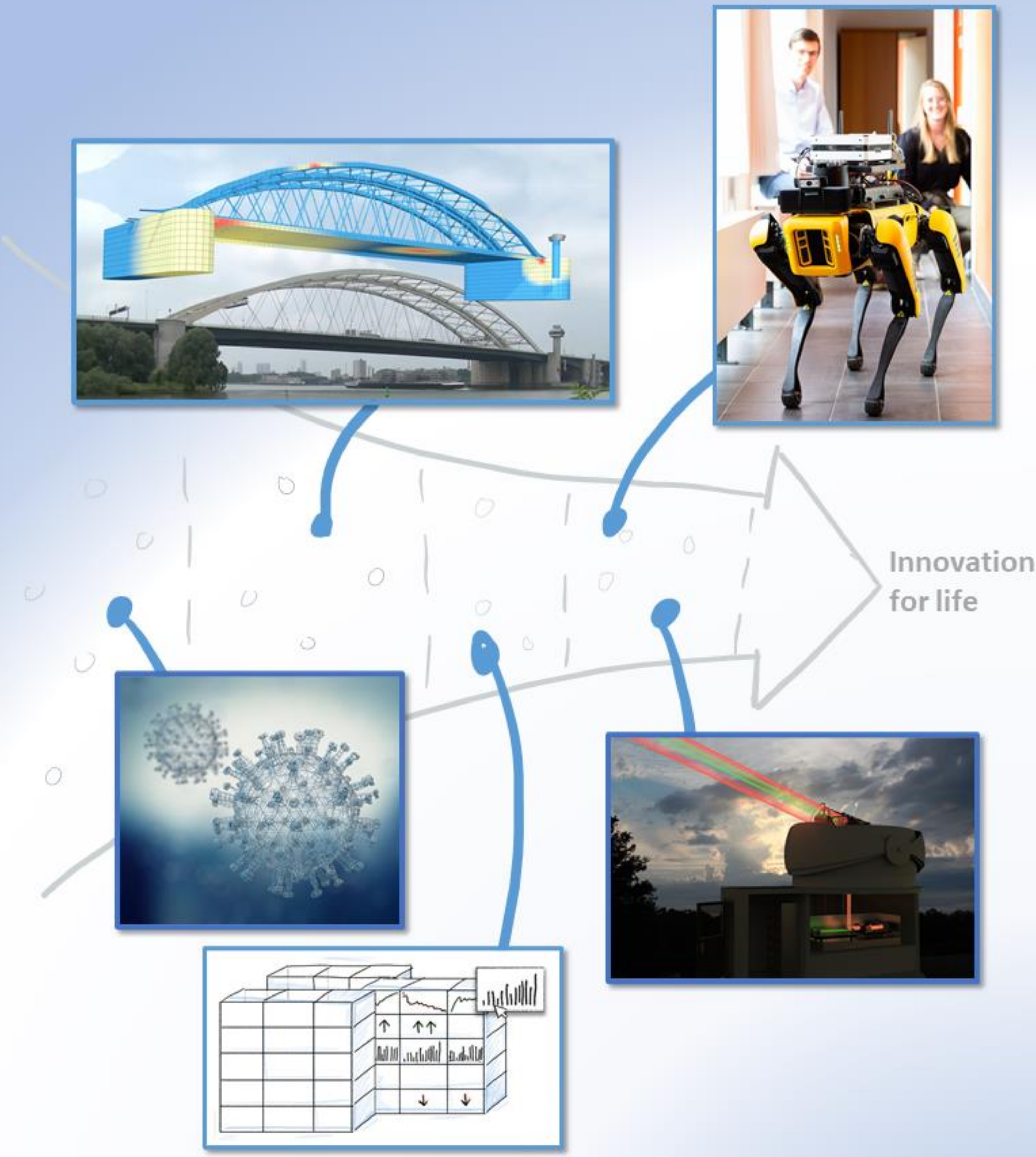

TNO EARLY RESEARCH PROGRAM ANNUAL PLAN 2022

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TNO 2021 R11720

Contents

Introduction

The Early Research Programs (ERP's) presented here reflect TNO's vision where to focus its early research efforts to be able to build strong technology positions and to contribute, together with knowledge partners and stakeholders, to answers to societal challenges and creation of economic impact. The programs are meant to build, renew and maintain TNO's knowledge assets ('Kennis als Vermogen'). The ERP's represent about 5% of TNO's turnover. The remaining 95% is steered by TNO's stakeholders: clients, 'Topsectors' and Ministries (via consultation) and MOD, EZK and SZW (via task financing).

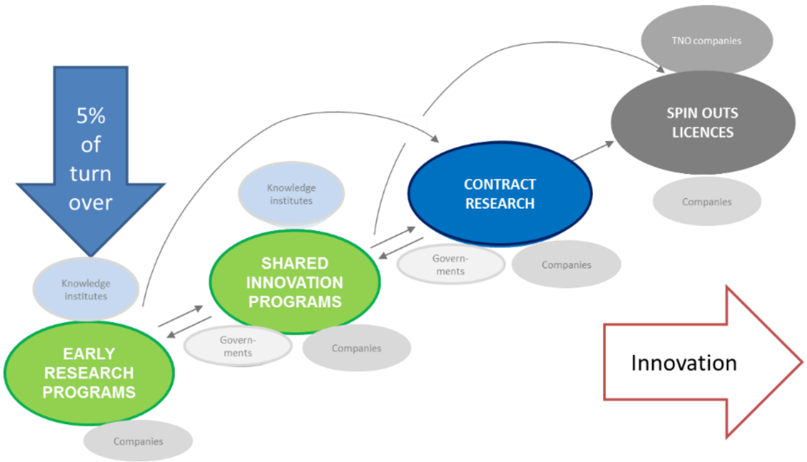

Figure 1: Visualisation of how ERP's contribute to innovation

The main characteristics of the ERP portfolio are as follows:

- The programs build and renew strong technology positions in the focus areas defined in the TNO Strategy Plan 2022-2025
- The programs are use-case inspired and have clear research goals: ERPs feed multiple innovation roadmaps of TNO, often from different units with common requirements for lower-TRL technology breakthroughs. The output of the ERPs is transferred to (higher TRL) shared innovation programs and contract research.
- The programs aim for added mass through collaboration with knowledge partners such as universities and additional co-investments by stakeholders.
- The programs have substantial mass (usually > 1 mln Euro ERP budget per program) and have a typical duration of four years.
- ERP funnel management (involving reviews by TNO Corporate Science Office and by the board of TNO's Science Directors) is in place to monitor the progress and to adjust and reallocate resources if necessary.
- Together with our ministry of Economic Affairs (EZK) we inform the Topsectors and Ministries of our approach of building our knowledge base via the ERP's, aiming at early involvement of companies and other stakeholders in public private cooperation.
- 'Full ERP' programs are usually preceded by one-year 'Seed ERP' projects that explore the feasibility of the topic, substantiate the impact to be expected and build required partnerships, thus developing the full ERP program. Out of the ten 'Seed ERP' projects 2021, the five strongest were selected for continuation as Full ERPs in the period 2022-2025.

The ERP portfolio (as illustrated in Figure 2) includes a larger number of programs initiated in 2019 versus only a few in 2021 and 2020. An important goal of the ERP portfolio management is to bring the portfolio to a 'steady state' in which every year a similar number (4-5) of existing ERP's ends and new ERP's can be initiated. Only then will TNO be able to respond continuously and with agility to new technology trends and needs. Furthermore, TNO's researchers will be stimulated to continuously be on the outlook for impactful new research directions, knowing that there is an instrument to award and adopt the best ideas.

In 2022 six new ERP's will start. These concern 'Digital Health Measures', 'Pandemic Preparedness', 'Subsidence and building damage', 'Opto-Acoustics', 'Auto-Adapt' and 'MicroPlastics'. They all concern to domains with clear scientific challenges and high societal relevance. The topics were selected out of the ten 'Seed ERP' topics of 2021. The first five get a regular funding for a 4 year Full ERP program. The topic 'MicroPlastics' gets a two year funding. In addition to these six, 'Qutech' receives a second four-year funding that will start in 2022 and end in 2025.

In 2021 we have for the first time reached the intended 'steady state' goal for portfolio renewal from the funnel *inflow* perspective, selecting 10 new Seed ERP's and 5 new ERP's starting their 4 year Full ERP phase. We feel that a success rate of about 50% for Seed ERP's to be promoted to Full ERP's is a healthy situation. We need three more years to reach the ' steady state' equilibrium of 5 projects also on the funnel *outflow.*

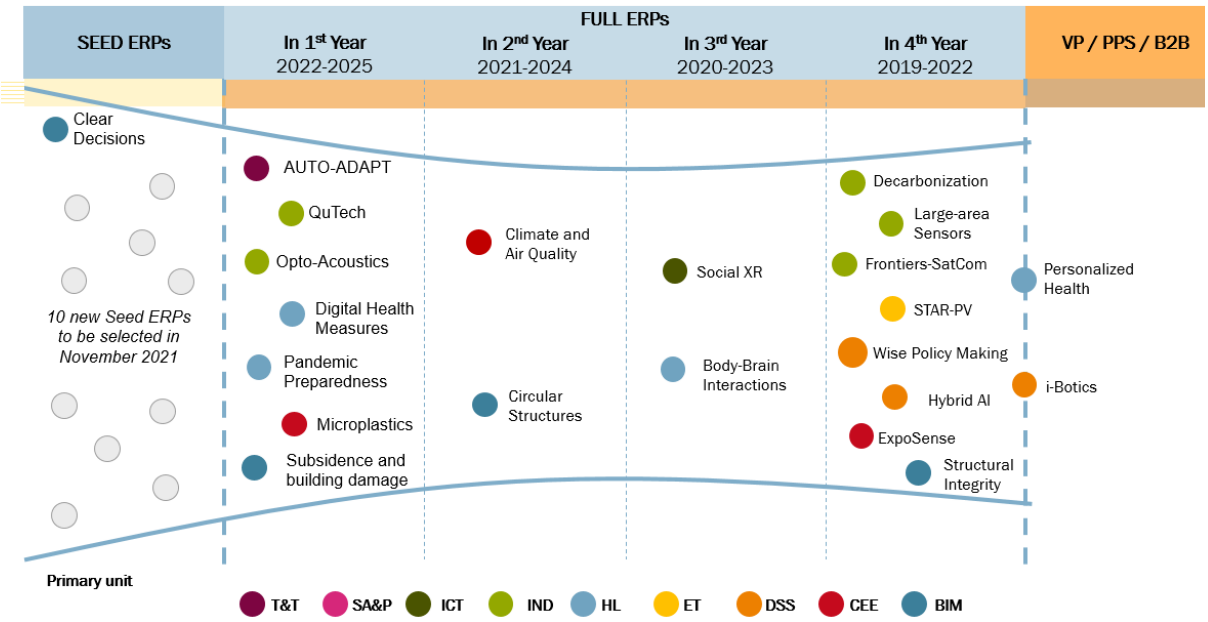

Figure 2: ERP Funnel 2022
(Legend (TNO unit names) - ICT: Information and Communication Technology , HL: Healthy Living, BIM: Buildings, Infrastructure & Maritime, IND: Industry, DSS: Defence, Safety & Security, SA&P: Strategic Analysis & Policy, ET: Energy Transition, T&T: Traffic & Transport, CEE: Circular Economy & Environment))

In the following chapters of this report each of the ERP's is described by its overall goals and approach and its results achieved in 2021 and intended results in 2022. The first section 'Overall program description' contains a description of the context and objectives and the overall approach and is more or less 'constants' over the program duration, whereas the second section 'Results 2021 and plan year 2022' provides the 'actuality' perspective as it regards the intended results 2022 against achieved results 2021. Each chapter consists of paragraphs describing (1) Context and overall program objectives (problem definition, expected impact to stakeholders), (2) The overall program Approach (overall program focus, overall research plan, targeted partnerships), (3) Results 2021 (concrete results achieved in previous ERP year), (4) Plan year 2022 (focus year 2022, activities and concrete results targeted in 2022)

The ERP portfolio management conforms to four TNO policies / procedures. TNO's Publication policy provides guidelines and sets targets with regard to publicizing research outcomes. The IP policy describes TNO's way of working and goals regarding protectable intellectual properties. Publications and IP are key outcomes of all ERP projects. The PhD policy guides project teams on how to properly and effectively involve PhD's in TNO's research. TNO's Professorship policy provides guidance with regard to the establishment of professorship positions of TNO scientists at universities. PhD's as well as TNO-enabled professorship play an important role in the execution of our ERP research.
Table 1 provides the ERP summary, listing the ERP titles and a selection of the most prominent targeted results in 2022.

Table 1: Highlighted results 2022 as planned in TNO's Full ERP's

Overview Full (4-year) ERP's	
(Link to) Chapter #: ERP-title ***Short description***	**Planned results 2022**
5th year projects: Start 2018 – End 2021 –-> These programs should have ended in 2021, but could not finish part of their activities due to circumstances related to the Covid 19 pandemic. Therefore, budget is shifted from 2021 to 2022 to finish the study and accomplish the set goals in 2022.	
Personalized Health *We develop a system providing personalized advice on sustainable lifestyle habits based on biological understanding of inflammatory dynamics, dysmetabolism, AI modeling and health community support.*	In 2022 we will complete the Slimmer+ volunteer study, followed by data analysis and dissemination of the results. This will give insight in the extent to which personalised tools and technologies can stimulate adherence to a healthy lifestyle and in the effect of combined lifestyle interventions on low-grade inflammation.
i-Botics *We focus on optimal human-robot interaction in challenging, unpredictable, dynamic situations. The focus areas are human controlled robots based on telepresence perception and manipulation capabilities for e.g. installation, maintenance, repair and emergency response; and wearable robots for human enhancement in rehabilitation and heavy work environments.*	In 2022, our focus is on a dissemination event for internal and external stakeholders and end users from e.g. ministries and related governmental organisations, industrial parties, academia and TNO itself. This event will be organized just after the final event of the international Ana Avatar XPRIZE competition in which we participate as one of the finalists. These finals are planned for June 2022. In our final ERP event we will showcase our XPRIZE submission.
4th year projects: Start 2019 - End 2022	
1: **Digital Twins for Structural Integrity** *We develop digital twins (simulation models fed with sensor data) mimicking the behaviour of macro-structures and guiding the design and management of these structures. Main challenges are multi-scale modelling, advanced sensing techniques, high speed computing and AI learning capabilities.*	We are targeting 1) Methods and tools (Bayesian model updating; fiber optic sensor system; ultrasonic prestress measurement system) integrated in TNO's digital twin system for efficient and reliable structural integrity assessments; 2) Flexibility measures integrated in TNO's digital twin system (through AI, by scaling of computations and for changing components) to repeat application for different assets; 3) Accurate and reliable system for traffic load information; 4) validated AI-supported design methodology.
2: **ExpoSense** *We develop solutions for personalized promotion of health based on non-invasive assessment of external and internal*	Our focus will be on the final occupational demonstrator combining sensor development (wearable PM-CID for chemical characterization of particulate matter) and external exposure modelling (interpretation of where and why workers are exposed) in the construction sector.

exposure profiles to Particular Matter (PM), by developing accurate, reliable and calibrated PM sensors and by predicting and interpreting personal external and internal exposures by quasi real-time modelling	Further development of the portable PM-CID and associated methods for exposure assessment and source apportionment in the environmental setting will also take place. Internal exposome markers will be validated and case studies for their application described. Since this is the final year of the ERP extra attention is put on maintaining and growing our network and establishing plans/leads for future uptake of the ERP technologies in TNO roadmaps.
3: **FRONTIERS - Optical Satellite Communication** *By using laser light instead of radio we aim to greatly enhance communication between satellites, ground stations and airplanes, providing ultra-high data throughput and ultra-secure and multi-point communication.*	In 2022 we will demonstrate the performance of our technology in experimental breadboards and detailed numerical simulations. In particular this applies to a very low volume optical telescope for multi-point communication, an adaptive background noise filter for quantum communication and a very high data throughput link from ground to LEO/GEO satellites.
4: **Wise Policy Making** *We develop a suite of instruments and methods to support policy makers to assess the impact of policy options on wellbeing (ex-ante) and to engage in unbiased and well-informed dialogue leading to decisions that prioritize sustainable societal wellbeing.*	Our ambition for 2022 is to deliver a prototype (TRL 5) of a 'Wise Policy Suite' of instruments and methods that has been tested and validated in practice and is geared towards practical use by policy makers. With this Wise Policy Suite, we will be able to assist policy makers 1) in quantifying the impacts of different policy options on wellbeing, and 2) to have fruitful dialogues about the policy options and deliberate on the impacts with each other, citizens and other stakeholders. This will enable them to develop and choose policy options that maximally promote wellbeing, based on scientific insights and legitimized by society.
5: **STAR-PV** *By gaining insight in and by developing improved control of basic degradation mechanisms we enable improved reliability and sustainability and lifetime extension (e.g. beyond 20 years) of integrated thin film devices (photovoltaic (PV) and other opto-electronics) integrated in building components and products.*	In the final year of this ERP we will implement and demonstrate the market potential of developed methodologies in focal points of TNO's PV Roadmap: we will assess to what extent perovskite PV tandems can handle partial shading. Sample extraction by coring will be used to evaluate flexible CIGS laminates for mass customization. Fiber Bragg and Humidity field-test monitoring and comparative LCA will be applied in Building-Integrated PV, Infrastructure-Integrated PV, Floating PV. Design rules for flexible interconnect reliability will be applied to sensors and PV mass customization.
6: **Large-Area Ultrasound** *We develop technology for large area, flexible ultrasound imaging/monitoring systems enabling to bring medical care to the home environment. Our essential approach is to build printed ultrasound transducers using cost effective display fabrication technologies.*	In 2022 our main goal is scaling up the flexible ultrasound technology from 1D arrays to 2D arrays that can image the entire 3D geometry of the carotid artery. Pre-clinical studies with healthy volunteers will provide feedback on acoustic imaging performance. Comfort and wearability aspects will be validated in an (internal) wear trial.
7: **Appl.AI** *This ERP, our largest, consists of a coherent set of program lines, two of which being the 'flagships' of the program: SNOW (AI capabilities for self-aware autonomous systems that can operate safely and effectively in an open world) and FATE (AI to provide fair advices by continuous*	In 2022 the research in SNOW will focus on profound integration of situation awareness and planning by goal-directed perception and on the integration of self-awareness and planning by semantic task agreement. FATE will focus on developing the viewpoints of the different user-roles towards role-based decision support. This involves developing the capabilities to continuously mitigate biases, provide secure actionable and fine-tuned explanations and realize effective co-learning, and showing the progress with these by Key Performance Indicators and by their effects on the collaboration of users with AI

learning from multiple potentially confidential and biased data sources). These two are surrounded by a set of use case projects.	systems. As 2022 will be the last year of the Appl.AI ERP, we will organize a large event for stakeholders. presenting results from the flagships and the use case projects.
8: **Decarbonisation (Brightsite)** *We target to reduce the dependency of the chemical industry (primarily at the Chemelot site) on fossil sources, by developing climate proof technologies and associated implementation strategies.*	We will demonstrate an optimized second generation (improved Hüls) plasma process producing hydrogen and acetylene with an improved selectivity towards acetylene. We will experimentally confirm the practical and commercial application possibilities of Upwash® and liquid phase pyrolysis (LPP®) technologies, focused on case(s) on the Chemelot site. The possibilities of a digital twin for gasification based on complexity science, artificial intelligence and smart industry building blocks will be demonstrated.
3rd year projects: Start 2020 – End 2023	
9: **Body-Brain Interactions** *We improve life-long health, performance and mental strength via mechanism-based understanding of the connections between body and brain, realized into a Brain-Body Interaction technology platform.*	We will finalize the datasets in the preclinical platform and disseminate the ERP results. For the acute stress human Body-Brain platform we will finalize the multi-level data set and start developing the algorithms. In the chronic stress Body-Brain platform the focus will be on finding robust connections and links of the organs to the brain and on dissemination of the results.
10: **Social XR** *We create a shared Social XR (Extended Reality) environment, where participants get an enhanced feeling of being in the presence of, and interacting with, other persons at a remote location.*	We target the following key results: 1) advanced capture of environments for use cases that call for expertise at a distance; 2) human representation and interaction through volumetric video; 3) end-to-end real-time and scalable communication; 4) slice adaptation based on cross-layer aspects; and 5) validation of Holistic Social Presence questionnaire and toolbox. Moreover, we expect to integrate results from 2021 into a first version of a social XR platform, building upon the social Vitual Reality platform developed in 2021. The social XR platform innovations are demonstrated in accordance with 1 or 2 use cases of providing expertise at a distance.
2nd year projects: Start 2021 – End 2024	
11: **Climate and Air Quality** *We develop a globally applicable, multi-scale atmospheric modelling system with resolution down to 25m to fully exploit the emerging observation capacities of satellites and sensors.*	We aim to deliver: 1) validated dynamic emission models for traffic and agriculture, 2) a prototype operational model system for the emission models developed in 2021 and 2022 and 3) a DALES model, in which deposition and boundary conditions routines will be implemented to study nitrogen deposition patterns.
12: **Circular Structures** *We develop knowledge and technology that enables for concrete structures a shift from traditional design strategies to a new engineering design method driven by supply quality-demand integration.*	The key targeted results e (i) a combination of EVEReST optimization technology with hierarchical decision trees and sequential chain models, (ii) fundaments for probabilistic safety verification of reclaimed elements, (iii) the concept of a multiscale model of recycled aggregate concrete, (iv) a proposal of a circularity indicator for Life Cycle Analysis, (v) characterisation of different Concrete Demolition Waste qualities in optimised binder & mortar combinations (vii) demonstration of design optimization for reuse of reclaimed elements
1st year projects: Start 2022 – End 2025	
13: **Auto ADAPT** *We aim to develop and demonstrate self-adaptive methods that optimize overall system performance with minimal efforts*	We aim to develop: 1) an awareness concept for uncertainty learning; 2) a virtual vehicle level demonstration for self-optimization and 3) a component-level demo for auto-commutation;

by changing the controlled system's behaviour and configuration.	
14: **Digital Health Measures** *We will develop tools and methodologies for meaningful, inclusive, digital health measurements*	Our main targeted results include: 1) Defined requirements to meaningful digital cardiovascular resilience measurements; 2) Validated algorithms for medical grade assessment of sleep (apnea) and 3) a modular health patch with integrated photonic sensor technology.
15: **OPTO-ACOUSTICS** *The ERP Opto-Acoustics will create a next generation acoustic platform, using optical means only, to generate and receive acoustic waves. Such a system will radically outperform existing (often piezo based) acoustic systems, can be miniaturized or multiplexed to cover large structural areas and long distances.*	In 2022 we will set-up the technical requirements for the use case 'next generation medical ultrasound systems' and 'composite structure', where we focus on an offshore wind turbine blade that can be recycled. We will work on the Opto-Acoustic platform technologies and in 2022 we will 1) improve the performance of a single Photonic Ultrasound Transducer (PUT) 2) be able to read-out a number of PUT's in parallel and 3) embed PUT's in composite material. New ideas will be patented which will result in new IP in 2022.
16: **PANDEMIC PREPAREDNESS** *We want to protect our society against the impact of future pandemic outbreaks by developing a scalable and multilevel testing strategy, optimally aligned with the needs during different phases of a pandemic outbreak.*	We will deliver a bioaerosol sampling protocol and mass fragment identification algorithm for untargeted detection and identification of pandemic pathogens. We will further establish optimized sample handling protocols and a mechanistic and mathematical model for CRISPR and LAMP based pathogen detection, enabling in silico test optimization. We will organize several stakeholder meetings to further strengthen our links with academic, publica and private partners.
17: **Subsidence and Building damage** *We aim at the reduction of huge costs for subsidence induced damage by building a chain of models which will be used to assess the causal relationship between subsidence and damage to the built environment ….*	Our targeted results are 1) a disentanglement procedure of multiple subsidence sources and the downscaling procedure for our large-scale subsidence predictions to the scale of buildings, 2) models for soil-structure interaction, 3) a categorization of Dutch masonry buildings into structural typologies based on their predicted susceptibility to subsidence induced damage and 4) a data assimilation procedure with observations, and 5) initiation of a co-creation/brokerage process between model developers and stakeholders.
18: **Qutech** *We exploit quantum effects in customized systems, materials and concepts, such as quantum computing and communication to pave the way for a second revolution.*	Regarding Quantum Computing we aim to deliver a proof-of-principle for direct spin readout and a cryogenic amplifier prototype. Regarding Quantum Internet we will demonstrate generation of entanglement between Delft and The Hague and realize a 3rd node with an additional 13C qubit. The QuBit Research will deliver a first Fluxonium qubit.
19: **MICROPLASTICS** *The ambition is to mitigate microplastic formation and release in the circular economy based on knowledge on microplastic formation and release.*	We will deliver 1) a detailed assessment of microplastic formation, correlated this material properties 2) demonstration of microplastic mitigation at large scale

To illustrate how the ERP portfolio relates to the TNO strategic areas as laid down in the TNO Strategy 2022-2025, Table 2 is provided.

Table 2: Relation between ERP's and TNO strategic areas (TNO Strategy 2022-2025)

Type		Early Research Project (ERP)	Safe & Secure Society	Healthy Society	Sustainable Society	Digital Society
Full ERP 2019-2022	1	Digital Twin for Structural integrity	x			x
	2	ExpoSense		x	x	x
	3	FRONTIERS - Optical Satelite Communication	x			x
	4	Wise Policy Making	x	x	x	x
	5	STAR-PV			x	
	6	Large-Area Ultrasound		x		x
	7	Appl.AI	x	x	x	x
	8	Decarbonisation (Brightsite)			x	
Full ERP 2020-2023	9	Body-Brain Interaction		x		
	10	Social XR				x
Full ERP 2021-2024	11	Climate Air Quality		x	x	x
	12	Circular Structures			x	x
Full ERP 2022-2025	13	Auto ADAPT	x			x
	14	DETERMINE - kunnen we deze naam vermijden?		x		x
	15	Opto-acoustics		x		x
	16	Pandemic preparedness	x	x		
	17	Subsidence and building damage	x			x
	18	Qutech				x
Full ERP 2022-2023	19	Microplastics		x	x	
Seed ERP 2022	20	Clear Decisions	x		x	
	21	*New Seeds (to be selected)*	?	?	?	?

1: Digital Twin for Structural Integrity

ERP Contacts: B. Luiten (Project Lead), H. Miedema (Lead Scientist), A. Adriaanse (Science Director)
ERP Duration: 2019 – 2022

Overall Program description

1. Context and Objectives

- **Problem definition**

As recent discussions on renovation or renewal of Rijkswaterstaat's so-called baby boomer bridges demonstrated, our society depends heavily on the availability of reliable and safe complex macro-structures, both stationary macro-structures (e.g. bridges, offshore wind structures, pipelines) and mobile macro-structures (e.g. vehicles, trains). Asset owners have to ensure their availability, but they have no efficient and accurate way to do so. Nor do industry and service companies that assist asset owners have these means. Our society risks high costs for renovation or renewal, massive congestions due to construction works and unsafe operations.

