	-	-	325	161	110	92	-	-	533	44	188	88	-	-	50	-	-	-	-	-	-	-	-	14 130
WP 1	19566	10 884	441	-	4 546	2 994	1 360	-	3 341	514	-	132	-	134	-	2 259	375	-	280	-	-	-	5	22	-	22	46 875
WP 2	17901	11 022	907	539	33	6 797	175	13 748	17	1 688	800	-	1 818	32	-	-	5 406	1 000	8 729	3 114	2 796	-	-	60	29	76	76 687
WP 3	1617	1 442	-	-	34	107	75	92	-	-	-	-	-	-	1 758	-	-	106	70	-	-	-	-	-	-	-	5 302
WP 4	38467	27 019	247	4 770	585	1 368	32	2 560	-	880	-	1 939	-	50	9 600	-	-	6	1 197	1 251	1 678	326	315	-	10	-	92 299
WP 5	11714	9 419	160	28	426	1 664	668	1 135	682	-	300	607	260	313	363	152	603	464	385	186	360	10	9	11	10	-	29 929
Sum:	**96000**	**65 504**	**1 842**	**5 337**	**5 624**	**13 255**	**2 471**	**17 645**	**4 132**	**3 082**	**1 100**	**3 211**	**2 122**	**717**	**11 810**	**2 411**	**6 384**	**1 625**	**10 661**	**4 551**	**4 834**	**336**	**330**	**93**	**49**	**98**	**265 223**

OST: Oxford Semantic Technologies
AS: Aker Solutions
UiO: University of Oslo

Comment:
The work packages have been changed during the centre period. In the following table, you may see the conversion.

Current WP	**2015-2017**	**2018-2023**
Management	WP9	WP0
WP1	WP3	WP1
WP2	WP4	WP2
WP3	WP5	WP3
WP4	WP6	WP4
WP5	WP1 and WP2	WP5

Cost

TOTAL Work Package	UiO	NTNU	UOXF	SIMULA	EQUINOR	IBM	DNV	SCHLUBERG	Bouvet	OSI-SOFT	NUMASCALE	TECHNIP FMC	EVRY	DOLPHIN	KADME	COMPUTAS	SAP	AIBEL	AS	BOSCH	OST	ONTOPIC	Billington	Prediktor	ENVESTER	Metaphacts	Sum:
Management	11 968	571	-	-	325	161	110	92	-	-	533	44	188	88	-	-	50	-	-	-	-	-	-	-	-	-	14 130
WP 1	22 785	2 877	-	9 775	2 994	1 360	-	3 341	514	-	132	-	134	-	2 259	375	-	280	-	-	-	5	22	-	22	-	46 875
WP 2	23 074	5 942	1 316	70	6 797	175	13 748	17	1 688	800	-	1 818	32	-	-	5 406	1 000	8 729	3 114	2 796	-	-	60	29	76	-	76 687
WP 3	3 020	-	-	73	107	75	92	-	-	-	-	-	-	1 758	-	-	106	70	-	-	-	-	-	-	-	-	5 302
WP 4	56 565	1 612	11 654	1 257	1 368	32	2 560	-	880	-	1 939	-	50	9 600	-	-	6	1 197	1 251	1 678	326	315	-	10	-	-	92 299
WP 5	19 719	1 043	70	915	1 664	668	1 135	682	-	300	607	260	313	363	152	603	464	385	186	360	10	9	11	10	-	-	29 929
Sum:	**137 132**	**12 045**	**13 040**	**12 090**	**13 255**	**2 471**	**17 645**	**4 132**	**3 082**	**1 100**	**3 211**	**2 122**	**717**	**11 810**	**2 411**	**6 384**	**1 625**	**10 661**	**4 551**	**4 834**	**336**	**330**	**93**	**49**	**98**	**-**	**265 223**

OST: Oxford Semantic Technologies
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Current WP	2015-2017	2018-2023
Management	WP9	WP0
WP1	WP3	WP1
WP2	WP4	WP2
WP3	WP5	WP3
WP4	WP6	WP4
WP5	WP1 and WP2	WP5

Appendix *2*

Postdoctoral researchers with financial support from the centre budget

Name	Nationality	Years/period in the centre	M/F	Scientific topic
Jens Otten	German	2019-2022	M	Ontology Engineering
Jiaoyan Chen	Chinese	2017-2020	M	Semantic Integration
Medha Atre	Indian	2018-2019	F	Semantic Integration
Daniel Lupp	German	2019-2021	M	Ontology Engineering
Stefano Germano	Italian	2019-2021	M	Semantic Integration
Jieying Chen	Chinese	2019-2022	F	Semantic Integration
Chi Mai Nguyen	Vietnamese	2019-2022	F	Analysis of Complex Systems
Silvia Lizeth Tapia Tarifa	Peruvian	2017	F	Analysis of Complex Systems

Postdoctoral researchers working on projects in the centre with financial support from other sources