Our solutions are: a) flexible and adaptive Digital Twins (DT) for assessing structural integrity during the operational phase of existing civil structures; b) a DT for supporting the design of new military structures. The DTs for existing structures integrate physics-based models with data from sensoring, data management and machine learning. Flexibility and adaptivity enables the specialization of the same DT platform to varying individual structures. The DT for the design of structures replaces the 'engineering judgement' of the optimal combination of design parameters for a structure that is safe, in addition to fulfilling other requirements, by an intelligent search for the optimal parameter combination.

- **Expected impact to stakeholders**

With the current way of working (application of norms which are generic and hence for most structures far-too conservative, or which require extensive costly modelling efforts) costs of the structural integrity assessments and of asset management in general are sharply increasing, interruptions for unforeseen maintenance are difficult to prevent and proper levels of safety are under threat.
Our DT for existing structures, which relatively easily adapts itself to a specific structure, will support asset owners in their task of maintaining their infrastructure at a proper level of safety, minimizing the risk of interruptions and at reasonable cost. We support them directly and indirectly by providing engineering and service companies with new technologies.
Our DT for design of structures aims at safe designs that are better and faster than can be obtained with engineering judgement. This DT is first developed for the material and component level of a military vehicle.

2. Approach

- **Focus**

By developing our DTs for existing structures, which integrate physics-based and data-based models with sensors, data management and artificial intelligence for creating adaptivity and optimization, we enable systematic widely applicable structural integrity assessments and redesign. Our technological development will combine the strengths of our domain technologies with our information

technologies and will ensure flexibility and adaptability to ensure easy reuse of our solutions for other structures. We will concentrate on system integration with containerized and scalable components, data platform technologies, Bayesian updating and scientific machine learning, AI supported design, advanced FEM and surrogate modelling, and fiber optic and acoustic sensor techniques. The DT for the design of structures focusses on the combination of models for extremely high dynamic loads (blasts) with AI algorithms for finding parameters with which the Page 2
models predict optimal performance.
The development is guided by the following 4 use cases: (1) *DT Bolted Flange* for twinning a bolted ring flange connection in an offshore wind turbine foundation (monopile) for optimization of design, installation and maintenance, and for limiting the need for inspections and repair. (2) *DT Steel Bridge* for twinning a steel bridge in the highway network for assessing its safety and monitoring it when the structure approaches its safety limits. (3) *DT Road Network* for twinning the highway or an urban road network for providing accurate localized information on vehicle loads on structures, such as bridges, in the network. (4) *DT Design of structure* for twinning (parts of) a composite light-weight military vehicle to accelerate the design process and optimize the design.

- **Research plan**

Overall objective: Structural integrity assessment during design and asset management of structures by integrating physics-based model with data from sensoring, data management and AI technology in adaptive Digital Twins. The DT for the design of structures focusses on the integration of physics-based model with AI technology. The work is divided in four research lines. Line A and B are directed at DT Bolted Flange and DT Steel Bridge, Line C at DT Road Network and Line D at DT Design of structures.

Line A. –Digital Twin Technologies
Research question: (1) Which structural modelling approaches can represent real-world assets accurately, flexibly (adaptable and reusable), requiring minimal human effort to build and use; (2) How can the components and entire workflows be integrated in a user friendly environment enabling fast, and reproducible analyses? (3) How can components for structural integrity assessments be orchestrated in flexible workflows and be deployed on cloud based compute infrastructures?
Activities: We explore and pilot jointly with Line B an array of structural models with the aim to accurately predict the behaviour of their real-world counterpart. We consider traditional physics-based models, e.g. FEM, sparsely parametrized physics-based models in combination with Bayesian statistics, extensively parametrized physics-based models in combination with machine learning (scientific and physics-informed machine learning), and “pure” machine learning models. To facilitate the digital twinning approaches for structural integrity assessment, a flexible IT platform is developed to support scalability needs from two perspectives: a) scaling computational power to reduce the wall-clock time of computations such as FE analyses, which can in turn reduce the wall-clock time of dependent analyses such as fitting surrogate models and Bayesian parameter estimation; b) connecting data management to model to facilitate structure specific calculations for structural safety assessments. Eventually the platform will support a fitting/calibration-phase (building generic technology 2021/2022) and assessment-phase (2022 and beyond, applying generic technique to specific use field sites – in this ERP IJsselbridge and Moerdijk bridge; other steel bridges in the future). This is achieved with uniformized model wrapping techniques (containerization). Flexible data infrastructures using graph databases connect data processing with bridge ontologies and supplement the ontologies with data produced by calculations. Reusing the developed IT platform for new bridges will enable efficient reuse of the integrated technologies.
Time line: In 2022, the above listed modelling approaches, supporting tools, such as surrogating, and the IT-platform will be used to demonstrate their functionality and utility for the field site Moerdijk bridge. By the end of 2022 tooling/software will be developed into a standalone tool that can be reused for other bridges, e.g. by TNO for future structural integrity reviews for RWS.

Line B. Existing structures: component & structure – Modelling & Sensing

Research question: Which modelling and sensing components are essential to be integrated in the DT? **Activities**: We will further develop our physics-based and data-driven simulation models so that they can be flexibly applied to different structures and can be connected to the developed sensoring systems of our use case Steel bridge and Bolted Ring Flange Connection. In parallel a tool is being developed for (probabilistic) parameter estimation to enable system, load and damage identification. This tool interacts with the physics-based and data-driven simulation models and is further developed with BAM within an open-source frame. For the DT Steel Bridge the overall objective is to increase the reliability index to reduce the safety factor. Our fiber optic technology for distributed, multi-parameter sensing will be validated in practice at the field site DT Steel bridge. Specifically for DT Bolted Ring Flange Connection, we will elaborate the way pre-stress loss and fatigue damage in bolts of a ring flange are incorporated as factors affecting safety. The next step for our ultrasonic sensing technology for pre-stress measurement will be a proof of principle, followed by a proof of concept by incorporation in lab demo DT Bolted connection. **Time line:** For the Bolted Ring Flange demonstration, the last year of the research targets on steps to apply/demonstrate the developments in the field. In parallel with the ERP work the Bolt & Beautiful (B&B consortium has been formed that will build further on the system and sensor developments. Research proposal of B&B will be submitted to the TKI Hernieuwbare Energie Subsidy+ provided by RVO. The finalising ERP work on demonstration will be effectively integrated in the first year's work in B&B on a scaled ring flange connection demo.

Line C. Existing structures: network - Vehicle load

Research question: DT Road network ("Loadmap") updates its information on traffic loads from distributed data sources and can be used to explore future vehicle load scenarios. Using this load information in assessments of the integrity of structures in the network and of their expected lifetime, these become more accurate. A Bridge Weight-in-Motion (Bridge-WiM) system adds local traffic load information to the Loadmap based on measurements by sensors on the steel structure of a bridge.
Activities: The components for estimating the loads at each point in the network will be integrated in a Loadmap, a system with a GUI and facilities for exploring future traffic load scenarios. The load estimation will use traffic models to increase its accuracy. The accuracy of our Bridge-WiM will be validated in the field site for our DT Steel bridge. Achieved accuracy Page 4
of the load estimation by the Loadmap and by the Bridge-WiM will be compared with requirements from future users of the systems. The Loadmap and Bridge-WiM will be demonstrated on highway and an urban road networks in close interaction with potential users.
Time line: Both for the Loadmap and Bridge-WiM will be finalised and integrated in a proof of concept system. This system will be demonstrated in the field site Moerdijk bridge with RWS and for the city of Amsterdam, and evaluated with the first potential partners for further development and commercialisation.
In the field site Moerdijk bridge the structural integrity analysis of line B meets the traffic load predictions with Bridge-WiM and the Loadmap of line C.

Line D. Design of structures

Research question: DT Design of structures that accelerates and optimizes the design of components of composite structures. Demonstration of the DT for parts of a composite military vehicle (underbelly, doors).
Activities: Based on experimentally validated numerical models at different scales, a DT for design of composite structures is developed. A proof of principle will be given of a machine learning-supported design process. The DT will be extended from the material to the component scale. This will challenge the first version of the DT by increasing the design space and adding computational complexity. Due to the increasing computational demand we plan to explore high performance computing in order to reduce wall clock time to a reasonable value. The result will be a second version of the machine

learning supported DT which is more generically applicable. **Time line:** The building blocks developed in the previous years will be combined into a multi-fidelity optimization tool. It can be used as a design tool for composite laminated panels optimized for high dynamic loading. The tool will be demonstrated by optimization of a composite laminated panel and the result validated by a blast experiment.

- **Targeted partnerships**

Line A. Existing structures: DT Technologies.
Industry: In 2021 collaboration with DIANA FEM software started on “cloud based FEM” and containerization of DIANA to integrate it with the TNO Digital Twin platform. Together with Akselos we do a pilot to explore the results of their high speed FEM which uses alternative algorithms.
Governmental: RWS for the use case Steel bridge in general and the field site Moerdijk in particular. For that field site companies offering sensoring services and structural safety calculation services (engineering companies) will be invited to participate. In this way RWS acts as the launching customer of these technologies. They will support TNO financially as the launching supplier to orchestrate the co-development in the field site with internal and external partners.
Universities & RTOs: PhD with University of Groningen on adaptivity of digital twins with scalable computational resources. Ongoing cooperation with Bundesanstalt für Materialforschung und -prüfung (BAM) on the basis of common yearly plan.

Line B. Existing structures: Modelling & Sensing.
Industry: The Grow-Offshore Wind consortium, with Shell, RWE, Gemini, DNV, Sif, KCI, ITH, Siemens-Gamesa, Intomachines, Boltlife, Althen, Van Oord, Eneco, Bureau Veritas, SBM Offshore, Bluewater, has defined a project complementing and extending the ERP work on the use case Bolted flange connection.
Universities & RTOs:
TU Delft and TU/e participate in the above consortium as well as Leibniz University Hannover, Fraunhofer IWES and Belgian research organisation Sirris. A NWO proposal with 3 PhDs and 4 PDengs, together with a.o. TU/e and UT, extends the ERP work on use case Steel bridge. It has successfully passed the first evaluation round.

Line C. Existing structures: network vehicle load
Governmental: Loadmap en Bridge-WiM part of planned field-lab Moerdijk bridge with RWS. Application of the Loadmap to municipal networks is explored with city of Amsterdam, for which a demo is prepared.

Line D. Design of structures
Industry: The EDA program Lightweight solutions for armed multi-purpose vehicles (L-AMPV-II) complements and extends the ERP work on design of composite structures. In this consortium we work in close collaboration with Solico, the engineering company and Kraus-Maffei Wegmann (KMW, GER), the consortium lead. TNO supports KMW for the development of an door. Nexter Systems (FRA) is involved mainly for the dynamic calculations for the development of the door. TNO supports Nexter in this effort. (It is likely that L-AMPV-III will start after a successful conclusion of L-AMPV-II.) **Governmental**: Material developments of the patented material lay-up of the composites will continue in new projects for the Defence Material Organization. These projects, of which budgets will be available for TNO until 2027, will be mainly directed to increase blast and ballistic performance of the material and decrease costs, in order to make an interesting business case for potential industrial partners.
Universities & RTOs: We collaborate closely with Netherlands Aerospace Centre (NLR) in L-AMPV-II as well as for the development of a mission module for the Defence Boxer vehicle in a National

Technology Project for the Ministry of Defence. TU Delft is a partner in development of FEM, and in close collaboration with TNO for projects with 2 NWO PhD students, working on research questions derived from the ERP. It is very likely that they can start in 2022.

Results 2021 and plan year 2022

3. Results 2021

- **Results achieved in previous Full ERP years**

Line A. –Digital Twin Technologies
IT-platform that integrates the DT components flexibly and adaptively, to enable easy reuse for other structures:
Structural modelling approaches:
- A Python package for Bayesian parameter estimation and model selection for computationally demanding civil engineering problems. General improvement and maintenance of the code, breaking it up into smaller standalone packages, improving testing and documentation. The package is open-sourced which already resulted in contributions to the source code from our strategic research partner BAM. It is also made available to German universities.
- Exploration and piloting a physics-informed neural networks (PINN) modelling approach for synthetic beam cases (Python and Julia implementations). Comparison of the model predictions and generalizability with traditional physics-based models and pure machine learning models. For the considered cases, PINN outperforms the other approaches although it has limited capability to generalize.
- Investigation of the effect of spatial and temporal dependency on Bayesian inference. Identification of the cases where dependencies should be taken into account. Derivation of a novel, computationally efficient likelihood evaluation method. Besides synthetic cases, the methods were demonstrated for the IJssel bridge case.
- Exploration and piloting a scientific machine learning (SciML) modelling approach for a synthetic beam case and for the IJssel bridge case (Julia implementations). Comparison of the model predictions and generalizability with pure machine learning models (neural networks). For the considered cases SciML outperforms the neural networks by far and it has a much better ability to generalize than PINN because it captures an “essential” part of the modelled object.

Surrogate modelling:
- Bayesian neural network implementation, added as a surrogate function option.
- Extended the implemented adaptive surrogating algorithm.

Scaling computational power flexibly:
- Offloading API (Application Programming Interface): a cloud-based scaling mechanism to “off-load” heavy FEM-calculations so that they do not have to be executed locally, but can be parallelized (i.e. distributing computations in parallel computer clusters) and be executed in the cloud (which enables ad hoc adding unlimited computer power).
- A flexible structure, making use of the offloading API, to train and derive surrogate models as FEM replacements.

Flexible module infrastructure: Standardized component interaction by “containerization wrapping” of a FEM-model
- Tools to flexibly switch between specific FEM and surrogate models when performing Bayesian Inference using the IT infrastructure (containerization).

Data management: BIM-to-FEM automation (exploratory desktop study). Data management connected to Data processing by using shared database technology. Instantiation in a graph database (OrientDB) to keep track of calculations results and meta data of the structure.

Line B. Existing structures: component & structure – Modelling & Sensing
General: combing our structural engineering and ICT strengths
- Python based toolbox (tarrali version 2.0) for parameter estimation as a unified platform for system, load, and damage identification. This toolbox is also available open-source which already resulted in improvements by our strategic research partner BAM. It is also made available to German universities.

Offshore wind (bolted ring flange connection):
- 3D ring flange model calibrated with improved stress measurement and tentatively validated by lab test.
- Proof of principle of ultrasonic sensing system for pre-stress measurement of bolts in a ring flange.

Steel bridge:
- Joint paper (TNO, RWS and RHDHV) on the reduction of safety factor using a single (strain) sensor only.
- Parameter estimation using multi (> 10) traditional strain measurements to derive the safety factor.
- Method for quantifying uncertainties and Bayesian updating on the basis of sensor data. A table top demo was realized with BAM and presented on the Hannover Messe in 2021 (www.youtube.com) and the same table top demonstrator will be used to generate data for a joint paper of BAM & TNO.
- Start of the field site DT Steel bridge and lab demo DT Bolted connection.
- Proof in practice of a fiber optic system for static and dynamic distributed strain measurements of steel bridge.

Line C. Existing structures: network - Vehicle load
Loadmap: interactive GIS-tool for traffic load information
- Traffic flow predictions in the urban environment of Amsterdam are used to improve the accuracy of the Loadmap
- Desk study evaluation of the added value of induction loops (data source related to traffic intensities)
- Improved predictive model in Loadmap with increasing accuracy
- Integration of Loadmap in a GIS-tool (Urban Strategy), enabling replacement of (often conservative) normative traffic loads by case-specific estimated traffic loads

Bridge-WiM: bridge as a scale for trucks
- Inventory of accuracy requirements for WiM and Bridge-WiM systems
- Improved accuracy of the weight measurement for multi-axle vehicles
- Assessment of added value of AI technologies for the accuracy of Bridge-WiM
- Application of the toolset to a bridge with less optimal sensor layout
- Tool restructured such that it can be applied for any bridge
- Preparation of integration with Loadmap and with Digital Twin of the steel bridge

Line D. Design of structures
WP1: AI design optimization algorithm
- Improved optimization criterion for the algorithm.
- Multi-fidelity optimization algorithm using basic and advanced FEM model.

WP2: Numerical model development
- Reliability check of physical models by comparison with TU Delft analysis methodology and earlier experiments
- Validated methodologies for coupling meso and macro scale modelling
- Understanding of unexpected differences between versions of the commercial FEM software which significantly affect the outcome of our analysis, together with the software firm

WP3: Experimental validation for uncertainty reduction
- Further validation of the behaviour of the composite panels predicted by physical models to reduce the uncertainty in the simulation driven optimization
- Off-axis composite samples tests with a Split Hopkinson Bar (SHB)
- Plan for improving future diagnostics of off-axis SHB results using Digital Image Correlation (DIC) in combination with high speed image recording

4. Plan Year 2022

- **Focus year 2022**

The main focus for the existing structures will be the integration of the results from lines A, B, C, in digital twins and their demonstration and validation. For use case steel bridge there will be a field site Moerdijk bridge and an auxiliary field site for specific technologies at the Papendrecht bridge. For the use case bolted connections there will be a lab demo. Bridge-WiM and the Loadmap will be demonstrated on the Moerdijk and possibly the Papendrecht Bridge. The Loadmap will also be demonstrated for the urban network of the municipality of Amsterdam. We will involve the owners of these assets and as much as possible industrial partners, and invite them to participate actively. RWS and Amsterdam have given their commitment; other parties have shown their interest. The field site Moerdijk bridge has also been mentioned to be incorporated in several national innovation programs such as Nationaal Groei Fonds initiatives.
For the design of structures (Line D) the main connection with the other parts in the ERP lies within line A. Line D will aim at a procedure for machine learning optimized material and structural design. The composite material will be further developed in affiliated projects with mixed funding and projects funded by industry or MoD. The highly non-linear, and perhaps even discrete, nature of the response of the case studied within this line is a very challenging test case for the tools and methodologies developed within line A. The input from line A can enable steps to higher scales that are impossible with conventional techniques.

- **Activities & Deliverables Year 2022**

Line A. –Digital Twin Technologies
The IT-platform's functionality, developed in 2021, will be demonstrated for the Moerdijk field site. This will demonstrate the flexibility in deploying different computational workflows on a scalable cloud infrastructure, the ability to repeat calculation workflows and the traceability of performed calculations. The activities and deliverables will be:
- Integration of specific components (models, sensor data) from research line B for the field site Moerdijk
- Instantiation of the generic bridge ontology and data management for Moerdijk to keep track of data and calculation results
- Multiple specific workflows for assessing structural integrity in the field site case,
- Demonstration of specific Moerdijk computational jobs on the platform
    - Based on a FE model of the field site bridge different approaches to derive surrogate models for this bridge will be executed on the IT-platform.

- Bayesian interference techniques will be used for parameter estimation (and model selection) in combination with surrogate models with actual sensor measurements from the field site bridge
- Demonstrate the platform flexibility for Bayesian parameter estimation within reasonable time and small user effort, utilizing developed components such as surrogate modelling and offloading.

- Scientific machine learning (SciML) modelling approach, extended with uncertainty quantification and validated against measurements.
- IT platform support for the SciML workflow.

By doing the above we close a feedback loop from real life measurements, to models, to the actual structure. The IT-platform ensures that this loop is repeatable and reproducible.

Line B. Existing structures: component & structure – Modelling & Sensing
Offshore wind (bolted ring flange connection):

- 3D ring flange model calibrated with improved stress measurement and validated under realistic conditions. Compared to 2021 the ring flange is much larger and a realistic representation of what is used in the field.
- Technical validation of an ultrasonic sensing system for pre-stress measurement of bolts in a ring flange in a field environment.

Steel bridge:

- Proof in practice – field site Moerdijk bridge. In order to obtain the required small sensing length (strain measurement within 1 to 10 mm), the fiber optic sensor and cable routing will be further improved. The final goal is demonstrating the combination in one fiber optic system of (very local) distributed strain measurement for load monitoring with vibration / acoustic sensing for detecting damage. The combination must enable system identification.
- Statistical match between model and the distributed multi-parameter (line-like) fiber optic data using our toolbox (tarrali version 3.0)
- In addition to the distributed fiber optic data, also other sensor data generated at the field site will be fed into the toolbox to evaluate the added value of different types of sensor data.
- Joint paper TNO & BAM on matching model and sensor data for system-, load- and damage identification based on field site Moerdijk.

Line C. Existing structures: network - Vehicle load
Loadmap: interactive GIS-tool for traffic load information

- Feasibility assessed of integrating traffic flow models developed for the highway network in the LoadMap
- Implementation of the methodology for generating and analysing future scenarios (e.g. innovations of the transport sector such as truck platooning)
- Feasibility of integrating Loadmap in existing workflows and its added value accepted by the sector
- PoC Loadmap ready for further development towards commercial application

Bridge-WIM: bridge as a versatile scale for trucks

- PoC Bridge-WiM in field site, providing required information on actual traffic loads that can be integrated in the loadmap and the digital twin
- Easy to apply Bridge-WiM for other steel bridges in multiple application scenarios

Line D. Design of structures
WP1: AI design optimization algorithm

- Multi-fidelity assessment with incorporated uncertainty levels of the analyses
- Multi-fidelity approach, validated on component level
- Updated design tool with improved optimisation criterion for composite laminates subjected to high dynamic loading

- Demonstration of the tool by optimisation of a component subjected to a high dynamic loading.

WP2: Numerical model development

- Advanced FEM model with decreased analysis time to enable incorporation in upscaled AI supported design algorithm
- Assessment of the uncertainty levels of the analyse tools when used at the boundary and beyond standard capabilities.
- Validation of analyses methodologies based on comparison of results obtained with TU Delft approach and results from validation analyses of experiments.

WP3: Experimental validation for uncertainty reduction

- Blast panel test on the optimized panel design resulting from WP 1 to evaluate the effectiveness of the multi-fidelity assessment.

2: Exposense

ERP Contacts: R. Goudriaan (Project Lead), A. Pronk (Lead Scientist), A. Dortmans (Science Director)
ERP Duration: 2019 – 2022

Overall Program description

1. Context and Objectives

- **Problem definition**

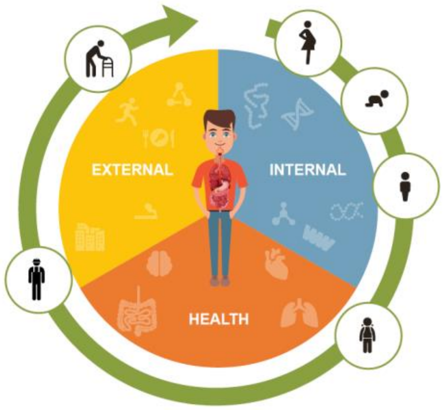

Figure 3: Our health is influenced by both the genome and exposome, the latter being our environment since the day we are born

Our health is impacted by the environment we live and work in, resulting in a combination of potential exposures (e.g. lifestyle factors, chemical exposures, social interactions and stress). Many common disorders are closely linked to these exposures, and the complex interrelations between exposures and effects are still a scientific challenge. We often do not know why one person develops a disease and the other does not, and which exposures have played a detrimental role. The concept 'exposome' – the totality of exposures a person experiences during a lifetime – will help to close this gap in knowledge. Moreover, better understanding of how exposures are related to disease will enable the development of effective personalized preventive measures in this area.

The rapid development of sensor technologies that can provide real time digital data with a high resolution in time and space poses an opportunity to transform the field of exposure science, with ultimately applications like a personal 'early warning system' or 'exposure coach' (e.g. integrated in a wearable / portable device) or group based exposure management tools consisting of new sensor technology and new interpretation of the data. This combination will warn people in unhealthy situations (e.g. heavily polluted areas) and enable corrective actions which should lead to a lower burden of disease. For this an integrated approach is needed for assessing, interpreting and providing feedback on exposures and relevant health effects.

The aim of this program is to deliver comprehensive equipment and models for the management of the impact of particulate matter (PM) exposure on human health, both in the general environment and in the occupational domain.

- **Expected impact to stakeholders**

The WHO estimates there are around 400,000 early deaths each year in Europe related to air pollution. In total 80-90% of the population in Europe is exposed to concentrations above the WHO limit values. In 2020 the report "Health costs of air pollution in European cities and the linkage with transport", published by CE Delft and commissioned by the European Public Health Alliance, estimated health related damages by air pollution cost the average city resident in Europe €1276 every year; for the Netherlands, this is estimated at €1170/yr (Cleanair4health[1]). As example, this totals to 1055 MEUR per year for Amsterdam alone.

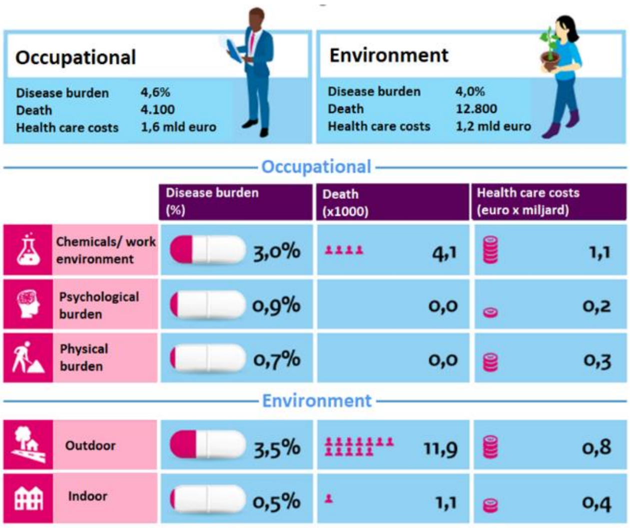

Figure 4: WHO estimates how deaths each year are related to occupation and environmental effects

More than 80% of these costs are associated with exposure of the population to PM. This is both true for cities in the Netherlands as well as other cities in Europe. In addition, 3% of the Dutch burden of disease is accounted for by chemical exposures at work which are often particulate related, e.g. construction dust, wood & agricultural dust, combustion particles, welding fumes. Together, these environmental and occupational (chemical) exposures amount to over 2 billion Euros in health care costs alone. This is apart from additional impact like lost working hours through distress and/or disease and reductions in quality of life of workers.

The comprehensive equipment and models aimed at management of impact of PM exposure developed in this ERP will contribute to reduction of this burden of disease and related costs to society. In addition, it will transform the field of exposure science. Conventional measurement equipment is costly, needs qualified (laboratory) personnel, results in average exposure levels over days or weeks and often takes days to weeks to be analysed in a laboratory. A transition to low-medium cost, easy to use sensors that provide high resolution data opens up many opportunities, like DIY tools empowering citizens or workers as well as a shift from reactive exposure monitoring to more proactive exposure management. The exploratory work done in this ERP on quantification of PM health impact through non-invasive sensing of biomarkers might bring an even more personal, tailor-made approach to risk-based exposure management in future. The technologies developed in this ERP focus on PM, but the modelling approaches are applicable to other exposures as well when relevant sensors become available.

2. Approach

- **Focus**

In both occupational and environmental settings we investigate how modular systems of sensors and models enable real-time risk management for individuals and/or groups to minimize impact of PM exposure on human health. To achieve the ERP aim, four research lines with distinct technologies and/or methods were defined:

A. Sensor development for PM: portable and wearable PM sensors with chemical identification capacity.
B. Analysis and interpretation of external sensor data and integration with models (external exposome) into actionable information for management of external PM exposure.
C. Internal exposome: Developments on the future vision of adding non-invasive biomarker approaches to assess early markers of health effects of PM exposure.

[1] https://cleanair4health.eu/

D. Demonstrators linking A&B in two use cases (environmental & occupational setting) with stakeholders (alternating each year).

Although both the sensor platform and modelling approaches show promising potential for other (chemical) exposures, which will enable future developments, this ERP has a focus on PM because of its societal burden.

- **Research plan**

The overall research aims and questions are described in this section. The activities, results and timelines per year per research line are captured in section 3 and 4.

Research Line A - Sensor development for PM: We aim to differentiate particle size as well to chemically identify PM with respect to both organic and inorganic components. Concentrations of PM which have to be measured are in the range between 10µg/m^3 to 25µg/m^3 to be in agreement with the European Air Quality standard[2]. Key research questions are:

- Is it possible to differentiate PM by their spectrochemical signature?
- Is it possible to achieve sensor performance compatible with regulations and end-user preferences?
- What are the unique detection challenges by scenario (occupational, environmental, defence)?
- Can we develop technology for a wearable solution while retaining its chemical identification performance?

Research Line B - Analysis and interpretation of external sensor data and integration with models: We aim to predict personal exposures levels over a (working) day and determine when (high resolution in time), where (high resolution in space) and why (identification of exposure sources and other determinates) exposures occur. Key research questions are:

- How can we combine sensor data with existing (source apportionment) models in order to assess (sources of) environmental PM with a high resolution in time and space?
- How do we combine these updated models with population dynamics/location data to obtain exposures that are linked with health impact assessments?
- How can we combine sensor data with existing exposure models and data analytics techniques in order to assess worker exposure to PM with high resolution in time and space?
- How can we apply context sensors for appropriate interpretation of exposure profiles?

Research Line C - Analysis and interpretation of internal exposure data and integration with models: We aim to develop a set of biomarkers related to PM exposure via the automated combination of literature and database information, integrating the information on proteins, biological pathways, chemicals, and biological matrices as a starting point for the development for non-invasive tests. Key research questions are:

- Can text and data mining help to discover biomarkers that predict exposure and health effects from internal exposure to PM? Can this TNO technology be positioned as general approach for biomarker discovery?
- Can these PM biomarkers be further developed towards detection in a non-invasive manner?

Research Line D – System integration to an environmental and occupational demonstrator: We aim to develop demonstrators for exposure management that combine sensors and models to provide meaningful results. These systems will be constructed with stakeholder input to realize the potential benefits of the technologies and create a collaborative environment for future developments. Specific

[2] http://ec.europa.eu/environment/air/quality/standards.htm

research questions are:
- Is it possible to combine the sensor development and external exposure models into proof of concept demonstrators for PM management with stakeholders?
- What feedback options can be used to reach the objective of real time risk and health management?

- **Targeted Partnerships**

In both the occupational and environmental setting we are looking for and establishing partnerships through various parts of the value chain. These include sensor manufacturers (e.g. Agilent), IT companies (data and dashboards) and end-users. We also foresee links to indoor air quality. A selection of these is listed groups below:
- *Occupational setting:* In 2019 / 2020 a scientific collaboration with NIOSH and HSE was started. In ERP ExpoSense an interest group of 10 Dutch construction companies has been formed, including Mateboer where the demonstration of 2020 was performed. There is growing interest in VOHA from many commercial companies. Various EU projects on this topic are executed.
- *General environment:* TNO partners in a sensor network in Eindhoven consisting of AiREAS, gemeente Eindhoven, Prov. Noord-Brabant, ODZOB, GGD, RIVM and Universiteit Utrecht. We foresee cooperation with Fontys and TU/e in the near future. For the 2021 demonstrators we collaborate with Eindhoven-based companies Zichtopdata and VTEC. Additionally we aim for more international partners and/or projects.
- *Academic cooperation:* Through the ERP we share a senior scientist with IRAS (Utrecht University) on Exposome research. A PhD student of UU-IRAS is evaluating sensors in the working environment: this is funded by ERP Exposense, EU EPHOR and the KIP Sustainable Work. A PhD student of The Aristotle University of Thessaloniki is involved in data assimilation for air quality modelling. We have a signed Research Collaboration Agreement with Aarhus University on exploration of biomarkers. In addition, we have succeeded to participate in the NWA/NWO ‘Virtual Human Platform for Safety Assessment’ in which data rich technologies are developed and employed which support research line C.

Results 2021 and plan year 2022

3. Results 2021

In ERP Exposense 2021 we investigate how a modular system of sensors and models can be used to address environmental (air pollutant) exposure and provide actionable information to municipalities (and citizens). We combined air quality modelling with mass/concentration sensing and chemical sensing for source apportionment. The resulting concentration maps are being overlayed with dynamic population maps to generate population exposure maps, which are more relevant for understanding health effects than concentration maps. We will also combine this with functionality for assessing individual exposures using mobile sensor systems. For the occupational domain we are preparing the demonstrator of 2022, with developments on context sensors, validation of user requirements with construction focus group members and design of a miniaturized version of the CID which will be wearable.

- **Results achieved in previous Full ERP year(s)**

The table below presents the milestones per year of the ERP. The research lines associated with each result are shown between brackets and correspond to the research lines as shown in section 2. The focus and activities of 2022 are described in section 4.

Year Milestones

2019 *Demonstrator: Environmental - [Personal exposure profiles in Amsterdam](https://www.youtube.com/watch?v=zL0eIYElXWo&list=UUowrFy3JghpFkwYCuV6Gsrw&index=6)*[3]

(A) System design for IR detection, increasing particle concentration & chemical identification of PM
(A) Validation of PM sensor measuring weight and various Proof of Concepts allowing chemical identification of PM
(A) Patent application on Analyte Detector with nano-Antennas
(B) Integration of air pollution models LOTOS-EUROS (background/regional concentrations) and Urban Strategy air module (local concentrations)
(B) Modelled PM exposures validated against measured PM exposures with Utrecht Exposome hub
(B) Evaluation of TOPAS for linking source apportionment to personal exposure levels
(B) Selection of CFD modelling and kriging for modelling occupational exposures in space: 2D maps.
(C) BDC-INDRA literature mining-based workflow implemented and identification of candidate biomarkers responsive to external exposure

- ERP Exposense Roadmap established.
- Demonstration of mobile measurements using high-end equipment for measuring NO_2 during the Nijmeegse Vierdaagse.

2020 *Demonstrator: Occupational -[Realtime sensing of crystalline silica at Mateboer constr. site](https://www.tno.nl/en/tno-insights/articles/demonstration-of-real-time-crystalline-silica-sensor-at-construction-site/)*[4]

(A) Ability to identify and classify spectra of unknown sources of PM with CID confirmed.
(A) Developed mini cyclone to separate more than 95% of airborne particles larger than 0.6 µm.
(A) Portable CID demonstrator for measuring crystalline silica constructed
(A) Demonstrated detection ability for other components, like microplastics and Chromium VI
(A) Three patent applications covering “In-Line Identification of Aerosol Particles”, “IR waveguide with inner coating for gas detection” and “IR waveguide with outer coating for liquid detection”
(B) Pilot study CFD modelling and kriging to create concentration maps
(B) End user focus group within the construction sector to guide development established
(B) Research data infrastructure EXCITE enables the combination/synchronization and analyses of sensor data (developed in collaboration with VP Sustainable Work)
(B) Ability to translate sensor data into real-time understandable feedback through apps or dashboards integrated in EXCITE: feedback of basic statistics: profiles, cumulative exposure
(B) A new GPS module is developed and implemented in Urban Strategy. The module collects data from SAFE, part of the EXCITE platform.
(C) Shortlisted candidate biomarkers based on database text mining

2021 *Demonstrator: Environmental - Personal and population exposure with source contributions in Eindhoven*

(A) Integration of CID with FTIR to reduce size and enhance performance

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[3] https://www.youtube.com/watch?v=zL0eIYElXWo&list=UUowrFy3JghpFkwYCuV6Gsrw&index=6
[4] https://www.tno.nl/en/tno-insights/articles/demonstration-of-real-time-crystalline-silica-sensor-at-construction-site/

(A) Lab and field validation of CID for various particulates in our living environment
(A) Newly designed portable CID demonstrator for chemical characterization in ILM sensor network
(A) Miniaturization CID hardware for wearable solutions for occupational demonstrator 2022
(B) High-res source apportionment (1x1km^2) integrating air quality models and sensor network data
(B) Dynamic exposure estimates on population and personal level in the urban environment with Utrecht exposome hub and Zichtopdata
(B) Determination of relative contribution of different source sectors to exposure levels feasible
(B) Exploration context sensors for interpretation of exposure profiles in the working environment
(C) Verification of shortlisted biomarkers with Aarhus University in preparation of wet-lab validation

4. **Plan year 2022**

- **Focus Year 2022**

The focus in 2022 will be on the final occupational demonstrator combining sensor development (wearable PM-CID) and external exposure modelling (interpretation of where and why workers are exposed) in the construction sector. Within this final year of the ERP further development on the portable PM-CID and associated methods for health impact assessment in the environmental setting will also take place. In addition, the internal exposome markers will be validated and case studies for their application described. Since this is the final year of the ERP we will pay extra attention on maintaining and growing our network and establishing plans/leads for future developments of the ERP technologies.

- **Activities Year 2022**

Research Line A: "Sensor development for PM"

The main focus in sensor development is the miniaturization of the CID into a wearable device. Specific challenges to be solved are related to the following research questions: 1) Can we replace the large optical hardware by smaller alternative optical solutions, and retain the required sensitivity and spectral range (to include all relevant PM sources)?; 2) Can we adapt the optical hardware (reduce power consumption by e.g. selective emitters) to make a fully 8hour wearable device?; 3) Can we generate a (multivariate) data processing protocol to derive information on PM sources and concentrations from the reduced data flow generated by the miniaturized device?

The wearable version of the PM-CID will be addressed by replacing the compact spectrometer with miniaturized optical components. We will select discrete wavelengths characteristic of each PM category and identify light source(s) and detectors that provide sufficient signal at low power consumption. The sensor performance (e.g. detection limit, response time, dynamic range, etc.) will be assessed using these new components and compared with the results from the compact spectrometer. This will allow us to quantify the impact that miniaturized components have on the wearable system performance, and assess its feasibility. A multivariate data processing protocol will be drafted to retrieve the most relevant information from the limited data set. In parallel, further development of alternative hardware (e.g. valves, pump, cyclone, waveguide) will be performed to facilitate the size reduction. When these activities are complete, the optimal combination of components and data processing techniques will be used to produce wearable demonstrators (3 – 5 devices) for field tests at construction-sites. Communication and power solutions will be implemented in cooperation with Holst Centre.

The accuracy and calibration needs of these devices will be evaluated based on comparisons with the (portable) PM-CID and conventional measurement equipment.

Research Line B: "Analysis and interpretation of external sensor data and integration with models"

For the occupational setting two modelling approaches for visualization and interpretation of personal exposures are applied with the aim of (real time) sensor based risk management. Firstly, (near-)real-time concentration maps (WHERE) are created based on sensor data by implementation of kriging modelling in the EXCITE platform and visualization on a dashboard. The incorporation of kriging in (near-) real-time in EXCITE may pose a challenge and if so focus will be on demonstrating the approach. Secondly, methods will be developed for interpretation of determinants of exposure peaks by the combination of sensor exposure data and context sensor data (personal feedback through app). Statistical methods for time series data are being developed in the KIP Sustainable Work. The challenge and focus of this ERP is the methodology for collecting contextual (determinant) data at a high resolution with sensor data. A general framework for collection of contextual data will be developed and will be applied for the case study.

For the environmental setting the developments on the source specific characterization factors and population dynamics will be extended by implementing a consistent modeling framework for calculating characterization factors for emissions of primary PM2.5 and secondary PM2.5 precursors for different scenarios. This brings together developments on source apportionments and population dynamics from previous years and will result in an impact assessment tool, which we will demonstrate changes in DALYS (Disability Adjust Life Years) per unit emissions for different sectors (e.g. road traffic, aviation, industry and agricultural sector) and locations.

Research Line C: "Analysis and interpretation of internal exposure data and integration with models"

In collaboration with Aarhus, a wet lab validation of the obtained biomarker list will be performed based on Danish inhalation chamber study samples and/or Danish blood bank study samples. A challenge can be that the validation does not show a good correlation. The text mining approach for obtaining biomarkers will be disseminated. The ultimate goal of using non-invasive samplers/sensors for assessing (these or other) internal markers of exposure or (early) health effects of PM, to be used in combination with PM sensing, lies beyond the horizon of this ERP. Within the ERP we will describe some promising use cases linked to the demonstrators in which we see this non-invasive technology applied and write a plan for the next steps towards the development of non-invasive technology in (one of) these. This can be a plan for a PPS, EU or Seed-ERP proposal.

Research line D: "System integration to an environmental and occupational demonstrator"

We will demonstrate the wearable PM-CID for crystalline silica in combination with models for interpreting these sensor data in the construction sector in collaboration with the stakeholder group. Advances in this demonstrator compared with the Mateboer demonstrator in 2020 are: 1) the application of a wearable sensor and the advanced data interpretation of personal exposure and 2) dynamic 2D concentration maps (where) and methods for assessing determinants of peaks in personal exposure profiles (when and why) making use of context sensors in a construction setting in collaboration with stakeholders. (Near) real time feedback for exposure management will be provided in an app and/or dashboard. For this the models will be implemented in EXCITE using the privacy by design concept. Stakeholders will be consulted on optimal feedback options and ethics and privacy issues. In addition, as an extension of the demonstrator 2021, a demonstrator showing the changes in DALYS per unit environmental emissions for different sectors and locations will be made.

- **Deliverables Year 2022**

Research Line A:

(A) Portable PM-CID with lower detection limits and increased capabilities for chemical characterization
(A) Wearable PM-CID for silica, to be demonstrated linked with the interpretation models
(A) Demonstration of the accuracy (and possibilities to calibrate) of the CID

Research Line B:

(B) Kriging model coded on EXCITE platform + protocol on required measurement data input (required coverage in time and space)
(B) Data models using sensor exposure data (CID) and context-sensor data to interpret exposure profiles
(B) Acceptability of deployment of context sensors and personal or groupwise feedback based on it: end user focus group meeting minutes
(B) Privacy-by design concepts implemented in EXCITE
(B) Modeling framework for calculating characterization factors for emissions of primary PM2.5 and secondary PM2.5 precursors for different scenarios

Research Line C:

(C) A set of verified biomarkers from PM studies (use cases) in non-invasive and/or invasive matrices, in particular for novel biomarkers. Described in a report (spanning the entire ERP duration) including aim, methods, results, and outcome of use cases.
(C) Vision document on non-invasive biomonitoring of PM exposure and effect markers including an outlook /plan towards continuation beyond this ERP.

Research Line D:

(D) Demonstrator at construction company integrating the wearable PM-CID, context sensors and modelling
(D) Field validation of the PM-CID in the demonstrator setting
(D) Demonstrator changes in DALYS per unit environmental emissions for different sectors and locations
(All) Dissemination of ERP results in the form of (scientific) papers and presentations

3: FRONTIERS - Optical Satellite Communication

ERP Contacts: J. van Driel (Project Lead), N. Doelman (Lead Scientist), C. Hooijer (Science Director)
ERP Duration: 2019 – 2022

Overall program description

1. Context and Objectives

SOCIETAL NEED for HIGH-SPEED and SECURE COMMUNICATION
Our Digital Society requires an omnipresent, ultra-high broadband communication and secure infrastructure, which fully supports its information-oriented characteristics such as Cloud Computing, the Internet of Things, the Internet of Everything and High-speed Connectivity. To illustrate this, the European Commission has formulated her vision to turn Europe into a Gigabit Society. The main objectives of the EU Gigabit Society are:

- Gigabit connectivity for all main of socio-economic drivers,
- uninterrupted 5G (and 6G) coverage for all urban areas and major terrestrial transport paths, and
- access to connectivity offering at least 100 Mega-bits-per-second for all European households.

Figure 5: Illustration of space communication network.

For the Digital Society, the data communication needs are growing exponentially. With respect to Internet traffic for instance, Cisco has predicted that the Annual global IP traffic will grow by 26% and arrive at nearly 5 Zettabyte (ZB) in 2022. Other critical requirements for features such as availability, reliability, security, dependability and low cost are evolving in a similar fashion.

With respect to security specifically, the EU has launched the Quantum Communication Infrastructure (QCI). A pan-European QCI system aims at covering, from a public sector perspective, the domains of: (1) Inter and intra EU government communications, (2) Data centres interconnections and (3) the Critical infrastructure. On national level, free-space optical communication is an important technology in the KIA Veiligheid (MMIP 3.4).

- **Problem definition**

Satellites and also aerial and maritime platforms will play a crucial role in the overall communication network. Complementary to the terrestrial network, a satellite network offers key capabilities such as: instant, flexible and global coverage and secure links over long distances. The field of Satellite Communication finds itself at the brink of

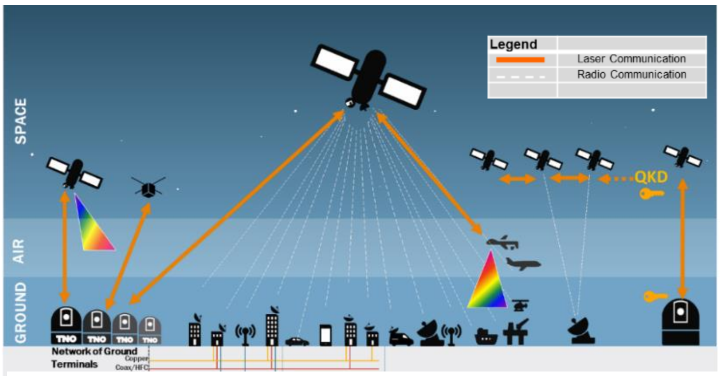


Figure 6: Diagram of various free-space communication links.

a technological revolution: the transition from Radio-Frequency (RF) waves to Optical waves. The **disruptive step** from RF to Optical Satellite Communication will enable various strong advantages, such as much higher bandwidth, very high data rates, quantum key distribution, immunity to interception and a much higher energy efficiency.

- **Expected impact to stakeholders**

This ERP addresses (fundamental) technology challenges of Optical Satellite Communication, to unleash and materialize the strong advantages of optical waves over RF waves in the context of wireless data communication for the Digital Society. The impact of the ERP can be summarized as a contribution to:

1. **The societal transition of digitization and the digital infrastructure**. This holds for NL but also worldwide (see paragraph above).
2. **Increase of the Dutch Gross Domestic Product** (BBP) and employment opportunities. The impact of the ERP technology innovation can be illustrated by the expected, long-term revenues and employment for Dutch industry in this field. It is estimated that in the field of Optical Satellite Communication, NL can acquire a position which amounts to: 5 billion Euro (cumulative up to 2035), 800 million Euro/year from 2035 and 5000 high-quality jobs; see graph.
3. **Connection to an international movement**. Several R&D programmes on Optical satellite Communication have been launched recently. On European level these are being co-ordinated by the EU, the ESA member states and EDF; the overall program amounts to about 170 million Euro per year.
4. **The creation of a Dutch research eco-system**. This ERP can take a leading role in the creation of a research consortium of university groups (and users) that will address the fundamental research challenges of Optical Satellite Communication, for instance in the framework of an NWO program.
5. **Development of knowledge and key-technologies**. Next to the direct application for Optical Communication, the technology development will apply to a much wider application area. The specific Key Enabling Technologies within this ERP are: Encryption Technologies/ Digital Security (ST2-4), (Opto)Mechatronics (ST3-1), High Frequency and Mixed Signal Technologies (ST3-4), Sensors and Actuators (ST3-7), Imaging Technologies (ST4-1), Integrated Photonics (ST4-2), and Quantum Communication (ST6-1).

2. Approach

The main objective of this ERP is to build a very strong knowledge and technology position in Optical Wireless Communication, with emphasis on Fast (high data throughput) and Secure (quantum encrypted) communication. In further detail, the ERP aims to:

- Design novel and strongly improved concepts of systems (ref. state-of-the art)
- Focus on critical technology building blocks
- Co-operate with university groups for high risk / high impact developments
- Optimize and combine technology developments to selected communication cases
- Seek other applications and cross-overs
- Demonstrate tech development in the lab, on (sub-) system level – reaching TRL4 by 2023.
- Follow-up by a continued development with Dutch and International industry and to contribute to the very strong business case of Dutch industry (see Section 4).

- **Focus**

The driving application field is Optical Wireless Communication over long distances. This includes various communication links between: Ground, satellite, air and maritime platforms. From these, the following representative research lines have been selected:

A. Very high data throughput – a ground-based communication terminal for terabit/s class feeder links.
B. Ultra-secure communication – a quantum key distribution link from a LEO orbit node
C. Multi-point communication – a multi-beam optical space terminal, simultaneously receiving data from multiple gateways and transmitting towards multiple users.
D. Very long distance communication – a ground-based receiver for data download from a deep space science mission. [*this research line has been discontinued in 2020*].

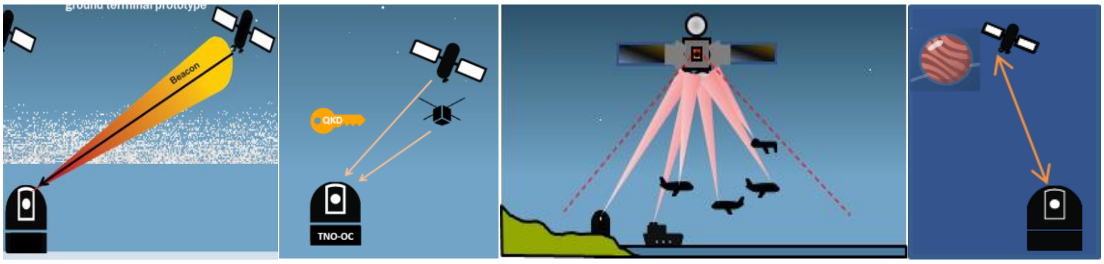


Figure 7: Illustration of the research lines for the ERP FRONTIERS – 1) very high data throughput, 2) ultra-secure communication, 4) multi-point communication and 4) very long-distance link.

- **Targeted partnerships**

A research collaboration of TNO, with academic partners, institutions such as ESA, and industry partners is pursued, focused on the development of knowledge and technology for future optical wireless communication products.

On the application side a close interaction with industry is taking place. ERP technology concepts are to be matured further in a continued development with Dutch and International users and industry. In follow-up phases, partial funding should come from industry and the other part for this phase could be provided by SMO, TKi, EU or ESA. After that, the product realization phase starts which is led by industry, and in which TNO could have an advisory role. Industrial development partners can be large system integrators, satellite operators and service providers, or are suppliers of optics, photonics, mechatronics, electronic or space equipment.

Partners

A. *University:* TUDelft, TU Eindhoven, Univ Leiden, UnivTwente, VU Adam.
B. *Institutional:* ESA, NASA, DLR, NCT.
C. *Industrial, per category:*
   - Large System Integrators: Airbus, Tesat, Thales, OHB
   - Technology suppliers: Demcon, Nedinsco, Hyperion, VDL, Hittech, Lionix, Aircision, Celestia,..
   - Communication Service providers: Eutelsat, Viasat, SES, Inmarsat
   - Telecom providers: KPN,
   - Users: financial (ABN), MODs, Governments, …

Results 2021 and plan year 2022

3. Results 2021

- **Results achieved in previous Full ERP year(s)**

The results of the ERP up to now are shown below (organized in the research lines structure).

Research Line A: Very high data throughput – a ground-based communication terminal for terabit/s class feeder links.
System concepts:
- Ground communication terminal for 10 Terabit per second link to a GEO-stationary satellite.
- Ground communication terminal for a 0.2 Terabit per second link to a LEO satellite.

Critical technologies:
- High power optical beam combiner for spectral multiplexing.
- High spectral efficiency data modulation approach.
- Diversity and coding approach to handle strong irradiance fluctuations of an atmospheric channel.
- Network traffic splitting and switching approach to enhance link availability; method and simulation verification.
- Adaptive optics correction for strong turbulence cases.
- Adaptive optics correction of uplink scintillation.
  Adaptive transmission strategies to handle time-varying channel states.

Research Line B: Ultra-secure communication – a quantum key distribution link from a LEO orbit node.
System concepts:
- Design of LEO based QKD link for BB84 protocol with enhanced secret key rate.
- Design of a concept for a LEO QKD link with maximized operational time.

Critical technologies:
- Profound performance analysis of QKD protocols, in the presence of channel loss and noise.
- Concept design of Adaptive QKD link.

Research Line C: Multi-point communication – a multi-beam optical space terminal

System concepts:
- A wide Field-of-View multi-beam space communication terminal.
- An array of low volume single-beam space communication terminals;

Critical technologies:

- Low volume telescope for multi-beam communication terminal.
- Large Field-of-View, low aberration transmitter and receiver telescope design.
- Dynamic tracking system for aircraft links.

Research Line D: Very long distance communication – a ground-based receiver for data download from deep space
System concepts:
- Concept for a ground-based receiver for order Megabit per second data communication.
  [*this research line has been discontinued in 2020*].

Applicable to all Research Lines: Generic Space Terminal results

- Improved receiver sensitivity concept.
- Technology for a low-cost optical space terminals.
- Technology for photonics based (low swap) space terminals.
- Vibration controlled space platform.
- Low mass telescope design.

Research Partners

On the fundamental research side, co-operations with university groups have been built to address the more fundamental, high-risk/ high impact research challenges. The NWO Perspectief program "Optical Wireless Superhighways" has been granted in March 2021 and was established by a strong support and contribution from this ERP. The total program amounts to 5.4 Meuro and has 5 university partners and 16 users/industrial partners.