Name	Source of funding	Nationality	Years/period in the centre	M/F	Scientific topic
Violet Ka I Pun	FP7	Macanese	2015-2017	F	Analysis of Complex Systems
Silvia Lizeth Tapia Tarifa	RCN FRINATEK	Peruvian	2015-2017	F	Analysis of Complex Systems
Elena Parmiggiani	RCN PETROMAKS	Italian	2015-2020	F	Industrial Digital Transformation
Crystal Chang Din	RCN FRINATEK	American	2016-2021	F	Analysis of Complex Systems

Vidar Klungre	RCN PETROMAKS	Norwegian	2020-2023	M	Ontology Engineering
Eduard Kamburjan	RCN PETROMAKS	German	2020-2023	M	Analysis of Complex Systems
Christian Kindeman	RCN PETROMAKS	German	2021-2023	M	Ontology Engineering
Foivos Psarommatis Giannakopoulos	Horizon Europe	Greek	2021-2023	M	Ontology Engineering
Evgenij Thorstensen	FP7	Norwegian	2015-2017	M	Ontology Engineering

PhD candidates who have completed with financial support from the centre budget

Name	Nationality	Years/period in the centre	M/F	Thesis title	Main Supervisor
Vidar Klungre	Norwegian	2015-2020	M	Adaptive Query Extension Suggestions for Ontology-Based Visual Query Systems	Martin Giese
Alessandro Ronca	Italian	2015-2020	M	Rule-Based Stream Reasoning	Ian Horrocks
Farhad Nooralahzadeh	Iranian	2016-2020	M	Low-Resource Adaptation of Neural NLP Models	Lilja Øvrelid
Temitope Ajileye	Italian	2018-2021	M	Materialisation and Data Partitioning Algorithms for Distributed RDF Systems	Ian Horrocks
Andreas Thune	Norwegian	2017-2020	M	High performance computing for reservoir simulation	Xing Cai
Frederico Igne	Italian	2018-2021	M	Conjunctive Query answering over unrestricted OWL 2 ontologies	Ian Horrocks

Anthony Potter	British	2015-2017	M	Query Answering in Distributed RDF Databases	Boris Motik
Peyman Rasouli	Iranian	2019-2022	M	Local Explainability of Tabular Machine Learning Models and its Impact on Model Reliability	Ingrid Chieh Yu
Yuanwei Qu	Chinese	2020-2023	M	PhD Thesis submitted and will defend with title: Knowledge Modelling for Digital Geology	Martin Giese
Marta Rozanska	Polish	2019-2023	F	PhD Thesis submitted and will defend with title: Utility Based Optimization of Cloud Application Resources	Geir Horn
Ole Magnus Holter	Norwegian	2019-2023	Domain Adapted Data Science	PhD Thesis submitted and will defend with title: Semantic Parsing of Textual Requirements	Basil Ell
Ratan Bahadur Thapa	Nepali	2019-2023	Semantic Integration	PhD Thesis submitted and will defend with title: Elevating Standards: Mapping and Querying Relational Data on the Semantic Web	Martin Giese

PhD candidates who have completed with other financial support, but associated with the centre

Name	Source of funding	Nationality	Years in the centre	M/F	Thesis Topic	Main thesis Advisor
Shiji Bijo	EU FP7 FET	Indian	2014-2018	F	Formal Modelling of Cache Coherent Multicore Architectures	Einar Broch Johnsen
Johanna Beate Stumpf	RCN FRINATEK	German	2015-2018	F	Virtually Timed Ambients: A Calculus for Resource Management in Cloud Computing	Einar Broch Johnsen
Daniel Lupp	University of Oslo, Dept. Of Informatics	German	2015-2018	M	A Higher-Level View of Ontological Modelling: Rule-Based Approaches for Data Transformation, Modelling, and Maintenance	Arild Waaler
Leif Harald Karlsen	University of Oslo, Dept. Of Informatics	Norwegian	2014-2018	M	A simple, General and Efficient Representation of Qualitative Spatial Information; An Approach Based on Bintrees	Martin Giese
Daniel Bakkelund	University of Oslo, Dept. Of Informatics	Norwegian	2017-2020	M	Order Preserving Hierarchical Clustering	Jon Henrik Forsell
Summaya Mumtaz	University of Oslo, Dept. Of Informatics	Pakistan	2017-2020	F	Hierarchy-based Similarity Measures and Embeddings —	Martin Giese

					Supporting Machine Learning by Knowledge	
Erik Bryhn Myklebust	University of Oslo, Dept. Of Informatics	Norwegian	2019-2022	M	Ecotoxicological Effect Prediction using a Tailored Knowledge Graph	Ernesto Jimenez Ruiz
David Tena Cucala	University of Oxford	Spanish	2018-2020	M	Consequence-Based Reasoning for the Description Logic SROIQ	Ian Horrocks
Shuwen Liu	University of Oxford	Chinese	2021-2024	F	PhD Thesis submitted and will defend with title: Deep Learning with Knowledge Graphs Using Graph Neural Networks	Ian Horrocks
Alina Petrova	University of Oxford	Russian	2017-2020	F	Entity Comparison in Knowledge Graphs	Ian Horrocks