The university partners are:

- TUDelft: Opto-Mechatronics, Optics, Space Systems
- TU Eindhoven: Electro-Optical Communications, Control System Technology
- UTwente: Communication Systems, Pervasive Systems, Photonics Systems
- UnivLeiden: Astronomy Instrumentation
- VU A'dam: Theoretical Physics

Within the NWO Perspectief program", the ERP will actively participate in 6 PhD projects, TNO will be the representative of the industrial user group and 2 of the in total 5 work-packages will be led by TNO representatives (Hooijer and Doelman).

4. Plan year 2022

- **Focus & Activities year 2022**

Next year will be the final year of this ERP. The emphasis will be on the performance verification of the designed and developed system concepts and critical technologies, in accordance with the general objective of reaching TRL4 in year 4. For the research lines, the plan is:

Research Line A: Very high data throughput – Terabit per second links Ground to Satellite

1. Verification test of high data rate and high reliability feeders (several use cases)..
2. Analysis of low-power spectral, in-fiber multiplexing concept (for LEO case).
3. Turbulence model verification.
4. Continued fundamental research in NWO Perspectief on: Resilient beams, Advanced diversity concepts and Adaptive Optics for fading channels.

Research Line B: Ultra-secure Communication – Quantum Key Distribution

1. Design and Experimental breadboard of background filter.
2. Testing and verification of breadboard.
3. Assessment of impact on uses case in terms of QKD total key length, 24 h per day.
4. Continued fundamental research in NWO Perspectief on secret key authentication.

Research Line C: Multi-point Communication – multi-beam space terminal

1. Design and Experimental breadboard of the low volume telescope
2. Testing and verification of experimental breadboard.
3. Performance analysis and assessment for multi-point communication use cases.
4. Continued fundamental research in NWO Perspectief on: multiple-beam steering.

- **Main Deliverables Year 2022**

Nr.	*Deliverable description*	*Format*	*Due date*
Research Line 1 - Very high data throughput			
A1	Numerical Turbulence Model	Software tool	Q1-2022
A2	Overview of spectral multiplexing approaches for terabit/s links	Report	Q1-2022
A3	Verification tool and testing for high data rate and high reliability feeder links	Simulation Tool	Q2-2022
A4	Final analysis of high data rate and high reliability feeder links	Report	Q4-2022
Research Line 2 – Ultra secure communication			
B1	Detailed design of background filter	Report	Q1-2022
B2	Experimental set-up and testing of filter	Breadboard	Q2-2022
B3	Final analysis of high key-rate QKD links	Report	Q4-2022
Research Line 3 – Multi-point communication			
C1	Detailed design of very low volume telescope	Report	Q1-2022
C2	Experimental set-up and testing of telescope	Breadboard	Q2-2022
C3	Final analysis of Multi-point communication terminal	Report	Q4-2022

4: Wise Policy Making

ERP Contacts: J. Sassen (Project Lead), H.-J. van Veen (Science Director)
ERP Duration: 2019 – 2022

Overall program description

1. Context and Objectives

- **Problem definition**

In the midst of a pandemic, the demands on policy-makers and government officials are extremely high. Many of the policy options in a crisis are ‘wicked’ in nature: The complexity of issues is overwhelming, the potential side effects unclear, and the arena’s in which the policy discussions take place are ambiguous and volatile. The current Covid-19 crisis demonstrates this reality painfully. And it is not likely an isolated incident, but more probably indicative of what lies ahead for policymakers. The Netherlands is at the dawn of several other major, radical changes driven by e.g. climate change (the energy transition), technology (autonomous driving, Artificial Intelligence, surveillance, cryptocurrencies), national developments (population aging), and globalization (migration, new pandemics).

In order to get a grip on these overwhelming developments, policymakers and citizens alike are faced with some fundamental questions: How can we - endowed with all the currently available science, data and technology - aim at improving (or re-gaining) our nation’s level of wellbeing? What policy options will guarantee a future in which its people and other living beings can flourish? How can we know - and agree upon - what this future looks like? And how do we choose policy options that steer towards this future?

Policymaking that accounts for the wellbeing of our society, now and in the future, is essential to effectively manage the radical changes of the current crisis, and the crises to come. Steering towards wellbeing is in line with an important forthcoming and global (though mostly Western) trend in policy making best known as ‘beyond GDP’: the acknowledgement that GDP captures a relatively narrow aspect of wellbeing, i.e. economic growth —and that we need a new set of indicators that capture a broader range of sustainable wellbeing.

There are, however, currently only few and partial instruments available to assess the expected impact on wellbeing prospectively. Policymakers generally use frameworks like social cost-benefit analyses when weighing up the various policy options. However, many limitations are still encountered when trying to properly assess wellbeing, which is why it is often not fully considered in analyses. Unlike amounts of money, wellbeing is considered more difficult to translate into data that can be easily compared. This is complicated even further when trying to compare conflicting forms of wellbeing (like ‘privacy’ versus ‘safety’). Another hurdle that is recognized in policymaking, is that the policy making process is characterized by insufficient attention and guidance towards unbiased dialogue and towards creating consensus among multiple stakeholders, citizens, and other involved participants. With a lack of solid and reliable data on the effects of policy options on wellbeing, adverse effects of cognitive biases and vested interests in policy discussions are imminent.

This ERP aims to fill this gap. Our aim is to develop a suite of instruments and methods to support policy makers to assess the impacts of policy options on wellbeing (ex-ante). And to engage in unbiased and well-informed dialogue leading to decisions that prioritize sustainable societal wellbeing.

- **Expected impact to stakeholders**

The primary targeted stakeholders for this research are policymakers. In both public opinion and political debate it is considered problematic that the economic frame is dominant in addressing the big (and small) societal issues. Policy makers are aware of the skewed decision-making that results from this frame, but have no alternative. The tools they have to support their decision-making involuntarily guide them towards solutions that benefit the economy, but not necessarily our wellbeing.

Without supportive tools that reliably and convincingly assess the effects on wellbeing, the transition will be hard, if not impossible to make. The effect of a methodology that allows policymakers to directly steer towards a broader definition of wellbeing, might well be unprecedented. It answers to the plead of many policymakers and politicians who want to make sound decisions that benefit our societal wellbeing, without being side-tracked by the allure of precision that comes from calculating the economic costs and benefits of a decision.

So the effect of this ERP is that we enable policymakers to take important steps in policymaking ‘beyond GDP’. The WISE Suite is thus an enabler of new forms of policymaking that are eminent, but not yet established. What the merit of taking such steps will be, can only be hypothesized. We believe (and we are not alone[5]) that it can be the steppingstone towards policy that balances long- and short term benefits better, and that allows for more societal prosperity and fulfilment for a larger group of living beings.

It is time for the Netherlands to join the front-runners and be one of the first countries in the world to raise its standard of policy-making. We believe that policymakers who are seeking to steer towards prioritizing wellbeing, deserve the very best support. They are our national pioneers, which means they are paving the roads. For a vast majority to follow suit, it is necessary that the frontrunners can show them that it is possible, and how it’s done: By using hard data from scientific models, and then using well-supported ‘wise deliberation’ to examine the value of this data. The WISE Suite is being developed to do just that.

2. Approach

- **Focus**

Focus and scope
Our ambition for 2022 is to deliver a prototype (TRL 5) of a ‘Wise Policy Suite’. With this Wise Policy Suite, we will be able to assist policy makers
1) in quantifying the impacts of different policy options on wellbeing.
2) to have fruitful dialogues about the policy options and deliberate on the impacts with each other, citizens and other stakeholders.

The Wise Policy Suite’ consists of instruments and methods that are tested and validated in practice, and are geared towards practical use by policy makers. This will enable them to develop and choose policy options that maximally promote wellbeing, based on scientific insights ánd demonstrably legitimized by society.

[5] Among the proponents of ‘beyond GDP’ policy are internationally renowned Kate Raworth and Donella Meadows. But also in the Netherlands we have important thinkers like Kees Klomp and Rutger Hoekstra

Methodologies to be developed

<u>*WISE Cube:*</u> The WISE Cube is an ex-ante evaluation instrument to support policymakers in prioritizing and steering policies towards societal wellbeing. It is an interactive tool that gives a visual forecast of the effect of an intended policy measure on the sustainable wellbeing for the relevant parties that this policy concerns. The tool helps to assess the impact of policy options on wellbeing by quantifying the impacts using valid wellbeing models and data. The WISE Cube needs to be 'filled' with relevant data that is relevant for the particular policy measure that is considered and that is relevant for the specific domain in which it is used. This means, that the Wise Cube can be used for policy options in any domain, filling it each time it is used with the relevant data and context-specific relations. In this ERP we are using and testing the WISE Cube within the mobility domain, and within the security and safety domain. Hence, in these domains we have started building a data-library with relevant data that may be re-used for other cases in these domains.

<u>*WISE Tank:*</u> The WISE Tank is complementary to the Cube and contains a set of methods that help policymakers and stakeholders to conduct a well-structured, unbiased, 'wise' dialogue about policy options. Supported by an advanced formal dialogue representation tool, the participants are guided to reason in the discussion from values that they consider important, not only for themselves or their "sector" but also for later and for common well-being. The dialogue is used to map the most relevant values and knowledge for the policy options. The arguments for and against options, and the underlying facts, knowledge and values, are registered so a decision can be made that is transparent, explainable and can be stored for later reference. In this way, the WISE Tank complements the outcomes of the WISE Cube by supporting policy discussions on the outcome of the WISE Cube.

Leading use cases and broader application

<u>*Policy Practice*</u>

This line of research is about the transition from the theory towards the practice of wellbeing-oriented policymaking. To achieve this, we perform two types of case studies.

1. Governance level case studies: a set of extensive case studies on how wellbeing-oriented policy making is approached, set up and implemented in real-life cases in Scotland, New Zealand, and Wales. These are the current frontrunners worldwide. Based on these empirical insights we are shaping a "wellbeing policy framework" that can be used as a foundation for the Dutch policymakers who wish to incorporate long term wellbeing considerations and models into their policy-making cycles.
2. Domain level case study: we are conducting a set of iterative experiments that support the development and test the WISE Cube and WISE Tank in practice. Demonstrating, evaluating and tuning the results from the WISE Cube and WISE Tank is essential to make the transition from the technology- and methodology development into actual policy practices. Case studies in which we use our WISE Suite prototypes, advance our knowledge of how these tools can be used in practice; what restrictive or permissive conditions apply in terms of time, budget, and attitude towards a focus on wellbeing. This effort is geared towards making the tools in the Wise Policy Suite work for policy processes within specific domain contexts. We have started a use case in the Mobility domain which was contra-financed by the municipality of Rotterdam. We have also started a use case in the Safety and Security domain that we are financing within the ERP, but in which we can profit from the large data set that is another project is building up.

- **Research plan**

Timeline and activities

The Wise Policy Making roadmap (see figure below) incorporates the remaining ERP time (2021 and 2022) in the first two columns. In the last column it looks beyond the ERP period (2023-2031) as, evidently, the intention of this research is to continue in SMO and other research opportunities until we reach the level of maturity that is needed for full implementation in policy practices.

In the roadmap we have taken up

1. Milestones: The most important milestones per work package (note that for practical reasons, we have included the Wellbeing Policy Framework in the milestones of the WISE Cube work package)
2. Overall progress: The progress that is made relative to the end-goal of full implementation and use in a policy context (also per work package)
3. Market activities: both case studies with end-users as well as (potential) collaborations with partners are taken up in this section.

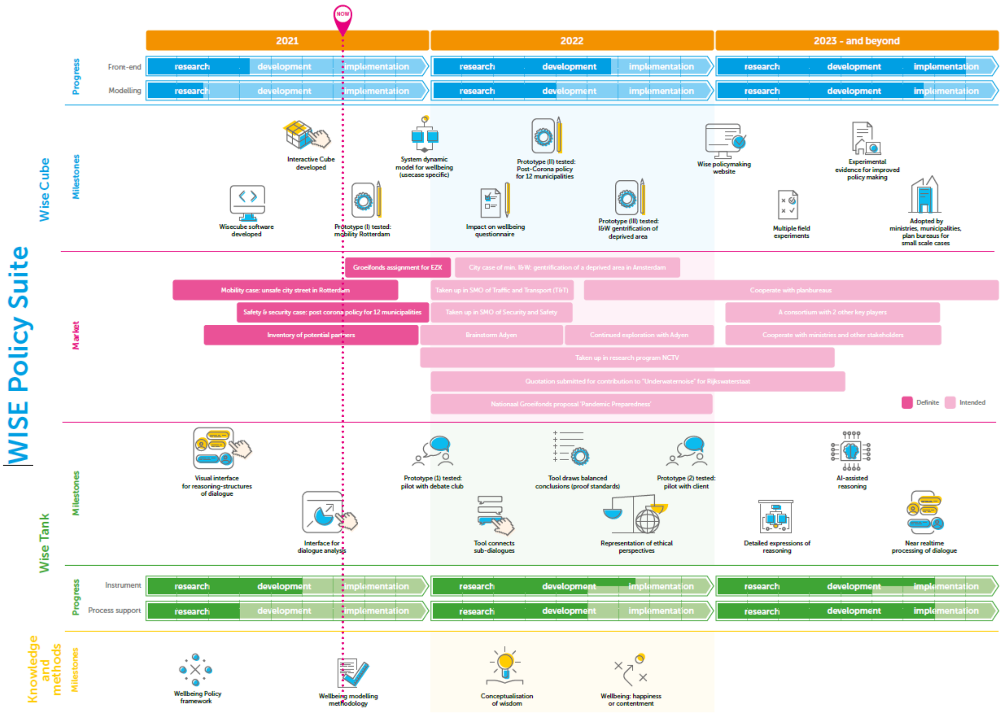


Figure 8: Roadmap ERP Wise Policy Making

How to read this roadmap:

- Flanking the market activity above are the milestones* and progress-bar** for the WISE Cube
- Centred in the middle in pink we see the market activity. Dark pink is definite, light pink is intended.
- Flanking the market activity below are the milestones* and progress-bar** for the WISE Tank
- In the bottom row we see the 'foundational research' that was needed to build the WISE Cube and WISE Suite. Knowledge and methods that determine our starting points and are at the basis of our conceptual ideation of the methodology and tools (such as: "what is wellbeing")

**The milestones in 2021 have already been reached, or will be reached before dec 2021. The milestones in 2022 however, are intended milestones that we expect to reach. The milestones in 2023 and beyond will be reached only if we are successful embedding the WISE Suite in other research-streams as the ERP has then ended.*

***The progress bars are divided in 9 steps as is common for Technology Readiness Levels (TRL). As this ERP develops methodologies (and not a purely technological tool), it is not a perfect fit for TRL, but can still be seen along the lines of research, development and implementation.*

The general research questions for the ERP Wise Policy Making (2019-2022) are:
WISE Cube
How to get insights in the expected effects of policies on wellbeing of groups?
- Supporting policy makers in quantifying the expected effects of policy options on wellbeing of groups. Developing an interactive tool that gives a visual representation of the effect of policy measures on the wellbeing of groups by using system dynamics modelling.

WISE Tank
How can a ‘wise’ dialogue be facilitated?
- Facilitating the rationality of real life policy decision dialogues by representing the logical interrelations among arguments with a Boolean network and providing the means to analyse this network. This provides an overview of and insight in the argumentation. An implementation is made in a representation and analysis software tool. Means are developed to optimize the use of the tool in a dialogue process.

Policy practice
What is needed to make the practical transition towards wellbeing-oriented policymaking?
- Study how the current frontrunners worldwide set up and implement wellbeing-oriented policy frameworks and processes.
- Develop a Wellbeing Policy Framework based on theory, best practices and lessons learned. This ‘developing’ should take place in close cooperation with the eventual users in the Netherlands.
- Demonstrate, evaluate and tune the WISE Cube and WISE Tank methodologies by means of iterative experiments in specific domain contexts.

- **Targeted partnerships**

The most important task of the ERP in this phase, is to find partners with whom to build a consortium or other type of partnership. Our aim is collaborate with partners with whom we can further develop the WISE Suite after 2022. Also, we are looking for end-users who want to use the WISE Suite once it is available. We differentiate in the partners that will end up using our tooling (we will call them end-users or ‘market’) and partners that are primarily interested in co-developing the WISE Suite. We have talked to many potential partners and end-users of whom the following at this point in time seem promising:
Partners:
- RABO research – collaborative paper: “developing surveys for measuring wellbeing ex ante” (with dr S. Hardeman)
- Hogeschool Rotterdam – action research and wellbeing fieldlabs (prof Kees Klomp)
- University of Utrecht (prof. Prakken) with respect to dialogue representation and analysis
- Adyen - Adyen sees much potential in a tool that assesses policy with a wellbeing perspective. And is interested to see how their big data proficiency can be matched with TNO’s WISE Suite.

End-users/market:
- Min I&W – we are in an advanced stage of finding a case study in which the ministry wishes to use the WISE Cube to gain insight in the effects of a gentrification-project in a suburb of Amsterdam or the Hague.
- Min EZK – as part of the project commissioned by EZK, in which we will support the ministry with the evaluation of the Groeifonds infrastructure proposals, a pilot will be carried out using the instrument for dialogue representation and analysis for the analysis of the reasoning line in two proposals. If successful it is likely that the instrument will get a role for evaluating proposals in futures rounds

- planbureaus - In particular with SCP as they have very relevant goals for the future in which they wish to be able to do ex ante monitoring for wellbeing
- Nationaal Groeifonds - Participating in a large consortium with Leiden University and Erasmus MC for the track 'Pandemic Preparedness'. We are asked to contribute with our Wise Cube methodology.
- Rijkswaterstaat - Contribution to "Underwaternoise" proposal. Quotation submitted. Goal is to assess the wellbeing effects of windmills in the north sea with the WISE Cube

Results 2021 and plan year 2022

3. Results 2021

<u>Research Line 1: WISE Cube:</u>

We developed a multi user web-based software application that provides policy makers with a visual representation of the expected effects of policies options on wellbeing indicators for multiple groups in the form of cube. With this tool experts and policy makers can model causal relations between policy options, change in behaviour and impact on wellbeing of groups and by determining the strength and speed of these causal relations short, medium and long term effects can be simulated (imports from MARVEL or Stella architect). The user can also indicate how causal relations are quantified, how certain one is and what knowledge is used to support it. This to calibrate trust in the systems model and its outcomes in the cube. To assess the wellbeing impact the user can select a subset of policy options, wellbeing indicators and groups to see expected wellbeing effects in the cube representation. The user can rotate the cube to see all planes and can order cells for right view on the data. This to support the dialogue about whether measures in policy options achieve their wellbeing goals. The user can navigate from the wellbeing outcomes in the cube to the systems model (and back) to understand what factors contributing to impact. A concept questionnaire has been developed that can be used to collect data from groups themselves about the perceived wellbeing impact of policy options.

<u>Research Line 2: WISE Tank</u>

Dialogue support

- Proofs of principle for (1) the representation of a dialogue as a Boolean circuit, (2) analysis of the represented knowledge and values, (3) querying the representation, e.g. if-then questions with respect to goal achievement depending on whether arguments or their negation hold.
- Interactive, graphically oriented software tool implementing the representation and analysis, consisting of algorithms calculating the answer to queries and an advanced i/o graphical interface.
- Pilot applying the tool to a dialogue (written, constructed on the basis of arguments found on internet dialogue site Kialo) on banning genetically modified crops. (proof with partially realistic conditions)
- Specification of dialogue forms (or formats) and interventions that support people to engage in debiased dialogues, about complex problems taking into account values, (lack of) knowledge, and facts.
- Published article: Retention and Transfer of Cognitive Bias Mitigation Interventions: A Systematic Literature Study, by Johan Egbert (Hans) Korteling, Jasmin Y J Gerritsma, Alexander Toet, published in Frontiers in Psychology, section Cognitive Science
- Paper "Value-Driven and Evidence-Based Dialogue: Formal Representation and Analysis" for journal Argument and Computation

Fostering wisdom

- In order to accommodate the budget-cut in 2021 and to make more room for opportunities to do experiments for real live case studies with the WISE Cube, we have decided to postpone this work package to 2022. It is still considered very important but could not be prioritized within the financial circumstances and opportunities that arose in 2021.

Research Line 3: Policy Practice
Our main goal in this work package is to turn the WISE Cube and WISE Tank to concrete use in the actual policy practice. In 2021, we have accomplished the following results:

Governance level
- We have conducted a set of comparative case studies, which look into how wellbeing-oriented policy making is approached and implemented in the 3 frontrunning countries in the world: Scotland, New Zealand and Whales. We expect to be able to publish this research as an academic paper in 2022.

Domain level
- We are currently conducting a set of iterative experiments that test the WISE Cube in practice. This effort is geared towards making the tools in the Wise Policy Suite work for policy processes (demonstration, evaluation). The case studies also function as the start of a 'track record' that illustrates what the added value of the WISE Cube can be. The WISE Cube has been tuned to the context of actual policy practice for two specific domains: Mobility and Security & Safety. By conducting these two case studies, we are able to further develop the dashboard (in which the interactive 'cube' and the system-dynamic modelling are integrated). Not only can we use the feedback from users, but we also learn from experimenting with how the dashboard works when we are filling it with an actual case for the first time. This has a very positive effect on the development of a functional and sturdy tool.
- The Mobility Case study has already concluded the first round of research, in which we made a causal model to define the effects from a mobility intervention (measures to improve an unsafe city street) to parameters of well-being. This gave policy makers insight in how direct effects – such as traffic congestion - are connected to less direct effects, such as autonomy or safety. The case study is now in a second round in the iterative process. The first feedback from Rotterdam is very positive. We also have presented out case to the ministry of I&W, who are also very positive.
- The Safety and Security case study focusses on the social impact of the Corona crisis in relation to the effects on societal wellbeing. We have looked at policy options aimed at resuming life during and after this pandemic for specific vulnerable groups in society due to the Corona crisis. So far, we have a system-dynamic analysis of two policy options that are being considered. These have been filled with assumed relations and potential effects on aspects of wellbeing. The case study will continue to validate the content and use of the WISE Cube in practice with municipalities. It will be concluded towards the end of 2021.

4. Plan year 2022

- **Focus Year 2022**

Our ambition for 2022 is to deliver a prototype (TRL 5) of a 'Wise Policy Suite' of instruments and methods that is tested and validated in practice, and is geared towards practical use by policy makers. With this Wise Policy Suite, we will be able to assist policy makers 1) in quantifying the impacts of different policy options on wellbeing, and 2) to have fruitful dialogues about the policy options and deliberate on the impacts with each other, citizens and other stakeholders. This will enable them to develop and choose policy options that maximally promote wellbeing, based on scientific insights ánd legitimized by society.

- **Activities Year 2022**

Research Line 1: WISE Cube

A. Improving and extending the functionality of WISE Cube with a library and method to select case appropriate wellbeing concepts, 2) advanced visualizations (e.g. uncertainty, bias mitigation, textual narratives), 3) improved navigation between cube and system model (wellbeing gap and policy impact), 4) questionnaires or participatory workshop formats for data acquisition, 5) improved API's with modelling applications.
B. Developing a wellbeing modelling methodology and modelling a wellbeing problems in two use cases using this methodology (post-corona policy and gentrification of deprived area)
C. Validating the improved and extended prototype and wellbeing modelling methodology with policy makers in two use cases (post-corona policy and gentrification of deprived area).
D. Writing paper for international journal

Research Line 2: WISE Tank

A. Extending the functionality of the tool for representing and analysing dialogues. These activities require theoretical development, algorithm development and extension of the functionality of the interactive, graphically oriented user interface.
B. Validating and finalizing the tool for supporting the facilitator of a dialogue. These activities require literature study and interaction with potential users.
C. Carrying out pilots. These activities require organisation, application of the tool for representation and analysis of a dialogue, and application of the facilitator tool.
D. Writing paper for international journal

Research Line 3: Policy Practice

A. Discuss the condensed theoretical and practical insights from the governance case studies against the contextual needs of and with Dutch policy makers. Write an academic paper for an international journal in which we present our insights from the comparison of existing wellbeing frameworks, and to what extent those results can be used as a theoretical foundation for the development of a Dutch model.
B. Case study / demonstrator with I&W in which the WISE Cube is implemented in the policy making process.
C. Implement WISE Cube and WISE Tank in various calls (such as Groeifonds, Rijkswaterstaat) as well as SMO research (T&T and Security & Safety) in order to iteratively continue the development of the methodologies of the WISE Suite.

- **Deliverables Year 2022**

Research Line 1: WISE Cube

A. Improvements and extensions of WISE Cube functionality
    1. Library and method to select case appropriate wellbeing concepts
    2. Advanced visualizations (e.g. uncertainty, bias mitigation, textual narratives)
    3. improved navigation between cube and system (wellbeing gap and policy impact)
    4. Questionnaires or participatory workshop formats for data acquisition
    5. Improved API's with modelling applications
B. Wellbeing modelling methodology
    1. Wellbeing modelling methodology
    2. Application for two use cases (post-corona policy and gentrification of deprived area)
C. Validation sessions
    1. Pilot post-corona policy: value and improvements for prototype and methodology
    2. Pilot gentrification of deprived area: : value and improvements for prototype and methodology

D. Paper for international journal

Research Line 2: WISE Tank

A. The following extensions of the functionality of the tool for representing and analysing dialogues
   1. recognizes and connects sub-dialogues
   2. automated subtopic detection
   3. draws balanced conclusions (proof standards).
   4. represents ethical perspectives
B. Extensions of the tool for supporting the facilitator of a dialogue dealing with
   5. mitigation participants biases, distinguishing between facts and values, distinguishing means and ends
C. The following pilots will be carried out
   6. pilot with debate club
   7. pilot with client
D. Paper for international journal

Research Line 3: Policy Practice

A. Workshop with Dutch policy makers. Aiming to start up a co-creation towards developing a Wellbeing Policy Framework
B. An academic paper in an international journal, which presents the comparison of governance approaches towards implementing wellbeing-oriented policy-making, and highlights theoretical and practical pathways.
C. Contra-financed case study for WISE Cube with the ministry of I&W under the umbrella of T&T
   D. Funnel of continued research both in SMO research (T&T and Security & Safety) as well as in other calls

5: Sustainability And Reliability for PV & (opto-)electric thin-film devices

ERP Contacts: A. Kuypers (Project Lead), M. Theelen (Lead Scientist), A. Faaij (Science Director)
ERP Duration: 2019 – 2022

Overall program description

1. Context and Objectives

- **Problem definition**

The societal impact of optoelectronic devices is enormous, and will continue to grow rapidly. In the form of devices for photovoltaic energy generation, sensors, data transport, and computing, as well as in lighting and displays, optoelectronic materials play an ever more critical role. Therefore the reliability of these materials, which are typically tailored on a micro- and nanometer scale to enable their desired functionality, is crucial. Moreover, because of their abundant application all such devices tend to evolve from high added value systems to commodities which are embedded in the lasting infrastructures we rely on.

Focus is on solar cells as a prominent example. By 2050, about half of the worlds electricity production may depend on optoelectronic PV materials, with critical dimensions well below the micrometer range while requiring a product lifetime of 35 years or more. In principle, such lifetimes are required for all types of solar cells (crystalline wafer-based as well as thin film), because the desired future scenario is to combine these technologies in tandem configurations with superior efficiencies. To maintain public acceptance when installing vast areas of PV, the national roadmap (IKIA, MMIP2) is focused on integration of PV in multifunctional surface areas of buildings and infrastructure or floating on water, implying multiple stress exposure of devices. The vast (km^2) scale of PV deployment provides a unique opportunity to achieve the project objectives, as degradation on nanometer scale can be studied with statistics on km^2 scale.

- **Expected impact to stakeholders**

On national level, GW-scale integration of PV in built environment, infrastructure and on water floating devices is foreseen in the coming years, involving multibillion euro investments. Predictable reliability and lifetime are required to enhance bankability and public acceptance, output, and thereby also the speed of the energy transition. This ERP develops novel methodologies to generate quantitative data and model based insight to assess lifetime and sustainability issues for stakeholders along the value chain (producers, investors, gatekeepers, installers, users, refurbishers and recyclers). It specifically addresses the market of novel and improved (more sustainable) PV devices, as well as novel PV environments where standard devices are exposed to multiple stress conditions. For these areas where reliability and lifetime are still relatively unexplored, more effective methods will be developed for stakeholders to assess reliability and lifetime, based on innovative gathering of outdoor field field data (sample extraction, sensors), combined with lab analysis and modelling.

2. Approach

- **Focus**

To improve reliability, reduce cost and reduce environmental impact, the focus of the project is to achieve more predictable and longer lifetimes of embedded optoelectronic devices in multiple-stress environments, through a model based understanding of degradation mechanisms. To achieve this, post mortem analysis of devices failed in the field will be used to guide accelerated lifetime testing in the lab, in combined-stress tests.

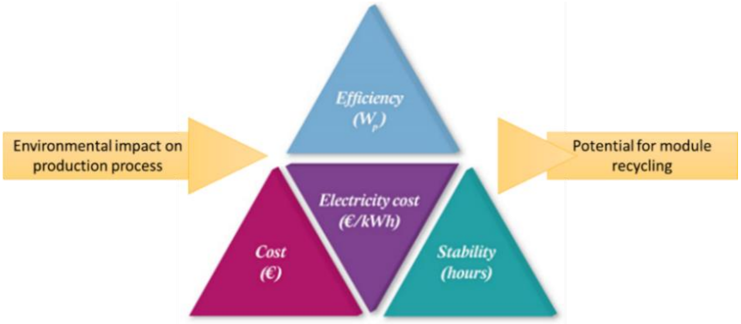


Figure 9: The triangle displays main parameters determining the cost competitiveness of electricity from a PV system. The yellow arrows indicate the additional factors that are relevant for the environmental impact of electricity produced by PV. A similar figure is valid for other optoelectronic devices.

More specific objectives of this ERP are to develop a more basic understanding of relevant degradation mechanisms at (1) the interfaces of and within the active and functional layer materials (CIGS, PSC, cSi, sensor materials), of (2) the flexible / ductile electrical interconnects (PV, device applications for medical and healthcare) and of (3) the encapsulation material after exposure to selected accelerated stress conditions. This basic understanding will facilitate smarter choices of encapsulation (cost effective / fit to purpose / flexible / designed for disassembly) and integration. A TNO position paper is written concerning sustainability and circularity of integrated PV and other optoelectronic devices, connecting to the European actions on Ecolabeling.

Research line 1: Reliability
The qualification and attractiveness of a solar panel or optoelectronic device is primarily determined by its performance, costs and lifetime. Any product will be exposed in its operational lifetime to external stresses like humidity, temperature, mechanical deformations, chemicals, electric currents, radiation, hail storms, wind forces etc. which will lead to a gradual decrease of the performance and in some cases to (unexpected) catastrophic failures. It is evident that it is desirable to minimize the degradation as much as possible and even more important, to be able to predict degradation phenomena so that measures can be taken before the product fails. It will also enable a more accurate description of the expected service life of the product.
Hence, in this ERP the long term goal is to be able to predict and prevent the occurrence of small and large failures in (integrated) optoelectronic devices. This will enable a decrease of the degradation rate and an increase of the lifetime. This will be reached by:

- A more **fundamental physical and chemical understanding** of failure mechanisms by performing post-mortem analysis for selected cases. This will lead to understanding how failures initiate and propagate in material stacks. Special attention will be on vulnerable spots such as interfaces where components are joined and different materials are combined. Both quantitative and qualitative schemes describing the mechanisms will be presented. The knowledge will be used by colleagues and customers to develop **novel materials- and process solutions to improve reliability and durability**, thereby strengthening TNO's technology proposition in PV and flexible electronics (i.e. product, enabler, service) and increasing market impact in specific domains of device integration.

- The development of **accelerated test protocols** for new types of flexible or rigid 3D-shaped devices in emerging application areas (like BIPV, Infrastructure Integrated PV, PV on water, Mobile PV, flexible sensor arrays and devices with stretchable interconnects) based on the fundamental understanding of material and interface degradation with results that can be translated into real life performance predictions. Special attention will be given to post-mortem analysis of devices that have failed under actual field conditions.
- A further strengthening of our image as an internationally recognized institute in this field of research and our position as partner in new joined commercial and scientific projects by playing a prominent role in international task forces and platforms like PVQAT, IEA PV task 13, ETIP-PV, PV-EERA for PV, and Photonics21, OE-A and EMIRI for flexible electronics.

Research line 2: Sustainability

The large scale introduction of photovoltaics and other optoelectronic devices should have a minimal environmental impact. This is important in the production process (carbon footprint, scarce materials), during the functional product lifetime, but certainly also after decommissioning. The large scale recycling of PV modules will therefore become important within the coming decades. The potential market size for PV module recycling is estimated to be 15 billion dollars in 2050. As large scale PV production just started in the last decade, and product life time is typically 2-3 decades, PV recycling has not yet developed to an economic scale. However, recyclability and separation of waste streams is already an issue, especially when the PV is integrated into products, construction components and buildings.

Goal of this (rather exploratory) ERP research line is to position TNO in this field and to identify strategic opportunities where TNO could make an impact. In order to address circular economy aspects and reduce the environmental footprint of (integrated) PV and other optoelectronic devices, in the first two years of this ERP the contours of a long term TNO strategy for sustainability have therefore been drawn by identifying the key drivers, opportunities and market chances with the aim to initiate a separate R&D program for this theme. The direction chosen is to connect to the European actions on Ecolabeling, and to explore promising routes for design for disassembly of (integrated) PV devices. In the current year 2021, a TNO position paper will be issued on the basis of a literature study in which market and technology development, as well as Dutch and EU policy and regulatory framework are assessed. We will present this position paper not only by using international platforms like IEA PV Task 12 (where TNO is already actively participating), and in national PV consortia and media, but we will also condense it to a short video. In the current and next year of this ERP, prospective Life Cycle Analysis for specific examples of PV devices (thin film CIGS and PSC) is explored to assess more sustainable new and future PV designs, and scenarios for zero environmental impact in PV lifetime are studied.

- **Research plan**

All work in this project is executed to establish and demonstrate the innovative approach schematically shown in Figure 2. By the determination of failure mechanisms occurring in field- as well as lab-tested devices through an innovative method for post mortem analysis (“coring”) relevant in situ test methods and new optimized designs for integration can be obtained. For this, we:

1. Execute **post-mortem analyses** for degraded commercial and in-house produced products in order to find the bottlenecks in degraded devices. (Focus 2021: “coring” method standardized by improved tooling; analyze larger batches for more statistics).
2. Obtain a detailed insight leading to detailed phenomenological description (Focus: shading, PID, diffusion, mech. stress)
3. Define the critical interfaces, for example between the device and the outside world, or inside the device. Identify the failure mechanisms through controlled (in situ) testing. (Focus 2021: embedded sensors; testing under electrical/mechanical load)

4. Verify failure mechanism with dedicated test samples and propose improvements. (Focus: barrier/passivation layers; design)

The focus lies on failures that are related to **PV active layers, (inter)connection technology and interfaces.** Many of these effects are generic and allow for a maximum synergy between the different PV and (opto-) electronic technology lines.

Process development is excluded from the project and will be done in other projects. However, results and knowledge from this project can directly be used to obtain material designs and process flows optimized for reliability.

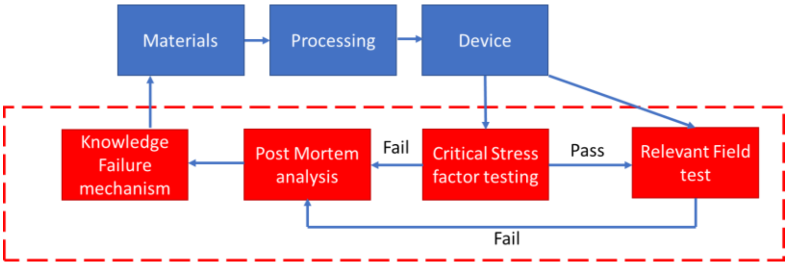


Figure 10: The scope of this project is displayed in the red blocks. Parallel activities within TNO focus on the production of layers and devices. In this ERP, we study these devices as well as already existing products for their intrinsic (material related) and extrinsic (device and environment related) stability and reliability.

- **Targeted partnerships**

The TNO teams involved in this project are those of TNO Solliance (STA), Solar Energy Petten (SE), Holst Centre, MAS, and TNO Circular Economy (CAS). Participating universities are TUD (2 PhD's on partial shadowing), RU (1 PhD active on circularity), UT (1 Postdoc on post mortem analysis), TUE (1 PhD active on CIGS field performance, 1 PhD on PSC stability), Nantes (F) (CIGS degradation) and HELMO (B) (1 researcher active on circularity for IIPV). The project combines the knowledge on PV with available strengths of TNO in the specific areas of integration (Building-, Road and infrastructure-, Agriculture-, Maritime-related demands) and TNO Circular Economy for the Sustainability topic. This provides a unique position for TNO to generate more insight in required specifications for PV lifetime and performance testing conditions, and to develop smarter integration strategies. Moreover, company partners of these groups are involved.

Results 2021 and plan year 2022

3. Results 2021

- **Results achieved in previous Full ERP year(s)**

In this phase, the sampling methodology by coring was made more reproducible, and continuous spatially resolved monitoring by Fiber Bragg sensors was added. These methods are used to study reliability and lifetime in specific integrated applications (partial shadowing, mechanical stress) and in improved design concepts (encapsulants designed for disassembly or temperature control). Deeper insight is obtained in the relation between on the one hand reliability and lifetime, and on the other hand sustainability and circularity, based on explorations in Progressive Life Cycle Analysis, end of life scenarios, and a combined study to come to a TNO position paper on PV Sustainability. Even more than was expected or foreseen, this ERP addresses a societal and political issue that is rapidly gaining attention: PV is renewable, but has to become more sustainable. As one of the consequences, predictable lifetime under novel device- and integration conditions is gaining importance.

Research Line 1: Reliability

- In 2021, the developed *Coring* and *Delamination* techniques have been applied on a number of PV modules. Based on our extensive studies of full scale modules, we have identified the three main degradation mechanisms that can occur in CIGS PV: Humidity ingression, Potential Induced Degradation and the impact of partial shading. On these three topics, manuscripts are currently submitted for publication, or being written. PhD on partial shading is writing thesis;
- In order to identify the (external) stresses on a module, *Fiber Bragg sensors* were introduced. These wires of 200 mm diameter can measure both mechanical stresses and temperature and can be fully integrated into PV modules. In collaboration with Hasselt University, we have successfully integrated a temperature sensor between two glass plates. These sensors have a high and real-time sensitivity, and are virtually invisible, also in IR (Figure x). Next step will be integration in several PV test modules.

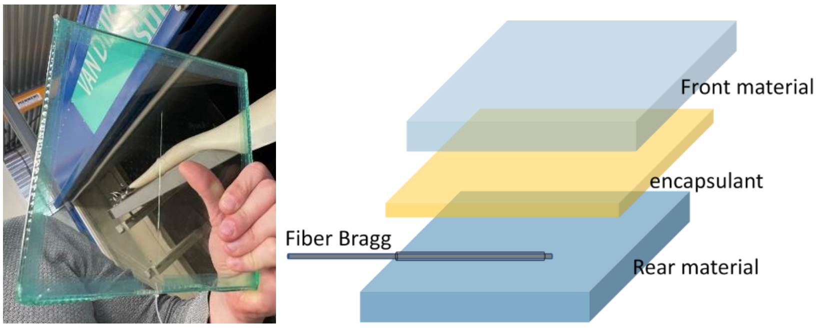


Figure 11

- Positioning of TNO in the field not only through publications but also through invited lectures, co-organizing and chair MRS Spring Meeting 2021, co-organizing IEEE PVSC 2021, and scientific committee and chair EU PVSEC 2021 (all by lead scientist).
- In 2021, the reliability of a series of bifacial glass glass based c-Silicon laminates has been investigated by exposing these laminates to a variety of stress conditions like T, Light and PID. Three different types of commercial encapsulants nature have been applied, failure modes have been identified and are dependent on the chemical nature of the encapsulant. Post Mortem analysis using the coring method is used to investigate the degradation mechanism. It is planned to write a publication on this topic. In the research towards manufacturing modules that are designed for recycling, a novel release encapsulant was provided and integrated in the aforementioned bifacial glass based laminates. Work is in progress to develop methods that will lead to fast disassembly after their operational life while maintaining long term reliability at critical stress conditions.
- Based on the knowledge gained in 2020 of failure mechanisms of stretchable interconnects and modeling of localized deformation of printed conductive lines, we formulated design rules for devices. In 2021 we validate these integrated devices by means of reliability during controlled and repetitive strain applications (Figure). Next we increase the complexity level to study the mechanical reliability of hybrid stretchable interconnects, i.e. understanding effects of electrical functionality when bonding components on stretchable interconnects. By the end of 2021 we expect knowledge to deliver design rules for stretchable hybrid interconnects.

Figure 12

Research Line 2: Sustainability

- Prospective LCA and End of life scenarios of Perovskite solar cells has been performed on the basis of in-house data on production of PSC laminates, including prospective elements for upscaling of production. The use-phase has been modelled for xSi/PSC tandems, including sensitivity analysis for stress factors. Several end of life scenarios for recovery of critical materials are included. Also,

a comparative LCA study has been started to compare CIGS BIPV with conventional building added PV modules.
- The TNO position paper on PV Sustainability is in concept phase, and will be made public this year. It is written in a collaboration between ET, SE and CEE.

4. Plan year 2022

- **Focus Year 2022**

This will be the fourth year of this ERP, and the developed methodologies will be put to work in the most relevant identified applications to fully demonstrate their market potential. Focus will be on the prioritized markets of the TNO Solar roadmap: Tandems, Mass customisation, and Field testing (BIPV, Floating PV, and IIPV) supported by roadmaps of CEE and Holst. For these markets, concrete acquisitions are ongoing that include validation of his ERP (HER, DEI, Groeifonds, EU, MOOI, B2B). More specifically, partial shading will be focused on PV tandems with Perovskite, Coring will be applied to assess lifetime of flexible CIGS laminates as used for mass customisation, and the FB-sensors will be used to demonstrate combined stress monitoring in outdoor field testing for BIPV (Sunovate), IIPV (Rolling Solar) and floating solar. Gained insights and methods for stretchable interconnects (Holst) will be applied in mass customisation of laminates. The program line Sustainability will compare LCA's of BIPV roofs with standard modules on roofs, and also of floating solar with solar on land. Available results from prospective LCA of CIGS will be made accessible through a software tool that predicts carbon footprint of CIGS device stacks.

- **Activities Year 2022**

<u>Research Line 1: Reliability</u>

- Until now, the *coring and peeling* procedures were only used on rigid thin film PV modules, since these are the most dominant on the market. These modules allowed us to study the impact of a decade of outdoor exposure effects and find the relevant degradation mechanisms. However, current market development point at the crucial role of thin film PV based on flexible substrates, like metals and polymers. These substrates also allow the integration of PV in a wide range of novel applications, like road elements, curved guardrails and corrugated roof tiles. On top of the earlier identified degradation mechanisms, these new combinations will introduce new (combined) stress loads. In 2022, we will take the step from mass produced rigid thin film to flexible thin film PV products, and perform coring and peeling on lab- and test field- exposed samples developed to be produced by mass customization. Multiple stress monitoring will be performed during both lab and field exposure tests, using also the developed FiberBragg sensor technology.
- Degradation behaviour of Perovskite based tandem devices will be studied under partial shadowing conditions, utilizing the insights and methods obtained in this ERP on CIGS partial shadowing. As high efficiency tandem cells will find their first application in areas where surface area is scarce, partial shadowing will be an important aspect which is still unexplored, and where TNO is in the rather unique position to perform this novel research because we can generate Perovskite sample modules in house.
- Novel release encapsulant will be applied in laminates based on novel types of bifacial X-Si solar cells and perovskite based tandems designed for recycling. The laminates will be exposed to critical stress conditions and in case of failures, postmortem analyses will be carried out to reveal the failure mechanisms. Dismantling methods will be explored and optimized to separate the module into its loose components.

- FiberBragg sensors will be integrated in small and full-sized x-Si based modules for in-situ analysis of mechanical strains and stress in accelerated mechanical lab testing and outdoor fieldlab tests. This should lead to valuable information input for the design of relevant accelerated lifetime test.
- Post mortem analysis will be carried out on degraded modules from various fieldlab tests in different application domains form the TNO roadmap ((offshore) Floating PV, II2PV, BIPV, ..)
- Based on the generated knowhow of stretchable interconnect testing, and on the developed set of design rules for printing flexible and stretchable (hybrid) interconnects, we will in 2022 apply the knowledge for a specific use-case: integration of flexible solar panels in roof-tiles. The approach will follow three main steps:
    1. Evaluation of the required stretch for the interconnects between the PV-units in the flexible solar panel, and for the interconnects between two solar panels.
    2. Design of the interconnects, based on the requirements defined in #1 and the developed design rules in the ERP project.
    3. Verification of the mechanical reliability and electrical functionality for one of the interconnect-designs in #2 using printed stretchable foils.

    Our main researcher in this project will retire by the end of 2021. If we experience a delay in appointing a successor, described work tasks might be affected.

Research Line 2: Sustainability

- Consistent technology and background scenarios will be included in the comparative LCA for BIPV and floating PV, and sweet spots for further research will be identified. The consistency of the developed prospective LCA approach for PV elements and their integrated use will be checked and further secured. A publication on prospective LCA of PSC in perovskite/Si tandem application will be prepared, and results of carbon footprint prediction as a function of chosen CIGS stack configurations will be made available by a software tool and publication. On these LCA topics collaboration with TU/e will be started (at least one student for the first half of 2022). Also CEE seeks to exploit the expertise built up in this ERP for further development and collaborations on novel methodologies for system analysis of the transition towards sustainability and circularity, where PV is recognized as a very relevant business case for its roadmap.

- **Deliverables Year 2022**

Nr.	Milestones and results 2022	Deadline (owner)
Research Line 1: Reliability		
1	PhD with TUD on reverse bias in perovskite solar cells: setup completed and first curve measured	M5 (STA&SE)
	PhD with TUD on reverse bias on perovskite solar cells: First report on composition impact	M12 (STA&SE)
2	Controlled coring of flexible CIGS modules demonstrated and operational	M3 (STA)
3	FiberBragg sensors for in-situ analysis of performance and mechanical stress installed in CIGS flexible and x-Si PV modules in accelerated mechanical lab testing operational and first results	M6 (STA, SE)
4	Impact of composition on Perovskite stability	M8 (STA)
5	Fiber Bragg integrated in x-Si module	M3 (STA)

6	Report describing an assessment of the reliability and dismantling of bifacial x-Si modules and perovskite based tandems containing a release encapsulant and designed for recycling	M12 (SE)
7	Report: Evaluation and design of stretchable interconnects within and between flexible PV panels for solar roof-tile application	M8 (Holst)
8	FiberBragg sensors for in-situ analysis of performance, mechanics and temperature on PV modules installed in Outdoor Field Labs for Floating Solar operational and first results	M12 (SE)
	Report: Verification of the mechanical reliability and electrical functionality of designed stretchable interconnect for solar roof-tile application	M12 (Holst)
Research Line 2: Sustainability		
9	Report/publication LCA impact assessment on integrated thin film PV	M12 (CAS)
10	Software tool/Paper CIGS stack carbon footprint	M9 (CAS)

Nr.	Planned reports, papers, conference presentations	
1	At least 8 scientific publications (5 STA, 1 SE, 1 CAS, 1 Holst)	(ALL)
2	6 presentations at seminars and conferences (3 STA, 1 SE, 2 Holst)	(ALL)
3	At least 1 organized symposium at international conferences (1 STA)	(STA)
4	Patents: 1 Holst	(Holst)
5	Thesis of PhD (at TUD) on CIGS partial shadowing (Klaas Bakker)	(STA)
6	Writing ERC Starting Grant Proposal (submission Q1 2023)	M12 (STA)

6: Large-Area Ultrasound: making medical imaging safe and affordable

ERP Contacts: G. Gelinck (Project Lead), P. van Neer (Lead Scientist), C. Hooijer (Science Director)
ERP Duration: 2019 – 2022

Overall program description

1. Context and Objectives

- **Problem definition**

Medical 3D ultrasound is the fastest growing medical imaging modality. Typically, echography (using the reflections of high-frequency sound waves to construct an image of a body organ (a sonogram) is performed in clinical settings, where a skilled sonographer correctly positions and orients an ultrasound probe on the body, and interprets the images. But since it does not need ionizing radiation (like X-ray and CT) it can potentially also be used to image outside of the radiology department of a hospital. Ultrasound is in fact the only suitable imaging technique for this; it provides real-time images of the body at high speed, where necessary directly at the bedside, is relatively inexpensive and does not burden the patient. The current first-generation point-of-care ultrasound (POCUS) transducers, for example, connect directly to a mobile phone and thus represent a huge potential for diagnostics in primary care.

3D ultrasound images require a 2D transducer array that can steer an ultrasound beam in two dimensions. Image quality, in particular the lateral resolution, can be shown to improve number and pitch of the elements. Field-of-view scales with the effective size of the array and makes it simpler to image large organs. With the incumbent (bulk piezo) as well as upcoming PMUT and CMUT ultrasound technology, increasing the size of the ultrasound array comes with a serious cost penalty. Currently, there is no ultrasound technology that can scale cost effectively to large size (> 20 cm^2).

A transition from a hand-held probe to a (hands-free) patch that can be attached to the skin enables continuous home monitoring as well as advanced imaging in secondary and tertiary care for better diagnosis. Such a patch should be comfortable to wear and thus be compact and light-weight. Good image quality requires good ('acoustic') contact between the ultrasound array and the skin at all times. Meeting these requirements is highly challenging for conventional (rigid and bulky) ultrasound arrays: with increasing array size the force needed to ensure good physical contact with the skin would increase to intolerable levels. This issue is solved when the ultrasound arrays are not rigid but mechanically flexible, so that it can follow the contours of the skin and the body movements during monitoring. Currently, the technology to realize flexible (large area) ultrasound patches does not exist.

In this ERP we develop large area ultrasound technology that is mechanically flexible and can be integrated in skin patches.

- **Expected impact to stakeholders**

The developed technology will be used for early diagnosis and prediction of disease progression to support timely and less invasive intervention, improving patient outcome and quality of life, while reducing hospital stays. More specifically, we focus on imaging the carotid artery and the heart as here our proposed technology promises a wealth of diagnostic information that is not yet available with which individual risk scores can be determined for an improved patient-specific treatment, which also results in a strong cost reduction in all lines of care. Detection of vulnerable plaques with 3D ultrasound, for instance, can lead to 4,000 fewer deaths and 400M$ in healthcare costs in the US alone.

In 2019, the ultrasound sensing module industry, with Philips and its (former) subsidiaries being one of the top-5 medical players, was an impressive market of US$4.6 billion (Yole report). The industry is expected to grow to US$6.2 billion at 2025 with a 5.1% CAGR. This market is a mix of applications, ranging from those that have reached a certain threshold of maturity, to others that are emerging with growth opportunities. Consumer and medical applications start to use CMUT and PMUT and grow two times faster offering new market opportunities. As analyzed by Yole’s team in the 2020 Ultrasound Sensing Technologies report, most of these new opportunities are due to developments in ultrasound micro-technologies. This has spurred significant financial investment in ultrasound start-ups, especially in the US. Expert studies predict that new ultrasound innovations could lead to a 10-50 times higher use of ultrasound for early disease detection and patient monitoring.

2. Approach

- **Focus**

The main objective of this ERP is to develop a cost-effective large-area ultrasound technology. The large size of the 2D arrays will lead to much larger field of view (making it simpler to image large organs such as the carotid and the heart). In the form of a skin patch, it enables hands-free measurements, which allows continuous monitoring of bodily functions. Leading use casus focus on the carotid artery (short term) and the heart (long term).

- **Research plan**

Medical experts have confirmed the need for large-area ultrasound and wearable ultrasound, and they explained to us that we have a long journey ahead of us. Other groups are pursuing large-area ultrasound as well, albeit with different fabrication techniques.

We therefore need to validate our technology in at least one relevant use case as quickly as possible. We aim to do this together with a partner who is in need of a (cost)effective and accurate system to detect and diagnose vulnerable atherosclerotic plaques using 3D elastography. Today, the associated manufacturing cost of such a transducer and required electronics are prohibitively high, so much so that the technique is out of reach to all but the most well equipped medical centres in the Western world. Furthermore, current transducers are rigid, leading to problems with very large apertures in terms of the acoustic coupling to the neck. We want to be the first in the world to demonstrate imaging with a flexible large-area 2D array to establish our reputation.

We continue to work with companies such to integrate ceramic piezo’s in skin patches. Irrespective of the ultrasound array technology, each piezo array is driven by a block with CMOS logic, analog reading circuit and high-voltage transistors for the emission. The process challenge is to integrate all these components on a (single) flexible substrate and thus maintain sufficient mechanical flexibility. In 2022 we will integrate our polymer transducers in (mechanically functional) skin patches as well, and compare the flexibility to that of the MUT tiling approach. We will investigate the acoustic performance of polymer transducers ((single elements and/or 1D array) whilst the device is being worn.