PhD students with financial support from the centre budget who still are in the process of finishing studies

Name	M/F	Nationality	Scientific area	Years in the centre	Thesis topic	Main thesis Advisor
Lars Tveito	M	Norwegian	Analysis of Complex Systems	2016-2021	Not Completed	Einar Broch Johnsen
Sigurd Kittilsen	M	Norwegian	Ontology Engineering	2017-2023	Not Completed	Arild Waaler

Mina Haghshenas	F	Iranian	Industrial Digital Transformation	2017-2021	In progress	Thomas Østerlie
Erik Hide Sæternes	M	Norwegian	Scalable Computing	2020-2023	In progress	Xing Cai

MSc candidates with thesis related to the centre research agenda and an advisor from the centre staff

Name	Year end	M/F	Scientific area	Thesis title	Main Thesis advisor
Sondre Skaflem Lunde	2021V	M	Analysis of complex systems	Commutativity Analysis in ABS	Einar Broch Johnsen
Gaute Berge	2021	M	Analysis of complex systems	Leveraging Language Tooling for Better Voice Coding: Implementing program awareness and structural editing for Talon	Einar Broch Johnsen
Vegar Skaret	2020v	M	Geological assistant	Knowledge Representation and Concretization of Underdetermined Data	Crystal Chang Din
Benjamin Edward Oliver	2019H	M	Ontology engineering	Equality Preprocessing in Connection Calculi (EPICC)	Jens Otten
Frank Hestvik		M	Ontology engineering		Jens Otten
Fredrik Rømming	2021V	M	Ontology engineering	Learning to Reason	Peter Csaba Ølveczky

Torgeir Lebesbye	2019	M	Analysis of complex systems	Boreas – Reducing Resource Usage Through Optimized Kubernetes Scheduling	Ingrid Chieh Yu
Ida Sandberg Motzfeldt	2021V	F	Analysis of complex systems	Modular Soundness Checking of Feature Model Evolution Plans	Ingrid Chieh Yu
Eirik Halvard Sæther	2021V	M	Analysis of complex systems	Three-Way Semantic Merge for Feature Model Evolution Plans	Ingrid Chieh Yu
Nina Gjersøyen Løkamoen	2022V	F	Ontology engineering	Query Interfaces and Class Hierarchies	Martin Giese
Ahmed Abdulrahman Hussein Abbas	2022V	M	Ontology engineering	Dead-End Detection in an Ontology-Based Visual Query System	Vidar Norstein Klungre
Birgitte Løwe Johnsen	2022H	F	Ontology engineering	Decentralized Knowledge Graphs in Enterprise Integration	Martin Giese
Marlen Jarholt	2022V	F	Ontology engineering	Frog: Functions for ontologies — An extension for the OTTR-framework	Leif Harald Karlsen
Preben Zahl	2023V	F	Ontology engineering	Efficient update of OTTR-constructed triplestores	Leif Harald Karlsen
Magnus Wiik Eckhoff	2023V	M	Ontology engineering	Efficient update of OTTR-constructed triplestores	Leif Harald Karlsen
Justyna Ozog		F	Domain adapted Data science	ONTOLOGY LEARNING FROM TEXTUAL REQUIREMENTS	Basil Fabian Ell
Eivind Grønlie Guren	2022V	M	Domain adapted Data science	Exploring Automatic Text Simplification of Requirements	Basil Fabian Ell

Henrik Syversen Johansen	2022H	M	Domain adapted Data science	Structural Anomaly Detection in Knowledge Graphs Using Graph Neural Networks	Egor Kostylev
Johanna Peersdatter Haarseth	2022V	F	Ontology engineering	Knowledge Extraction from Large Scale Ontologies with Aibel	Jiaoyan Chen
Erik Snilsberg	2022H	M	Ontology engineering	Reverse OTTR: A query language for RDF	Egor Kostylev
Shanshan Qu	2022V	M	Ontology engineering	Visual Construction of Ontology Templates	Martin Georg Skjæveland
Ole Magnus Holter		M	Ontology engineering	Combination of machine learning and semantics for ontology alignment // Semantic Embeddings for OWL 2 Ontologies	Ernesto Jimenez
Shuvo Mahmuda		M	Ontology engineering	Probabilistic soft logic (PSL) framework in ontology alignment tasks	
Nils Petter Opsahl Skrindebakke	2020V	M	Explaining machine learning predictions using semantics.	Understanding the Role of Background Knowledge in Predictions	Ernesto Jimenez Ruiz
Victoria Varzhel		F	Mapping Health Registry Variables to Biomedical Ontologies	Exploring the Use of Ontologies and Reasonable Ontology Templates (OTTR) within Health Registry Systems	Laura Ann Slaughter

Appendix *3*

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Appendix *4*

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