Entering the fourth and final year of this ERP, we come back to one of the original ideas of this ERP: the monolithic approach of flexible polymer transducers with flexible thin-film transistors to monitor the cardiac output of the heart using a 10x10 cm^2 sized array in a skin patch. Though very relevant (if not the most relevant!), this use case is also the most complex and therefore still relatively long-term. The polymer transducer-on-TFT approach is advantageous in terms of final footprint and convenient to manufacture. One main research question that will be addressed in 2022 is how to partition the electronics, i.e. which blocks can be made using TFTs without sacrificing performance, and which blocks will be CMOS-based, to address all >100.000 elements in the array individually. We do this together with the TU/e, as part of an NWO-TTW project Smart Sense. The required frequency to monitor the heart is 3.5 MHz (that of the carotid is 7 MHz). In 2022 we will develop the technology and realize the first 3.5 MHz transducers. This work will continue after 2022, most likely funded via public-private projects.

- **Targeted partnerships**

We are actively looking for strategic partners in medical ultrasound domain, both in academia and industry. Through previous and current collaboration in funded and industrial projects, we have established a close relationship with a number of renowned parties in the medical imaging domain. Through PENTA/EU project ULIMPIA we team up with TU Delft and Philips on wearable ultrasound patches based on Philips' CMUT technology. We have an active collaboration in place (NOW-TTW, 2 PhD's) with TU/e with expertise on mixed-signal circuit design for flexible electronics. We submitted a project proposal to the Wellcome Trust together with Radboud UMC. Prof. de Korte is leading the NWO-Perspectief program on new 3D ultrasound techniques to improve the diagnosis of vascular diseases (Ultra-X-Treme). We intend to engage with partners in Holst Centre's ecosystem on patch integration and acoustic coupling layers.

Finally, it is worthwhile mentioning:

- As part of a large Dutch US consortium we submitted a Gravity project proposal 'EveryWEAR' that aims to develop wearable ultrasound systems. When granted, six PhDs will be supervised by Gerwin Gelinck (via his affiliation with the TU/e) and Paul van Neer (via his affiliation with TU Delft) to work on our polymer transducer technology. At the time of writing, the project is under review after a receiving a positive evaluation in the first round.
- Point-of-care and home monitoring applications by ultrasound are integral part of the Groeifonds proposal MedTech (currently in preparation; prof. de Korte is coordinating the proposed US activities within this proposal).

Results 2021 and plan year 2022

3. Results 2021

- **Results achieved in previous Full ERP year(s)**

The first phase of this ERP (2019-2020) is best described as 'proof of concept of the polymer ultrasound technology'. In 2019 we selected the optimal transducer principle (thickness mode). We filed one base patent on the novel transducer structure and fabrication process and filed 5 more patent applications. We developed a unique process for fabrication of flexible thin-film ultrasound arrays, resulting in demonstration of the first printed single-element transducer operating in a medically relevant frequency range (between 2-10 MHz). We extended our simulation framework from discrete element in air to arrays in water.

By the end of 2021, we expect the following results:

- Performance of polymer transducers and readout improved by factor 4000 since Jan. 2020, to the level required for medical imaging.
- Design and realization of a 128-channel flexible linear array.
- First dynamic images of the array with interface to commercial ultrasound system.
- First mechanical and functional prototype(s) of wearable patch using both bulk piezo and CMUT components.
- Patch design and materials selection for PZT patches aimed for 72 h wear time.
- 5 more patent intakes on technology, device, system and application aspects of large-area ultrasound imaging systems.

4. Plan year 2022

- **Focus Year 2022**

See section 2 Research plan.

- **Activities & Deliverables Year 2022**

Internal reports

- Status update polymer transducer technology for carotid artery imaging (report, M6 and M12).
- Patch design rules regarding wear comfort, usability and imaging robustness for the two uses cases (Fig. 3) (report, M9).
- Design strategy for electrical routing (report, M8)

Demonstrators/proof-of-concept

- Design and characterization of quasi 2D array for carotid artery imaging using polymer transducer technology (and ideas for further integration). (report, M6)
- In cooperation with a partner validation of our technology for the use case of improved vulnerable atherosclerotic detection in the carotid artery using 3D elastography (report, M12)
- Functional patch demonstrator, (in collaboration with Philips; details under discussion with Philips).

Output

- >2 contributions to scientific conferences
- >3 patent filings and at least three more 3 patent intakes

Business development and plan for continuation in 2023 and beyond

The plan is to include the ultrasound technologies and proposition(s) developed in this programme in the 3F roadmap in the domain of wearable medical devices, for imaging and monitoring. In the course of 2022 the market communication and business development activities (towards PPP, EU projects, B2B) will be geared up to attract new funding from various sources. Welcome trust (pending decision) and Groeifonds MedTechNL (pending submission Oct. 2021) are the first examples, as well as continuation of the Philips B2B work in 2022.

7: Appl.AI (HybridAI)

ERP Contacts: J. Dijk (Project Lead), A. Huizing, C. Veenman (Lead Scientists), H.-J. van Veen (Science Director)
ERP Duration: 2019 – 2022

Overall program description

1. Context and Objectives

- **Problem definition**

Artificial Intelligence (AI) offers an enormous economic potential in terms of improving the effectiveness and efficiency of products and services for governments and companies, but also in finding solutions to grand societal challenges such as climate change and healthcare for an ageing population [9]. In recent years, AI has achieved remarkable success in specialized tasks such as speech recognition, machine translation, the detection of tumours in medical images, and the prediction of the 3D-structure of a protein from its amino acid sequence. Despite these successes there are also some clear signs of the limitations of current AI in real-world applications. For example, biases in AI-enabled face recognition and fraud prevention have shown that prejudice in AI systems is an actual problem that must be solved. Furthermore, accidents with self-driving vehicles demonstrate that AI cannot yet be trusted in safety-critical applications.

- **Expected impact to stakeholders**

Adaptive AI that adjusts itself during operations to different environments, purposes, risks, and team compositions will generally perform better and more efficiently than fixed and rigid AI that does not adapt itself. However, the drawback of adaptivity during operations is that the behaviour of an adaptive AI system is difficult to direct, predict and explain to the user. Directability, predictability and explainability of the behaviour of an AI system is crucial for building trust of users of an AI system. This is particularly the case for high-risk applications of AI systems where errors may have a big impact on people's lives, livelihoods, and fundamental rights. This need for trustworthiness has been recognized in Europe by the High-Level Expert Group (HLEG) on AI in the ethics guidelines for trustworthy AI that were published in 2019.Owing to the tremendous progress in recent years, Artificial Intelligence (AI) is now a major field of investment for governments, research institutions and companies with a total global corporate investment of more than USD 67.9 billion in 2020. This is also the case in the Netherlands, where organizations such as the Innovation Centre for AI (ICAI) and public-private partnerships such as the Netherlands AI Coalition (NL AIC) profile themselves with their specific instruments and programs. Recently, the Dutch government decided to reserve a budget of € 276 million for phase 1 of the AINED strategic investment program from the national growth fund.

2. Approach

- **Focus**

The long-term objective of the Appl.AI program is to improve AI by research and development along four dimensions:

- Purpose: from single-purpose systems to systems that can be used for multiple purposes,
- Environment: from operations in a controlled environment to operations in an open world,

- Risk: from applications where the risk of harm to human lives and livelihoods, and infringements of fundamental rights is low to applications where this risk is high,
- Collaboration: from acting as a stand-alone tool to collaboration in a team.

From this general direction in four dimensions, AI characteristics need to be identified that make the long-term objective achievable. To enable operations in an open environment an AI system should be able to adapt to changing environmental conditions and unexpected situations. Furthermore, AI systems should be able to adapt to different user requirements and purposes without a major redesign effort. In addition, AI systems must be able to assess and manage risks in complex dynamic situations. Finally, the transition from stand-alone operations to operations in a team also requires a capability to adapt to different team compositions. These trends are shown in Figure 14.

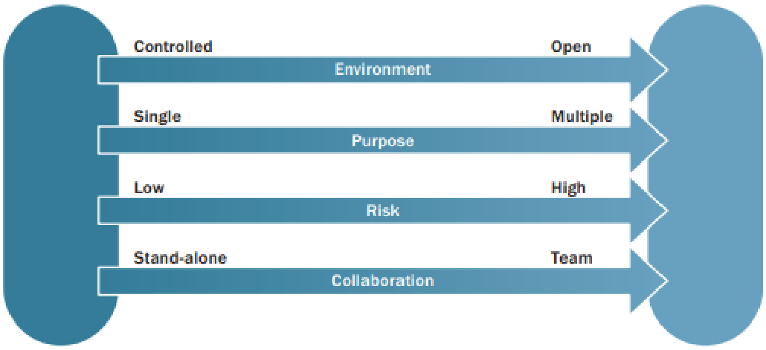


Figure 13: AI research direction along four dimensions

To pursue the long-term objective of the Appl.AI program a Research Strategy with three roadmaps has been defined that jointly develop, integrate, and demonstrate capabilities for Trustworthy Adaptive AI for 2022-2032 with the following roadmaps:

- *Roadmap Autonomous Systems:*
  In situations that are dangerous for humans or critical with respect to reaction time, AI should enable autonomous systems to conduct safely and effectively tasks without frequent intervention by a human operator. The roadmap Autonomous Systems defines AI capabilities that are needed for autonomous navigation, information collection, physical intervention, and collaboration in a system of autonomous systems.
- *Roadmap Federated Decision Making:*
  Humans can benefit from supportive tools in decision making for complex tasks. These systems can learn continuously and concurrently from and with various types of users. Federation enables the users to remain in control, responsible and diverse.
- *Roadmap AI Systems Engineering & Lifecycle Management:*
  Systems and software engineering methods as well as system governance or lifecycle management principles that have been developed for conventional systems cannot deal with the differences and especially the risks of AI-based systems that contain data-driven or self-learning components during operations. The roadmap AI Lifecycle Management defines capabilities that are needed to build and govern trustworthy AI systems that are model-based, data-driven, self-adaptive, or part of a system of AI systems.

To sharpen the roadmaps, all units have been consulted and several experts have been asked to provide their input directly. The roadmaps were also presented in a TNO-wide lunch colloquium and discussed with the external Appl.AI scientific advisory board.

The existing ERP Hybrid AI which is the scientific foundation of the Appl.AI program conducts AI research that contributes to the roadmap Autonomous Systems and the roadmap Federated Decision making. The ERP Hybrid AI comprises two integration flagship projects that develop, integrate, and demonstrate hybrid AI capabilities for the first two roadmaps[6]:

[6] The third roadmap will be further worked out as part of the seed ERP, see section 4A

- *SNOW: Safe autonomous system in an open world* (roadmap Autonomous Systems)
  The objectives of the SNOW flagship project are to develop, integrate, demonstrate, and evaluate AI capabilities for self-aware autonomous systems that can navigate and collect information safely and effectively in an open world. Major elements of intelligence required for an autonomous system include an awareness of the situation, an awareness of the preferences of the user, and an awareness of its own capabilities and limitations.
- *FATE: Responsible human-machine teaming in a dynamic world* (roadmap Federated Decision Making)
  The aim of the FATE flagship is to develop an expert assistant that acquires and extends its expertise through continuous learning from multiple potentially confidential and biased (subject) data sources and from human experts who add to and reflect on the AI-outcomes. As such both the system and the user learn from each other through iterative interaction. The resulting classifications, predictions and advices will comply with the applicable fairness principles and will be communicated in an understandable and trustworthy way to the direct stakeholders. Humans can interact with the system in various roles such as a domain researcher, a consultant, or a subject (affected person).

The capabilities developed in these two integration flagships are key for future AI applications in domains such as Health, Mobility, FinTech, Labour/Recruitment, Energy, Justice, Security, and Defence. Within the program several use case projects are executed in which the developed technology can be tested and further developed in real applications, see the Figure .

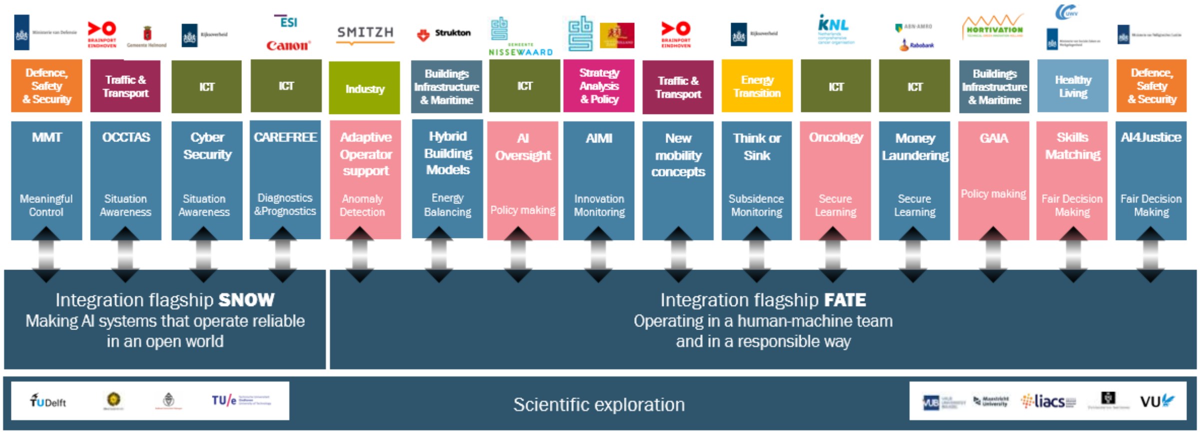


Figure 14: Overview of ERP Appl.AI program including the use cases and their relations to the flagships SNOW & FATE. For the use cases also the main TNO unit and the stakeholders are visualized.

- **Research plan**

Appl.AI program

In 2021 we continued the Appl.AI setup where all central activities with respect to AI are aligned into one program. We have learned that the use cases indeed strengthen the research lines of the flagships and added specific use cases funded by the kickstart means from Economic Affairs in close cooperation with the NL AI Coalition. We expect that the AI proposition of TNO will further improve in 2022 as we since last year articulate what we especially need from new use case proposals through the definition of research white spots for the two flagships.

Flagship SNOW

The integration flagship SNOW focusses on the realization of AI capabilities for autonomous systems so that they can operate in an open world and the integration of these capabilities for autonomous operations by a robotic system. The addressed AI-capabilities are:

- *Situation awareness:* can the system understand, from all that is known, also the part that is still unknown in the current situation, i.e., can it not only recognize novel types of objects but also understand how an object is related to the other objects in its neighbourhood that altogether characterize a situation.
- *User awareness:* does the system understand what behaviour is, in the current situation, expected from it by an operator or other team-mates. And if not, how could the system either acquire such understanding, or otherwise ensure it is not opposing to the user's or team's operational values.
- *Self-awareness:* does the system understand how environmental conditions may affect the accuracy and the results of internal components, and thereby of the task it is executing. And can it assess which component is (partially) responsibly of an underperforming system, even when not all conditions are known.

Flagship FATE

The FATE integration flagship aims to demonstrate capabilities for advising a user in a understandable way in high risk scenarios where multiple confidential databases and suitable expert knowledge are integrated for continuous learning hybrid AI solutions.

These capabilities are implemented in the general architecture of the FATE flagship and researched according to the following research lines:

- *Fair AI*: detection, mitigation, and auditing of bias in AI.
- *Explainable AI*: being able to explain the reasons behind an advice to various user roles.
- *Co-learning*: being able to integrate new (expert) knowledge into the AI-model "on the fly", and to adapt to the local user and the (global) system as a whole to trends in the population of data subjects.
- *Secure learning*: enable proficient handling of (distributed) sensitive data by identifying and assessing potential information leaks and proposing secure-by-design alternatives.

The year 2022 is the fourth year of the ERP Hybrid AI. That means it will be finished at the end of that year.

- **Targeted partnerships**

Applications, partnerships, and collaborations are three main drivers for the Appl.AI program. There are two work packages dedicated to applications and partnerships: scientific exploration and (inter) national collaboration. We work directly with different stakeholders from many domains in the use case projects.

The program has three different advisory boards: a Scientific Advisory Board, the Appl.AI Community consisting of all the stakeholders from the use case projects, and an advisory board with stakeholders from the different Dutch ministries of the Taakgroep TNO. In addition, we have developed and further explore collaborations with external partners such as CBS, Boston Dynamics, Fraunhofer and the Applied Physics Lab of Johns Hopkins University. At the national level, a collaboration is being initiated with the Hybrid Intelligence (HI) NWO gravitation programme to join forces in a HI in Practice (HIP) AINED-funded consortium that should strengthen the Dutch R&D position in this field and advances the application of the R&D outcomes.

Academic collaborations are developed and extended in the Scientific Exploration work package. The objective of this work package is to research concepts, methods and techniques that are needed to achieve the long-term Appl.AI goals. The work package will mostly deliver research papers and fundamental knowledge. The activities are primarily conducted by (associate) professors and PhD researchers. There are currently seven (associate) professors and six PhD students (partly) funded by the Appl.AI program. Several PhD projects are partly funded by two NWO research programs: Efficient Deep Learning and Smart Connected Bikes.

The objective of the (inter)national collaborations project is to identify, setup and work in national and international collaborations. This includes both direct collaboration with peer institutes and working in ecosystems. Through the program in general and this project in particular we want to position TNO as one of the top players in the AI field. We have initiated a joint project with Fraunhofer IOSB on "Value-oriented Design and Enforcement for Responsible Automated Decision Making" and are cooperating with the University of Amsterdam and CWI on Meaningful Control of Autonomous Systems (MCAS). We are pursuing a collaboration with the Applied Physics Lab (APL) of the Johns Hopkins University and participate in an early adopter program instigated by Boston Dynamics for their Spot quadruped robot. Within the Netherlands we work together with partners in the NL-AI Coalition and the NWA. In Europe we are part of the CLAIRE initiative and are partner within the Big Data Value Association (BDVA) and the AI, Data and Robotics association (Adra). We are part of the H2020 projects VISION and TAILOR which aim to build European networks of excellence in AI. Furthermore, we work on standards for AI at the national (NEN) and international level (CLAIRE, DAIRO) by participating in working groups.

Results 2021 and plan year 2022

3. Results 2021

In this chapter the results of 2021 are described. In section A the overall program is presented, in section B and C the flagships SNOW and FATE and their associated use cases, respectively.

- **Results achieved in previous Full ERP year(s)**

Appl.AI Program

Key results on program level for 2021 include contribution to 2 bln national Groeifonds proposal 2021-2027 AINED. TNO is well positioned within the NL AIC for the AINED calls expected in 2022. In 2021 the program was responsible of executing of 3 mln SMO funding by EZK for NL AIC for data sharing and co-financed Appl.AI projects. For the connection of all the unit to the AINED proposal we organized a seed idea contest, in which 10 seed ideas for a small AINED budget were selected.

We delivered the Appl.AI Research Strategy that will align and focus future TNO investments in AI research in the Appl.AI program with the objective of creating a distinctive technology position at TNO that is valuable for TNO's stakeholders and for the TNO units involved themselves. The goal of this research strategy is to develop capabilities for trustworthy adaptive AI systems. Input for the Research Agenda was the unit consultation on Appl.AI that started in 2020 and was also finished in 2021.

We continued the collaboration with Fraunhofer on the topic of 'Value-oriented Design and Enforcement for Responsible Automated Decision Making' and setup a collaboration with the Applied Physics Lab of the Johns Hopkins university.

To inform the TNO AI community, we have a monthly newsletter with more than 200 subscribers and a lunch colloquium on scientific topics. For business developers we developed a general Appl.AI Business Development presentation which was presented in a SAMEN event. We also organize a monthly meeting with Appl.AI unit coordinator and meetings on the developments in the NL AIC with different TNO stakeholders. For communication within TNO and with our stakeholders we also developed a virtual and physical Appl.AI lab to facilitate internal collaboration and external presentation of results.

To strengthen the Appl.AI network outside TNO we organized several online meetings for the Appl.AI Scientific Advisory Board, the Appl.AI Stakeholder Community, and the TNO Taakgroep klankbord. Goal of these meetings was to inform the different stakeholders and to receive their feedback.

Dissemination of the results was done through the TNO website, with on average 4000 visitors of the webpage per month and 75 clicks for contact information, the Appl.AI webinars *AI for Oversight Labs* and *Hybrid Scalable Buildings,* and through media attention for TNO AI work on NOS, Jeugdjournaal, AD, etc. on detection of humans in the water and publications on SPOT robot with autonomous capabilities as developed in SNOW in the Financiële Telegraaf and Elsevier Weekblad.

We are partner in multiple EU projects and proposals such as the VISION and TAILOR projects, in which roadmaps for AI on EU level are drafted and in NWO projects such as the Efficient Deep Learning program and Smart Connected Bikes.

Flagship SNOW

In the SNOW flagship, our integration efforts resulted in a definition of measurable KPIs (key performances indices) by which the level of autonomy of a robotic system can be assessed in experiments. The KPIs of the autonomous system include the operational effectiveness, mission preparation effort, and the number of operator interventions. Furthermore, to test our KPIs, actual experiments on the search and rescue scenario as defined in 2020 were conducted and reported. Next to that, we developed a new scenario that will demonstrate our research developments in 2021. Similar KPI-experiments will be conducted in this new scenario at the end of 2021, with the aim to demonstrate that the hybrid AI software can reduce the number of operator interventions during a search and rescue task with respect to a remotely controlled robot while maintaining the same operational effectiveness or is more effective in a more complex environment.

Our research efforts take place on three different types of awareness that are needed to create autonomous systems. For context awareness three different types of algorithms have been developed: finding objects based on their features, hypothesis testing combined with observations and guided visual questioning and answering. For user awareness a new type of planning procedure is developed: one that is aware of contextual changes and can cope with the uncertainties present in an open world. Also, an interface with semantic preferences is made. For self-awareness different modules are developed that assess the situation and the current performance of the system. Combining those two, I.e., situation and expected performance, this will provide input on which actions could be taken in the current situation.

So far, our tangible results are the following:

- A real-time hybrid AI autonomy stack that integrates sensor data with machine learning and a knowledge graph with symbolic reasoning on a quadruped robot. We demonstrate that the robot can complete a search and assist operation in a house, already with a very limited amount of prior information of the house and its victims.

- Live demonstrations of a search and assist operation for the Royal Netherlands Air Force Council, Royal Netherlands Marechaussee, National Police, Fire brigade Chemelot, and TNO Executive Board;
- Article on measurable KPIs to demonstrate improved autonomy from actual experiments (draft for Science Robotics);
- Article on planning with the Choquet integral to model user preferences (under internal review);
- Articles on the application of knowledge graphs in robotic systems for understanding the situation (submitted to IROS) and for understanding own capabilities (draft for Engineering Application of AI);
- Public articles on autonomous robots (Elsevier weekblad, de Telegraaf, LinkedIn)

The use cases associated with the SNOW flagship project in 2021 are:

- Meaningful human control (DASH): methods and algorithms that enable humans to keep control over autonomous systems.
- OCCTAS: AI algorithms for situational awareness in automated driving for shuttle busses.
- Tax Authority: detection of anomalies in large datasets.
- Carefree: diagnostics of production printers with Bayesian networks.

Flagship FATE

In 2021, the further integration of the four research lines within FATE is one the objectives. This integration is driven by 1) implementing the same use-case and 2) making the viewpoint of the user-role and her demands leading.

The use-case Diabetes Type 2 Onset Prediction (DT2), that started in 2020, has been the integrating use-case for FATE until Q2 this year. After that the use-case AI4Justice (AI4J) has been adopted in the flagship. In this way we were able to test the general applicability of the FATE architecture and to articulate and test the research questions in a completely different data and application domain. The DT2 case had as use-case research question how to predict if a client would develop Diabetes Type 2 in the coming 5 year using large scale population data. The data was tabular/structured and the prediction task was to yes/no develop diabetes type 2 in the coming 5 years including a confidence score and a justification in terms of properties from the client in the database. The demonstrator displays the research lines in the following way:

- Fairness is articulated as equal quality of system functionality for different sociographic subgroups;
- The prediction, hence lifestyle advice, is supported with a visualisation of important lifestyle attributes. The subject (client) user-role is most strongly addressed;
- The system learns from the user (co-learning) and adapts its behaviour when needed;
- Provided user interfaces according to a first set of explanation design patterns.

The use cases associated with the FATE flagship project in 2021 are:

- Hybrid Scalable Buildings: on energy advises for buildings and groups of buildings
- AIMI: on policy making for AI
- Applying AI for new mobility concepts
- Think-or-sink on subsidence modelling
- Secure learning for detection of money laundering
- Applying different AI technologies for justice applications (AI4justice)

Next to that, five use cases are financed by the NL AIC kick-start budget

- Adaptive operator support for smart industry applications
- AI Oversight Lab on developing data-driven policies for municipalities and other government organisations
- Secure learning for Oncology
- GAIA: AI for greenhouse horticulture
- Skills matching: Fair decision making in the job market

The use cases provide a close collaboration with different parties such as Justice, SZW and CBS on topics relevant in their daily practice. Also, cross-domain topics are identified, such as the skills matching application that can also be used in the defence domain.

4. Plan year 2022

In this chapter the plan for 2022 is described. In the first section the overall program is presented, in second and third section the flagships SNOW and FATE and their associated use cases, respectively. In the last section we end with a summary and outlook.

Appl.AI program

- **Focus Year 2022**

The key objectives for 2022 are
- Finalizing the ERP program Hybrid AI.
- Further improving research alignment between flagships and use cases
- Further strengthening the TNO AI community including involvement of all units
- Development of a successor of the Appl.AI program on the topic Trustworthy Adaptive AI for 2023-2026 based on the Appl.AI Research Strategy as a seed ERP funded and performed within the Appl.AI program.

- **Activities Year 2022**

In 2022 we will finish the Hybrid AI ERP, which is the ERP part of Appl.AI, with an external event in the second half of the year for which all different stakeholder groups will be invited. This event will contain sessions for all elements and stakeholder groups of Appl.AI, including separate sessions for the flagships SNOW and FATE.

For the continuation of AI research within TNO we will prepare a new ERP proposal for 2023-2025, based on the Appl.AI Research Strategy. The required activities are similar to those of a seed ERP. The request for the seed ERP will follow the regular process. The activities and the budget are covered by the Appl.AI program. Based on the Appl.AI Research Strategy, choices will be made as to what needs to be developed in the three roadmaps to achieve a world-leading capability, next to capabilities that we need to use or co-develop with partners. Next to that, we will start the first activities on the third roadmap by delivering a report on the state-of-the-art on AI Systems Engineering and Lifecycle Management.

By active engagement within the NL AIC and its eco-system, we will guard the funding of TNO AI through the AINED Groeiplan program and other relevant funding bodies such as at NWO, and the EU. The budgets and instruments are still to be established for the AINED groeiplan. If granted, we should a significant budget to TNO's AI funding in 2022. This potential budget is intended for higher TRL research together with partners that build on top of this ERP and on the roadmaps of the units.

A related activity is the profiling of TNO in different national and international AI communities. We will continue the partnerships with Fraunhofer, CBS and APL and the exploration of other potential partnerships. We will strengthen the relationships with universities, e.g., by close contact with the scientific advisory board, and by development of two ICAI labs together with universities and other stakeholders.

We will develop the different communities further: scientific advisory board, Appl.AI community and TNO Taakgroep Klankbord. On communication level we will organize 3 webinars, and further develop the Appl.AI labs. The labs have a virtual and physical component and can be used to disseminate results and ideas to stakeholders and work together with them. We also plan regular updates of these labs. Within TNO we continue to strengthen the collaboration and communication by newsletters and colloquia. One of the colloquium topics will be the Appl.AI Research Strategy.

- **Deliverables Year 2022**

- Big event on Appl.AI to share the results of the program and for networking
- SEED ERP Trustworthy Adaptive AI deliverables
    a. ERP Program proposal for Trustworthy Adaptive AI
    b. Report on state-of-the-art AI Systems Engineering & Lifecycle Management
- AINED proposals
- communication: 1 TNO event, regular updates website, 3 webinars, a virtual and physical Appl.AI lab, and a monthly newsletter
- Two ICAI labs connected to the flagships SNOW and FATE. See for more information 4B and 4C
- Three EU proposals submitted and granted

Flagship SNOW

- **Focus Year 2022**

The overall goal of the SNOW flagship is to develop, integrate, demonstrate, and evaluate AI capabilities for a self-aware autonomous system that can operate safely and effectively in an open world. The focus in 2022 is on a more profound integration of situation awareness and planning via the topic of goal-directed perception and on the integration of self-awareness and planning via the topic semantic task agreement.

- **Activities Year 2022**

- Research on the topic semantic task agreement
- Developing algorithms for situation awareness, user awareness and self-awareness and planning
- Development of hybrid AI software where the awareness (self and situation) is integrated with automated planning so that uncertainties in an open world are more quickly resolved by the system itself, thereby reducing operator interventions
- Thorough evaluation on the measured level of autonomy by the KPIs on mission preparation effort and user interventions as introduced in 2021.
- Integrating developed algorithms and methods into completely integrated robotic system and performing experiments and demonstrations with this demonstrator, potentially with other parties who also acquired a SPOT robot.
- Developing an ICAI Lab with KMAR, collaboration projects in AINED, and partnerships to evaluate the above results in in practice.

In addition to the generic research in the SNOW flagship project, additional research will be carried out in the Appl.AI program in 2022 in use cases that are connected to the SNOW flagship project. A call for proposals for these use cases, which has been published in the TNO organisation in July 2021, asks for research on topics that are highly relevant for the SNOW flagship project, and for the Appl.AI technology roadmap Autonomous Systems, but have not yet been sufficiently covered. These so-called white spots include [between brackets the capability in the roadmap Autonomous Systems]:

- Symbolic reasoning for context and novel object characterisation [Context Recognition Capability]
- Prior knowledge and user experience for more accurate and more effective plans [Contextual Planning Capability]
- Self-assessment of cause and effect of position uncertainties [Self-Assessment Capability]

- **Deliverables Year 2022**

- Integrated software on self-awareness, situation awareness and integrated planning.
- Report on evaluation of measured level of autonomy by the KPIs.
- An algorithm for goal specification indicating what information should be acquired, and where it might be found, to achieve the intel that was requested
- An algorithm for semantic reasoning and risk-based assessment, e.g., about causation, on whether a task assigned to the robot is achievable and where it should take place
- Live demonstration of the developed methods in a completely integrated robotic system
- Joint experiments with parties who also have acquired a SPOT robot.
- At least four scientific articles on this research
- ICAI lab related to the SNOW research line
- New partnership, e.g., with the national police.

Flagship FATE

- **Focus Year 2022**

The goal of the FATE flagship is to develop, integrate, demonstrate, and evaluate AI capabilities for ongoing --effective, fair, understandable, trustworthy, and secure—interactive decision support. The focus in 2022 is on developing the viewpoints for the different user-roles towards role-based decision support, that is (1) developing the capabilities to continuously mitigate biases, provide secure actionable and fine-tuned explanations and realize effective co-learning, *and* (2) showing the overall progress over time on Key Performance Indicators for the capabilities (such as explainability) and their effects on the collaboration of the user with the AI system. In the current use-case KPIs will demonstrate the effectiveness and efficiency for case law consultations.

- **Activities Year 2022**

- Developing algorithms that can detect and mitigate biases in textual data. These algorithms support these qualifications with explanations differentiated for the three user roles. Additional research activities are devoted to detecting and mitigating bias in existing (third party) algorithms.
- Developing algorithms that explain system outcomes for the three user roles, In case the situation at hand is considered to be outside the operating conditions, also that observation needs explanation. Where possible, the use of causal knowledge is explored to make the system more robust and explainable.
- Developing methods that are able 1) to create models from federated sources, and to do this while the sources themselves are not made public: secure learning, and 2) generating synthetic data to enable algorithm development for cases where confidentiality and trust are at stake. These synthetic data can also be applied in explanations that are based on examples.
- Creation of a system that can adapt its behaviour based on user feedback, where special care is taken that the system will not be operating out of bounds.

- Integrating developed algorithms and methods into a demonstrator, where focus is on demonstrating functionality.
- Developing an ICAI Lab, collaboration projects in AINED, and partnerships to evaluate the above results in in practice.

In addition to the generic research in the FATE flagship project, additional research will be carried out in the Appl.AI program in 2022 in use cases that are connected to the FATE flagship project. A call for proposals for these use cases, which has been published in the TNO organisation in July 2021, asks for research on topics that are highly relevant for the FATE flagship project, and for the Appl.AI technology roadmap Federated Decision Making, but have not yet been sufficiently covered in previous use-cases. These so-called white spots include [between brackets the capability in the roadmap Federated Decision Making]:

- Enhanced support for the role of the domain researcher. [Explaining for user-roles, Causal modelling].
- Testing causal relations between subject properties and the system output or advice. [Causal modelling].
- Creation of synthetic data that can be used to do further analysis with data in the use case itself cannot be shared. [Generating synthetic federated data].
- Adaptation (post-processing) of existing pre-trained models to repair biases, while maintaining or even improving properties required for trustworthy AI. [Debiasing data and models].
- Continuously learning scenarios, where after offering the advice to the user the result is fed back into the database and system models are updated. [Model adaptation].
- Learning advanced scalable models from large confidential databases, where advanced means that expected non-linear models (such tree based or neural nets) are the most suited to make the best models. [Learning secure federated models].

- **Deliverables Year 2022**

- A report on the KPIs for the FATE flagship to make the progress in the above activities measurable
- Software modules on the research topics described above
- Demonstrator of the integrated functionality
- At least four articles on the research activities
- At least one potential partner that will further develop these concepts into a pilot system that can be evaluated in practice.

Summary & outlook

In 2021, the Appl.AI program has expanded its impact in research, strategy, visibility in and outside TNO. Appl.AI yields research results that are in the frontline of the needs according to the EU AI research agenda. In the NL AI coalition Appl.AI is a recognized brand with dedicated Appl.AI use cases funded by the kickstart budget of the AINED program. To align and focus future TNO investments in early AI research even further, the *Appl.AI Research Strategy* has been developed in which technology roadmaps are defined that strengthen each other and point the way ahead for the coming 10-15 years. Based on this research strategy, choices are currently made and will be made to create a distinctive technology position at TNO that is valuable for TNO roadmaps and for the position applied AI of TNO as a whole and outside TNO. With the sharpening of our research focus, the establishing of advisory boards, and building on the results of 2021, our research will be even more guided in 2022 towards clear and impactful milestones.

8: Decarbonisation (BrightSite)

ERP Contacts: P. Winthaegen (Project Lead), A. Dortmans (Lead Scientist), C. Hooijer (Science Director)
ERP Duration: 2019 – 2022

Overall program description

1. Context and Objectives

- **Problem definition**

Accelerated global warming due to the exponentially increased CO_2 emissions in the last 100 years is a global societal challenge. Worldwide, governments and business communities have formulated objectives and measures to limit and reduce the emission of greenhouse gases (GHG). The Dutch government has formulated the ambition to reduce industrial GHG emissions at a national level by 59% by 2030 and by 95% by 2050 compared to 1990 (Klimaatakkoord).

The Dutch chemical sector makes a high contribution (about 60%) to the total national industrial emissions of CO_2 and other GHG such as N_2O. On a regional scale, the chemical industry, located at the Chemelot site near Geleen is responsible for about 30% of the total energy consumption and 30% of the emission of GHG of the Province of Limburg. The overview in Figure shows the current and required development of the GHG emissions at Chemelot. This shows that 2030 reduction targets can be met in principle, but that for 2050 new affordable, safe and acceptable technological options have to be explored and developed.

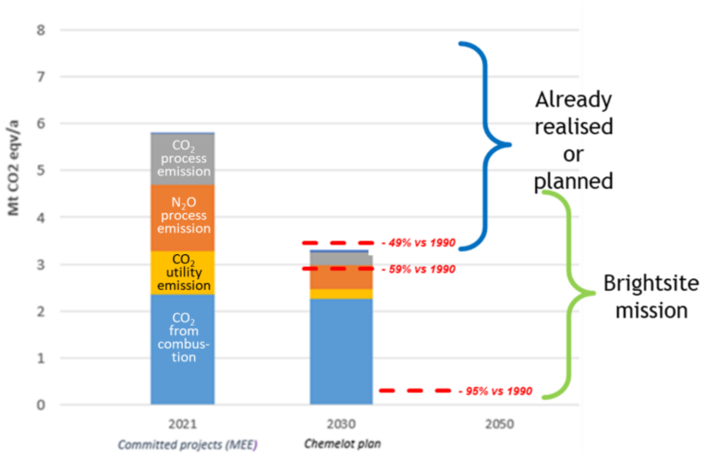


Figure 15: Origin and 2030/50 targets GHG emissions at Chemelot

The ERP Decarbonisation focusses on the exploration and development of these new technological options and is part of the broader "Brightsite" initiative, a shared research centre established in June 2019 by TNO together with Sitech Services, Maastricht University and Brightlands Chemelot Campus. The ERP Decarbonisation provides about 75% of the committed annual TNO contribution to Brightsite of 2,0 MEUR. In the Brightsite program, also contributions from TNO VPs of the contributing units Industry, Energy Transition and Circular Economy & Environment are included to ensure a seamless integration of the ERP-activities in the strategic plan of Brightsite and TNO roadmaps.

Brightsite

Inspired by climate change needs, a multitude of "green" technology options is pursued worldwide by academia, technology institutes and private companies at TRL 1-9, often supported by large scale regional/ national/EU public funding programs. In 2019 a Chemelot system transition study was carried out during the development and start-up phase of Brightsite as part of this ERP. The study concluded that the core of Brightsite should be based on programs on **(1) Electrification**: "*Preventing*

CO_2-emissions related to use of natural gas for heating and production of hydrogen", **(2) Recycling**: "*Replacing fossil carbon and hydrogen by use of (plastic) waste and biomass"* and **(3) Process Innovation**: "*Reducing emissions by increasing process efficiency or new after treatment methods".* These core programs are supported and connected by integral programs on **(4) Safety & Society**: "*Ensuring safe to apply and societally acceptable innovations"*, **(5) Transition Scenarios**: *"Modelling safe, durable and economical transitions to meet 2030/50 climate goals"* and **(6) Education & Human Capital**: "*Empowering a new generations of researchers and work force*".

Following a broader initial orientation phase in 2019-2020, the ERP Decarbonisation contribution has its focus on development of plasma-technology in program 1 and pyrolysis technology in program 2. In addition a new "harnassing complexity" approach is explored in program 3. Previous investments in Program 4 have resulted in a spin-off "safety monitoring tool" which broader market potential is pursued outside of the ERP.

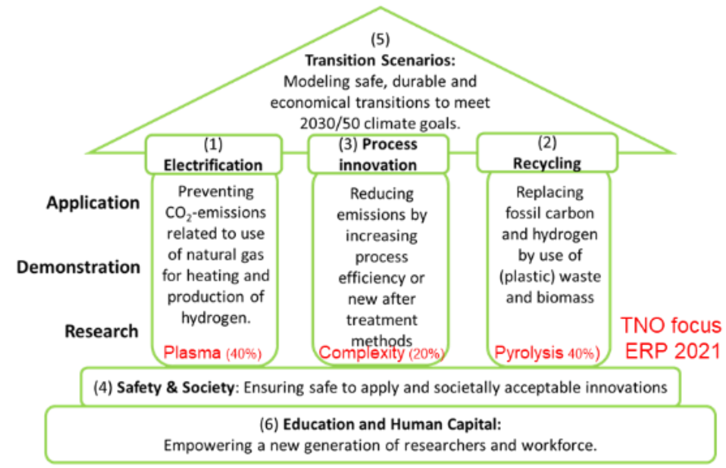


Figure 16: Brightsite program structure and TNO ERP-focus

TNO VP Industrial Transitions provides substantial co-funding for program 5 and program 6 funding is covered by Maastricht University and not further discussed here. Start-up funding of the province of Limburg, TKI-Chemistry and in kind contributions of various Chemelot companies complements the TNO ERP/VP investments, which together meanwhile provided the basis for successful additional funding applications. The 6 programs now firmly constitute the Brightsite program providing TNO and (founding) partners with the perspective of developing a new competitive position for comprehensive consultancy on greenhouse gas driven industrial transitions which can be exploited at inter-national level.

- **Expected impact to stakeholders**

The pursued results of the focus areas in the continuation of ERP-decarbonisation and their embedment in the broader Brightsite-partnership together provide new options for the Dutch chemical industry to meet the 2030/50 emission targets of the national climate agreement. As a result of this the perception of the relevance of possible TNO contributions has been rejuvenated for stakeholders in the chemical technology area and associated industrial, political and societal networks. For the Chemelot region the Brightsite initiative specifically contributes to repel the threat of facing the consequences of another "mine closure" situation when CO_2/N_2O emission targets (and costs) cannot be met in time. When this turns out to be the case this may lead to closure and reallocation of the current production facilities and associated loss of high quality employment and economic value. On the other hand, new market possibilities are emerging for Dutch based OEM's and suppliers of high-tech equipment in the global chemical industry once the proof-of-concept phase for new electrification and recycling technologies has been surpassed. In view of the scale and volume of the operations in this area a multibillion market is to be expected for companies which are able to provide the required equipment in time.

2. Approach

Research Line: Plasma technology

- **Focus**

As depicted in Figure "Electrification" is considered to be one of the main enabling technology pillars for the transition towards a CO_2-emission free future for the chemical industry. Based on the improved overview acquired in the early stage of the ERP on state-of-art, R&D and collaboration possibilities, the choice was made to completely focus on electrification by plasma-technology at the beginning of 2020. Plasma-technology had been identified as an "overlooked" possible way out to overcome technological, economical and societal limitations of CO_2-emission mitigation solutions considered until now at (inter)national scale. Based on review of literature, patent and market data, the possibilities for CO_2-free synergistic production of hydrogen and hydrocarbons and preferably ethylene from methane, was identified as the "holy grail" application in the chemical industry. In this relatively unexplored application field various options exist to establish new IPR-positions based on tailoring plasma-technology for use in industrial size chemical processes.

- **Research plan**

In order to both gain experience on state-of-the-art technology and establish a new (IPR) position in the plasma-chemistry field, a three generation roadmap was defined as a basis for the short, mid and long term R&D approach. The "first generation" oriented activities are based on understanding and identifying possibilities for improvement of a state-of-the- art plasma-arc based industrial process used by the German company Hüls, for a niche-market production of acetylene from methane. For this a bench scale plasma-arc reactor is currently made available by TNO and Sitech, enabling production of hydrogen and acetylene. In parallel a new approach is investigated by TNO to more efficiently convert acetylene into ethylene. Based on the obtained results and insights from literature research, practical experiments and modelling studies a "second generation" upscaled reactor system will be designed and constructed by TNO and Sitech enabling the demonstration of an improved methane to acetylene conversion and possibly formation of other valuable hydrocarbons. The "third generation" approach, mainly executed by academic partners Maastricht University and DIFFER, starts at a lower TRL to identify fundamental possibilities and limitations to obtain single step conversion of methane to ethylene by development of dedicated new versions of (e.g. microwave) plasma-technology.

- **Targeted partnerships**

Clearly much needs to be investigated and done at TRL 1-9 to get the (fundamental) promise of plasma-technology into industrial practice at relevant scale. For this the core of a completely new TNO-UM plasma-chemistry group has been established in the last year and a dedicated joint plasma laboratory will be opened at Chemelot at the end of 2021. Additional national partners from both the chemical (Shell, Dow) and high-tech industry (VDL, Demcon) have meanwhile been invited to join the plasma partnership in view of the emerging application possibilities and global market potential for providing high-tech plasma equipment. This provides the option to maintain and extend the international leading position and economic value of and employment in the Dutch chemical and high-tech industry. To be able to execute the required R&D and to demonstrate the plasma technology at industrial relevant scale, various funding applications have meanwhile been granted (TSE, MOOI) and submitted (Groeifonds).

Research Line: Recycling

- **Focus**

Following a broader initial orientation phase, the ERP-funded efforts in the recycling area are now mainly focused at upgrading the efficiency of use of various polymer containing waste streams by new pre-treatment and improved gasification and liquid phase pyrolysis methods. When successful, this will enable the reduction of use of fossil naphtha as raw material for e.g. the production of ethylene in industrial scale cracking processes such as operated by SABIC at Chemelot. In addition, a feasibility study started in 2020 on the possibilities for conversion/integration of CO_2 (CCU) at Chemelot has nearly been completed. Fundamental research at university of Utrecht on catalytic depolymerisation will be continued from 2021. The aim is to open up new recycle routes in addition to the thermo-chemical recycling routes.

- **Research plan**

Based on initial obtained results the possibilities of a generic new Upwash ® pre-treatment method to purify and upgrade polymer containing waste are investigated for use in existing and new gasification and pyrolysis recycling technologies. In relation to this the possibilities for adaptation of the Milena/Olga gasification technology developed by TNO in the past and marketed by joint-venture Synova at present for conversion of biomass to energy, optimisation of the output composition to the needs of potential users and to ideas for electrification preventing combustion and thus CO_2 production in the unit, are investigated. The leading goal is to find out if it is possible to convert (upgraded) municipal/industrial waste streams into a gaseous mixture which is compatible with the outlet of present industrial naphtha cracker furnaces. In this way the intake of fossil naphtha for polymer production can possibly be reduced significantly. In a parallel research line the possibility to create a polymer waste dispersion which can be mixed with the current 100% naphtha based cracker feed is investigated.

For recycling of CO_2 is clear that it should preferably be used as a carbon building block in production processes which are or can be operated at the same site as where it is produced. Based on the outcome of the recent review study for specific options at Chemelot a choice will be made to pursue this route with main problem owner OCI.

- **Targeted partnerships**

The obtained results and insights have specifically opened up previously closed doors for strategic contacts and discussions with SABIC and several other Chemelot site users. To extend the in-depth knowledge position in the liquid phase pyrolysis area, a partnership with the group of prof. Bert Weckhuysen of Utrecht University was established starting with joint funding of 3 Ph.D. positions to investigate catalytic depolymerisation of polymer waste materials. The agreed program comprises thermo-oxidative degradation of PE to valuable carboxylic acids, developing a supported catalyst for the supercritical solvolysis of PE and Rational design of an impurity-resistant catalyst for solvent-assisted polyolefin cracking. Furthermore, TNO has become involved in setting up a new dedicated polymer recycling technology group at Maastricht University around 2 prof. positions for which key candidates with international recognised positions have been approached and the first has been contracted recently. As a next step setting up of a Brightsite polymer recycling facility at Chemelot is foreseen in analogy to what is realised for plasma-technology.

To boost the ERP-efforts, submissions for execution of additional R&D have been made in the framework of national and European funding frameworks. As a result of this, additional funding was obtained from the national MOOI-program for execution of a national program in which more than 20 public-private are involved. Next to this an initially failed EU-application is prepared to be submitted again.

Research Line: Process Innovation

- **Focus**

In the Brightsite orientation phase, it turned out that the need and interest for reduction of CO_2/N_2O emissions of existing process facilities by longer term technology innovation such as pursued in TNO-ERP, is practically absent at Chemelot stakeholders. In practice, the problem owners only consider implementation of available and proven technology solutions for which a clear positive business case can be calculated. In view of this the ERP-activities in this area have been scaled down and pro-actively focused on areas for which it is expected that industrial interest and partnerships will emerge on longer term, resulting in the start of study investigating options for “harnessing complexity”. This study is aimed at investigation of the possibilities to develop a new generation of AI-based process control to be able to manage the increasing variations in use of green raw materials and energy supply sources to be expected in the near future.

- **Research plan and targeted partnerships**

The next stage of the “harnessing complexity” feasibility study will be oriented on gasification as use case. The research plan and partnerships for the follow up phase will be detailed once the initial results have become available.

Results 2021 and plan year 2022

3. Results 2021

- **Results achieved in previous Full ERP year(s)**

Research Line: Plasma Technology

Main goal for 2021 is to define and build plasma equipment in which the conversion of natural gas towards hydrogen and valuable hydrocarbon compounds - without formation of CO_2 - can be demonstrated at laboratory scale. To achieve this a broader joint Brightsite team with representatives from TNO, Sitech, DIFFER, OCI, SABIC and a dedicated new plasma-chemistry group at Maastricht University has been formed and laboratory and demo scale facilities are established at Chemelot to be able to pursue this route at all relevant TRL. To compliment the TNO-ERP and partner possibilities, successful applications have been made in the framework of national TSE-Industry and MOOI-funding programs, which were granted early 2021 resulting in additional funding of 4,3 M€ for execution of feasibility and R&D projects. Mid-term 2021 a literature, patent, market study regarding state-of-the-art plasma enhanced conversion of methane has been completed. These results have been transferred to choices for processes, feedstock, products and engineering of state-of-the-art (Hüls plasma arc) demonstration scale reactor system (first generation), enabling production of hydrogen and acetylene. Similar choices were made for investigating a process for conversion of acetylene to ethylene in a separate subsequent in-line process. In addition, basic modelling, design and set-up of equipment has been completed for realization of a prototype of second generation (improved Hüls) plasma processing reactor system, enabling more controlled and efficient conversion to acetylene and other (hydro)carbon products. Finally, a feasibility study was initiated aimed at the "holy grail" direct synergistic formation of hydrogen and ethylene in a third generation plasma chemistry reactor system. Collaboration agreements were established with SABIC, OCI, Sitech, Brightlands Chemelot Campus, University Maastricht and DIFFER for execution of TSE-feasibility and MOOI R&D projects. Next to this a first stage proposal for execution of R&D and realisation of demo-facilities has been approved for further detailing as part of a larger scale "Groenvermogen" proposal oriented at production of hydrogen based on green electricity. In addition, the development of plasma-technology equipment is part of more recent "Next Generation High-tech Equipment" and "Green Molecules Green Economy" Groeifonds pre-proposal selected for further detailing. As next step the submission of an EU-proposal together with key international private partners is considered at present.

Research Line: Recycling

The main goal for 2021 is to show the application potential of the conversion technologies that transform plastic waste and CO_2 back to chemicals, that can be used to reduce the overall carbon footprint of industrial production sites such as Chemelot. Mid-term, experimental and possibly patentable results have become available from investigation into application of Upwash® pre-treatment technology on standardized (DKR310) and industrial quality polymer waste samples to upgrade the use for subsequent gasification and pyrolysis recycling steps. Furthermore, conceptual development and detailing of experimental program has been completed to validate practical possibilities of Liquid Phase Pyrolysis® technology, aiming at use of polyethylene/-propylene waste materials to reduce use of fossil feedstock in state-of the-art industrial scale naphtha cracker plants. In addition, a feasibility study has been completed on practical application possibilities for reducing CO_2 emission at Chemelot by off site transport/storage (CCS) or on site conversion (CCU) into hydrocarbon products.
Clear interest and practical steps were made for practical evaluation of Milena Olga gasification technology as marketed by TNO joint venture Synova. A contract agreement was completed with University Utrecht enabling practical start of long term collaboration and joint funding of 3 Ph.D. positions in group of prof. Bert Weckhuysen oriented at investigation and development of possibilities for catalytic dissolution of polymer waste materials. Finally, 2 prof. position vacancies were fulfilled at University Maastricht as part of Brightsite collaboration program in the field of polymer recycling.

Research Line: Process Innovation

Mid-term 2021 a review was completed on mathematical methods for modelling and control of complex dynamic systems which will be summarized in a comprehensive report. In parallel an identification and detailing of optional case studies (Cracker, Gasification, Plasma conversion) was made in close cooperation with Brightsite partners. Based on these results preparations for a demonstration case study on gasification were completed to be executed in the second half of 2021. The first steps of dynamic modelling of a physical model (Gasifier) have been accomplished and initial statistic characterisation and AI analyses are in progress.

4. Plan year 2022

- **Focus, activities and deliverables**

Research Line: Plasma Technology

The main focus for 2022 is the practical demonstration of an optimized second generation (improved

Hüls) plasma process producing hydrogen and acetylene with an improved selectivity towards acetylene to > 90%. In addition, publication of initial second/third generation results is foreseen, showing feasibility of application of industrial scale plasma technology to tackle existing challenges and provide new options for the chemical industry. To realise these ambitions and expectations the execution of R&D-, modelling activities, literature studies and publication of results will be the main activities.

Research Line: Recycling

The main goal for 2022 is to develop and support the implementation of new plastic waste recycling technologies for companies on the Chemelot site and beyond to reduce overall carbon footprint. Activities and expected key results will be the experimental confirmation of practical and commercial application possibilities of Upwash® and liquid phase pyrolysis (LPP®) technologies. In addition, an in-depth insight in the fundamental possibilities of the possibilities for catalytic dissolution possibilities for conversion of polymer waste is expected from academic studies. Furthermore, a go/no go decision will have been made on continuation of CCS/CCU options with industrial (Chemelot) partners.

It is expected that a Brightsite recycling group with TNO, UM and Sitech key persons with associated practical facilities can be set up at Chemelot. In addition, partnerships with Chemelot site users for implementation of Milena Olga gasification technology may be possible depending on outcome of Synova investment decisions. For this a connection to RWE Furec on options for gasification of reject streams from other (Chemelot) polymer production sources is a prime possibility. Connections with the Nationaal Testcentrum Circulaire Plastics (NTCP) are foreseen to extend experience on practical application possibilities and limitations of Upwash® pre-treatment route. Finally, a collaboration with Fibrant concerning recycling of Nylon-6 wastes to further reduce caprolactam footprint will be pursued.

Research Line: Process Innovation

The main goals for 2022 are to demonstrate the possibilities of a digital twin for gasification based on complexity science, artificial intelligence and smart industry building blocks. This should be able to capture the emergent characteristics to better define boundaries and new options for process control and reduction of CO_2 emissions. In order to do this an accurate and fast predictive model (based on deep learning techniques) and a dynamic optimizer/control algorithm (based on non-linear control or reinforcement learning) will be developed. As input synthetic data (treated as field data) will be generated allowing modelling of gasification, pyrolysis and reactor dynamics. Based on this optimum control conditions of the gasification reactor/process will be defined to ensure optimal and safe temperature ranges in the column, desired slag quality and minimal energy consumption. In addition, an AI-model able to (stochastically) simulate and predict the impact of feed variation on process performance and emissions will be developed. Next to the Gasification also the AI tooling will be tested on the Plasma physical model.

9: Body-Brain Interactions

ERP Contacts: J. Kieboom (Project Lead), R. Kleemann, J. van Erp (Lead Scientists), P. Bongers (Science Director)
ERP Duration: 2020 – 2023

Overall Program description

1. Context and Objectives

- **Problem definition**

We hardly understand the complex Body-Brain Interactions (BBIs) because of missing mechanistic knowledge and a lack of suitable technology platforms to study them in humans or in preclinical models. If we understand BBIs better and have experimental body-brain platforms (BBPs), we (together with our partners) could effectively target body and brain health with nutritional, pharmaceutical and psycho-social treatments with broad novel applications in health and disease. Examples are: improve performance under acute stressors, ameliorate the effects of chronic stress, attenuate the development of neurodegenerative diseases and prevent obesity-associated metabolic diseases.

Our ambition is to establish two comprehensive BBPs: a human test facility with physiological and biochemical readouts and a complementary preclinical platform to study new mechanistic concepts that are not yet feasible in humans. These BBPs allow all sorts of ground-breaking research with our stakeholders (pharma and nutritional industry, diagnostics, defense and governmental institutions). These BBPs are timely and relevant and contribute to the need to improve mental, cognitive and physical fitness. This need is motivated by the demands of knowledge-driven economies and demographic and socio-economic changes. Unique BBPs enable us to come up with novel evidence-based concepts to stimulate overall health and performance based on BBIs identified in this program and ultimately enhance the effects of health-promoting molecules and to suppress the detrimental interactors that will impair performance or cause disease.

- **Expected impact to stakeholders**

Our societal (e.g. defence and security organizations) and industrial stakeholders (e.g. pharma and nutrition industries, medical doctors/eHealth-companies) require validated, robust and operational body-brain technologies. We address these requirements and will provide:

a) Complementary human and preclinical BBPs for complex studies on cognitive performance and brain health (e.g. alertness, mood, resilience to stress, cognitive decline), including critical elements of body performance (e.g. organ crosstalk, metabolism, inflammation, gut & microbiota health);

b) Operational availability of analytical and bioinformatical body-brain methods together with proof of their relevance to predict future performance and/or to stratify people;

c) Mechanism-based understanding of BBIs which is critical to advise how to intervene in an optimal way and how to efficiently analyse and interpret body-brain studies.

Many of our stakeholders realize that current approaches have reached a limit because they center on a certain aspect of either the brain or the body in isolation. Further improvements are only possible if body and brain are re-united. The societal impact includes: a longer time span in good health, well-balanced work-life and reduced risk from metabolic diseases and dementias, the latter being a great socio-economic burden in the decennia to come.

2. Approach

Our research lines have a common focus and unifying goal which is why we discuss them together where possible. In the 'Research plan', the new types of technologies being developed are delineated for each research line separately, albeit we already merge them among these lines.

- **Focus**

We aim to understand the causal determinants of both psycho-social and molecular-physiological mechanisms of BBIs that are currently still a black box. This requires:

- the development of comprehensive preclinical (research line A) and human (research line B) BBPs to evaluate cognitive performance concepts in health and disease.
- the development of dedicated analytical and big-data science technologies for sensitive measurements, multiscale data integration, and modelling algorithms/tools for biological and psychosocial mechanisms (research line C; for use in lines A and B).

Research with above BBPs will lead to the development of new mechanistic hypotheses and frameworks integrating psycho-social and molecular-physiological knowledge. Our method development occurs in iterative cycles and we combine technologies of all lines while they become continuously more sophisticated.

- **Research plan**

To understand the bi-directional BBIs, we defined three main research lines, each with two multi-year objectives.

<u>Research Line A 'Preclinical BBPs'</u>: develop new rapid translational models for mechanism-based preclinical research to assess innovative treatments that cannot be tested in humans, or analyses that are not feasible or practical in humans (e.g. analysis of brain tissue). Multi-year objectives:

a) to unravel causal mechanisms and molecular factors that signal between body and brain.
b) to test new treatment concepts that may improve cognitive performance and attenuate brain disorders (inflammation, dementias).

<u>Research Line B 'Acute stress human BBP'</u>: facility for comprehensive and simultaneous measurements of metabolism, inflammation, (neuro-) physiology, socio-psychological, and cognitive performance under influence of acute stressors (e.g. noise, sleep deprivation, nutrition). Emphasis is on relatively rapid (acute) cognitive performance changes of a person, for instance during challenging work. Multi-year objectives:

a) to comprehensively measure body- and brain-derived parameters and cognitive performance of a person exposed to one or more acute stressors.
b) to develop predictive algorithms that use these parameters to predict the cognitive performance of a person and inform on potential future decline or acute lapses.

Research Line C 'Chronic stress human BBPs': advanced molecular (-omics) techniques on human organ biopsies combined with systems biology data science to assess body determinants of chronic cognitive decline. The emphasis is on metabolic, inflammatory and other biological body-traits that determine cognitive performance and health in the long run, i.e. the biological setpoints on which acute stressors of research line B are superimposed. Multi-year objectives:

a) to develop novel analytical & bioinformatical methods for analyzing changes in liver, adipose tissue, intestine and microbiota and circulating molecules released from these tissues. These technologies must be generic to allow translation between the preclinical and human BBPs.
b) To develop new statistical methods to analyze non-linear relationships between lipidome, transcriptome, metabolome, microbiota and organ histology outcomes or cognition test results (incl. non-linear correlation analysis; stratification tools, personalization tools).

The main approach of line A and line B is to perform relatively short (6-9 months) human and rodent studies to identify key biological parameters. The main approach of line C is to develop and validate sophisticated analytical and bioinformatical tools dedicated for future body-brain research. We use unique longitudinal human tissues from the first clinical body-brain trial (BARICO; 2yr +3 yr follow-up) in collaboration with Rijnstate/Vitalys and Radboudumc/Donders. The tool box and outcomes can directly be used in the two other research lines A and B.

Modulation of BBIs based on knowledge about underlying mechanisms has very broad applications and can solve critical challenges of modern societies (e.g. coping with multiple stressors, enhancing cognitive performance and physical fitness, reducing cognitive-metabolic disease burden, etc.). This is relevant for roadmaps Operations and Human Factors, Biomedical Health, Child Health, Digital Health Technologies, and Work, Prevention & Health.

- **Targeted Partnerships**

Our research lines operate in close collaboration with partners and stakeholders (current ecosystem):

Knowledge partners:

Existing: LUMC - Clinical Genetics, Radboud Umc - Anatomy, Donders Institute, LCAB / Hogeschool Leiden, Universities of Tilburg and Ghent, Lowlands/WUR, Cardiff University.
New: LipidInflammaGene Consortium (University of Oslo, Norwegian Univ. of Life Sciences and 4 nutrition industry partners); Univ. of Nevada - Pharmacology, Physiology & Cell Biology; University Munich - Institute for Stroke and Dementia Research, Radboud - Nuclear Medicine.

Customers:

Existing: Industry: Kikkoman; Genomescan; Tecnilab; Unilver; Medicine: Rijnstate Hospitals, Obesity Clinic Vitalys; Government: Ministry of Defense, US Army Research Lab, ZonMw.
New: Nordic Biosciences, Maag Lever Darm Stichting; J.Hopkins Univ. - Applied Physics Lab; collaboration propositions prepared and currently evaluated at Heel GmbH (Pharma), Asahimatsu (Nutrition), Novo Nordisk (Pharma), Quanterix (Diagnostics) and Catharina Hospital Eindhoven.

So far, 7 PhD candidates have contributed to this ERP (C. Bottenheft; F. Seidel; I. Stuldreher; A. Tengeler; D. Vreeken, K. Lohkamp, E. Custers), five of which mostly financed externally.

Results 2021 and Plan year 2022

3. Results 2022

- **Focus Year 2021**

We anticipated that the Covid-19 pandemic complicated our human and animal studies which are critical because they deliver the data necessary to identify body-brain mechanisms and first predictive algorithms. We hence focussed on

a. the successful performance of the initiated experimental studies in research lines A, B, C
b. high-quality molecular (omics) analysis of a first batch of human tissues to identify first correlations with brain structure (MRI) and function (cognition& behaviour tests).
c. expanding our ecosystem and increasing visibility via new collaborations (and publications) not requiring further experimental work.

All three aims were achieved. We would like to emphasize that this ERP differs from other ERPs because we performed 2 large human studies in high-risk populations (n=170 severely obese patients; n=110 unvaccinated volunteers) with complex logistics involving hospitals and TNO locations. Covid-19 measures reduced the daily throughput of participants by 30-40%, increased costs due to safety measures and extra training of staff (mitigation plan), and reduced capacities at laboratories. We timely communicated this during our progress meetings, and the provision of extra time for this ERP was considered a realistic and fair request given our special situation (human studies in hospitals).

- **Achieved results in previous year(s)**

Research Line A 'Preclinical BBPs'

We developed the preclinical BBP in a stepwise approach based on individual mouse studies (each 7-9 months) that concentrate on specific aspects of the body-brain axis (e.g. gut-brain, liver-brain, etc.) to ultimately establish a comprehensive preclinical BBP. In parallel, we are further improving the experimental conditions (e.g. different diets as stressors) and expanding the array of quantitative biological readouts to measure blood biomarkers (aligned with research line B, C), and brain function and neuroinflammation.

The ERP started with a gut-brain interactions study (with Radboudumc and Donders Institute; PhD A. Tengeler), in which we identified a new molecular mediator (propionate) which signals between gut and brain (FASEB Journal, 2020). In 2020/21 we integrated the liver-brain axis into the animal model (jointly with LUMC & Cardiff University; PhD F. Seidel), with the aim to identify novel interactions between liver and brain, specifically focussing on liver-derived inflammatory factors. We found that complement C5 is overactive in obesity and its suppression improves blood supply to the brain. Mechanistic analysis and drafting of a publication are ongoing. In a separate study we investigated for the first time the role of the visceral adipose organ on cognition and brain function (with Radboudumc and Donders Institute; PhD F. Seidel). This study was completed in Q3 2021 and post-mortem analyses have just been initiated (to be continued in 2022). First results point to a direct communication between adipose tissue and the brain. Finally, a muscle-brain study was initiated (in collaboration with Tecnilab; PhD K. Lohkamp; neuroimaging funded by ZonMW and linked to TNO PPP 'Muscle Health' with nutrition and pharma companies) and will run into 2022. This study uses exercise and a dietary intervention with amino acids (building blocks of protein) as muscle-targeted interventions that are hypothesized to have an effect on the brain. All of these studies use (and simultaneously further develop) the same TNO proprietary preclinical ERP-BBI 'Ldlr-/-.Leiden model', which is also used in various collaborations to increase visibility (via publications) and stimulate wide-spread acceptance of the model in relevant scientific fields. In 2021, the preclinical platform was being used in a Norwegian

Food Consortium (with Univ Oslo & industries) to study the health effects of plant fats versus animal fats; by the University of Sevilla (published Nature Scientific Reports 2021) on the effects of antioxidants) and by the Institute for Stroke & Dementia Research Munich (brain to body effects; joint work in revision at Nature; acknowledged provision of tissues in Nature Commun. 2021). Importantly, analytical techniques and methods that were developed in 2021 and validated in research line A on mouse tissue were successfully implemented in human studies of research lines B and C.

Research Line B 'Acute stress human BBPs'

Smaller studies in the seed phase and the first year of the ERP BBI program on cognitive performance and physiology during acute stress led to the design and establishment of an integral v1.0 BBP for controlled acute stressors, cognitive and psychological tests, and physiological recordings combined with cortisol and biochemical readouts in blood and saliva. In Q4 2020, we obtained METC permission for a study in 2021 to a) Establish the relation between cognitive impairment due to sleep deprivation and an inflammatory stress response, to test the hypothesis that inflammation underlies cognitive decline, b) Determine (neuro-) physiological, psychological, metabolic and inflammatory parameters that predict inter-individual differences in cognitive decline induced by sleep deprivation and c) Determine parameters that predict upcoming lapses in cognitive performance within an individual with a focus on the innovative measure of physiological synchrony. In 2021, we analyzed n=110 participants using an improved v2.0 BBP during two subsequent mornings; n=60 were also measured during the night being awake (TNO Soesterberg). First results indicate clear effects of one night sleep deprivation on multiple measures of cognitive performance, and distinct responses in heart rate, skin conductance and to two types of social stressors.

Ongoing activities in 2021 include analyzing the above datasets and writing a draft paper of a preparatory study in which we tested wearables to determine interpersonal synchrony. We found that this is possible and indicative of attention (expected to be submitted later this year). Furthermore, brain-body concepts were disseminated in a paper describing methodological challenges and opportunities in Brouwer et al. Neuroergonomics 2021); a paper written together with a large international consortium, where we focused on eye tracking as a tool to obtain information on workload and stress; three accepted NATO papers (Tolstop et al.; Brouwer et al.; van Erp et al.) and presentations in which we collaborated with Airforce Research Lab on physiological synchrony; with John Hopkins University/Applied Physics Lab on the synergy between clinical and non-clinical Brain-Computer Interfaces; and within a NATO consortium on cognitive neuroenhancement. Furthermore, we started to employ analyses and tools that were developed in research line C in this research line and we prepared first joint proposals (PPS) for stakeholders (details see line C).

Research Line C 'Chronic stress human BBPs'

This research line centers around the longitudinal neuroprofiling trial 'BARICO', which was initiated at the start of the ERP (with Rijnstate Hospital, Vitalys, Radboud UMC). Patient recruitment and first baseline neuroprofiling (MRI), cognitive and behavioral tests were conducted in 2019/20. Covid-1 regulations delayed patient inclusion and organ collections (see above bullet point 'Focus Year 2021'). Despite Covid, we succeeded in 2021 to finalize all surgeries including organ collections and MRI, cognitive and behavior tests. Because of Covid drop outs, we had to recruit extra n=30 severely obese patients and perform all neurophysiological tests and the surgeries in 2021. The final cohort size is n=150 (as planned). A remarkable 70% of our patients had already their 6 months follow-up for repeated blood collections, microbiota sampling as well as cognition and behavior follow-up tests so that we can assess the effects of weight loss on cognition.

While the trial was ongoing in 2021, a decision was made to already analyze the available tissues and plasma (first batch of ~n=110), knowing that the final power of the full dataset will ultimately be higher. Reasons were: 1) ERP requires human evidence for molecular BBIs; 2) bioinformatical methods/algorithms development requires relevant body-brain datasets; 3) human data can cross-validate results from line A and cost-efficiently guide molecular analysis of line B.

In the first batch (n=110) we thus performed: 1) plasma metabolomics for fatty acids and amino acid composition (~60 molecules); 2) proteomics of inflammatory biomarkers released by liver and adipose tissue as well as vitamins, minerals, lipids in blood (~ 50 molecules); 3) a complete gene expression analysis of livers (all 20,000 genes); 4) liver histology and 5) adipose tissue histology. Obtained datasets were correlated with >50 brain readouts (e.g. size of hippocampus; blood flow in brain regions; grey/white matter, etc.) and cognition (memory) tests. Necessary bioinformatical tools and a data storage & exchange infrastructure were established. First results indicate that specific blood lipids and amino acids significantly correlate with brain health. Intriguingly, inner (visceral) fat but not subcutaneous fat has a detrimental impact on brain consistent with research line A. Also, accumulation of lipids in liver negatively impacts brain functions. A first paper is currently in preparation (PhDs Vreeken and Seidel). Parallel to the above, we kicked-off a first PPS (Q1 2021) to perform extra analyses on gut-liver (Maag-Lever-Darm Stichting) and test novel biomarker concepts (Nordic Biosciences).

4. Plan Year 2022

- **Focus Year 2022**

Research Line A 'Preclinical BBPs'

Complete muscle-brain study, identify causal molecules in adipose-brain interaction, disseminate results, and align biomarker readouts with lines B and C.

Research Line B 'Acute stress human Body-Brain platforms'

Complete analysis of sleep deprivation study, assess the role of inflammation and determinants of interpersonal differences, create algorithms to predict lapses within subject.

Research Line C 'Chronic stress human Body-Brain platforms'

Complete BARICO tissue analysis (n=150), establish correlations between organ characteristics, molecules in plasma and cognitive performance or brain structure. Establish bioinformatical patient stratification tools to define biological subgroups.

- **Activities Year 2022**

Research Line A 'Preclinical BBPs'

- Neuroimaging (non-invasive rs-fMRI) of mice in muscle-brain study and initiate histological tissue analyses on samples from this study as well as first plasma data analysis.
- Post-mortem analyses of samples from adipose-brain study focus on neuroimaging and behavioral datasets; identify proteins released by adipose tissue; start drafting a publication.
- Explore new body-brain connections using available tissues: role of vasculature as body/brain interface and conduit for sympathetic nerves (jointly with LUMC, University of Munich).
- Develop novel organ culture technology to quantify new molecular body-brain mediators secreted by adipose tissue (e.g. by proteomics, metabolomics in *ex vivo* organ culture).
- Implement tools from line A in line B and C (and vice versa).

- Disseminate own and collaborative studies with Oslo, Munich; Radboud/Donders; initiate new collaborations with UMC's (Princes Beatrix Fonds on lipid myelinization in CNS and PNS).

Research Line B 'Acute stress human BBPs'

- Finalize analysis of skin conductance data and of biochemical markers from blood, saliva, hair and fecal swabs. For biochemical markers, an exact cost-benefit prioritization will be made. Blood inflammatory molecules and bioactive metabolites (e.g. signaling molecules from lines A, C) are top priority.
- (Bioinformatical) analyses to describe the basic effects of sleep deprivation on our variables and assess whether inflammation underlies sleep deprivation induced cognitive impairment.
- First algorithms to predict inter-individual differences in cognitive performance after sleep deprivation using the collected body-brain parameters, including responses in stress tests.
- Analyses on interpersonal physiological synchrony as a measure of attention to predict lapses in performance.
- Continue work with Ghent University longitudinal cognitive performance study on real life stress (peer victimization at school, COVID), cognitive performance and inflammation.
- Writing scientific presentations and (draft) publications, finishing papers submitted in 2021.

Research Line C 'Chronic stress human BBPs'

- Complete molecular tissue analysis to obtain maximal power with the full dataset (n=150).
- Identify correlations between adipose tissue pathology state and cognition/brain structure incl. a mechanistic rationale via circulating signal molecule (use line A results). First manuscript.
- Explore the liver steatosis – brain connection and provide a mechanistic rationale using liver transcriptome datasets and/or fatty acid profiles.
- Explore intestine – brain connection with microbiota composition and/or SCFA/BCFA as links.
- Establish generic bioinformatical methodology for data-driven patient stratification including machine learning-based feature selection tools. Develop first predictive algorithms.
- Use new method to perform cluster analysis to identify which patients have better/worse outcomes in cognition using 6 months follow-up cognition test results.

- **Deliverables Year 2022**

Research Line A 'Preclinical BBPs'

- Dataset with in-life results of muscle-brain study; effects of amino acids on performance.
- Completed dataset of the adipose tissue – brain study highlighting causal interactors.
- Draft manuscript on molecular interactions between the adipose tissue and the brain.
- First results about a new body-brain connection via vascular (sympathetic) conduits.
- A new organ culture method to measure molecular mediators released by adipose tissue.
- Two manuscripts together with collaborators.

Research Line B 'Acute stress human BBPs'

- Multi-level dataset (dynamical physiol. and molecular data) of sleep deprivation (SD) study.
- First model v.1.0 to predict inter-individual differences in cognitive performance after SD.
- At least one scientific presentation and one publication on the first results of the SD study.
- Two publications: on interpersonal synchrony using wearables (preparatory study), on real-life stressors (with Univ Ghent), on eye tracking as part of the BBP.

Research Line C ‘Chronic stress human BBPs’

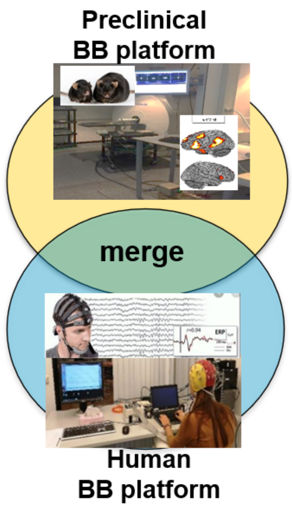
- Full n=150 person biological dataset with data from liver, adipose tissue and corresponding plasma & microbiota with first robust connections and rationale links of the organs to brain.
- Methodology to stratify and subgroup patients and define a person’s biological traits that underlie their cognitive performance.
- One manuscript that describes the connection of adipose organ to the brain in obese humans and one manuscript that provides a rationale for cross-talk between liver fat and brain.

SYNOPSIS: visual abstract

Gut to brain: mechanism established (v1.0)
Liver to brain: first mechanistic indications (v2.0)
Adipose tissue/obesity to brain: study ready for analysis
Muscle to brain: in-life study ongoing
New connections: (vessels & nerves): initiated

Data Science: bioinformatical tools for BB research: prototypes
Development of new analytical tools (e.g. first BB biomarkers) and start of technology transfer between both platforms
Predictive **algorithms**: first comprehensive human BB datasets

Acute stressors: prototype platform for multiple stressors: v1.0
Improved platform for sleep deprivation studies (v2.0): first datasets
Chronic stressors: Worldwide first clinical BB trial with brain-MRI and organ biopsies: subset of BARICO patients



Excellence: ecosystem & scientific output: International network of partners; first PPS & consortia with industries; relations with pharma, nutrition, diagnostics and governmental institutions; seven contributing PhDs; highest scientific quality: FASEB J, Nature Sci. Reports, J Neural Eng, Nature (in revision).

Figure 17: SYNOPSIS: visual abstract ERP Body-Brain Interactions

10: Social eXtended Reality

ERP Contacts: M. Boen-Leo (Project Lead), O. Niamut (Lead Scientist), P. Havinga (Science Director)

ERP Duration: 2020 – 2023

Overall program description

1. Context and Objectives

The TNO Strategic Plan 2018-2021 identifies the importance of media synchronization, with a focus on the combination of eXtended Reality (XR, the superset of AR/MR/VR), Cloud/5G and Tactile Internet. In the ERP social XR we aim to realize the first-time engineering of a shared and networked XR environment for holographic communication, where participants get the feeling of being in the presence of, and interacting with, other persons at a remote location. With such a system, national security personnel (e.g. police officers) can ask for remote assistance and discuss with an expert colleague about a crime scene on location; distributed teams of soldiers can jointly train for critical missions; companies can let their personnel meet and discuss remotely, and public services offering Mobility-as-a-Service concepts can add an entire new modality to their portfolio. Holographic communication involves the capture, coding, streaming and rendering of spatial audio, volumetric video and tactile data. To reach Internet-level scale, cross-layer and joint orchestration of media, computation capabilities and network functionality is essential in a holographic communication platform. We also consider key social cues in mediated, bidirectional, multi-party interaction and key factors that make and break the experience of social presence.

- **Problem definition**

Figure 18: Example of remote presence through holographic communication.

Transporting one's social and functional self to any place on earth is a compelling and exciting idea, providing expertise or skills at a distance e.g. in industry (co-working, inspection, maintenance), enabling remote education and training, and supporting inclusion of citizens with accessibility barriers. Enabling remote communication and collaboration provides a strong contribution to societal challenges. Examples include virtual meetings to reduce commutes, lower our economic and ecological footprint, and alleviate physical distancing measures in case of pandemics such as COVID-19. There is a strong need to make communication and remote collaboration as transparent as possible (meaning that the interface should appear to be imperceptible and almost nonexistent to the user), which can be achieved by increasing the quality of auditory and visual media, decreasing transmission delays and adding multiple sensory modalities like tactile and haptics. Holographic communication is such a future form of mediated social communication that enables collaboration and shared experiences. It has the promise to make this idea come true but they depend on breakthroughs in creating fast and open network infrastructures, in blending the digital and physical worlds into a multisensory, immersive world, in empowering edge devices, and in sensors and actuators for immersive multisensory telepresence. These build on current developments in the Cloud/5G/6G, Tactile Internet, Artificial Intelligence, and Augmented and Virtual Reality, (AR/VR) and together create new possibilities for communication and communication towards an era in which human capacities are supported and enhanced by an Internet of Abilities (IoA).

- **Expected impact to stakeholders**

Figure 19: Social XR: barrier-breaking technology for smart societies

We need a drastic reduction of our collective ecological footprint and impact on climate change, by travelling less; and we urgently need to combat an increased sense of loneliness and isolation experienced by the population in circumstances such as a global pandemic. Especially during the current COVID-19 pandemic, it has become clear that the ability to meet each other virtually, or to travel virtually, can be considered as a vital infrastructural need for every society, both for its economy as well as its wellbeing. That is, virtual meetings and traveling help to reduce commutes, lower our ecological footprint, provide expertise or skills at a distance, alleviate physical distancing measures in case of global pandemics such as COVID-19 and support inclusion of citizens with accessibility barriers. Enabling remote communication and collaboration provides a strong contribution to these societal challenges. But traditional video conferencing tools come with limitations that prevent efficient and meaningful remote communication and interactive participation. Extended Reality (XR) communication and collaboration is an emerging paradigm providing solutions to overcome these limitations, but one that sees significant R&D activities outside Europe. With ERP social XR we aim to develop world-class solutions for XR communication, so that Dutch industry can capitalize on our R&D efforts and thereby give the Dutch ecosystem for social and collaborative XR applications a significant boost.

2. Approach

- **Focus**

The focus within ERP social XR is threefold; first, we consider the representation of objects, spaces and humans in their actual dimensions and shape. We develop novel media formats and processing pipelines to enable real-time capture, processing, transmission and rendering of multimodal media. Second, we aim to support the trend of XR glasses becoming slimmer, sleeker, and more comfortable by provisioning complex and resource-hungry processing through cloud/edge resources; and by improving mobile network infrastructure to make mobile XR interactions as realistic and delay-free as they need to be. Third, we explore the human factors in enabling social XR at large. We consider how likely is it that people will use our technological innovations and what barriers stand in the way of adoption, what social parameters need to be adhered to, and which social cues are most important to transfer at the highest quality. Since different XR modalities are suitable for various use cases, we focus on tailored use-cases based on generic AR / VR / XR platforms. In particular, we focus on **virtual / hybrid meetings** and **expertise at a distance**, with applications in health, mobility, work and training/education.

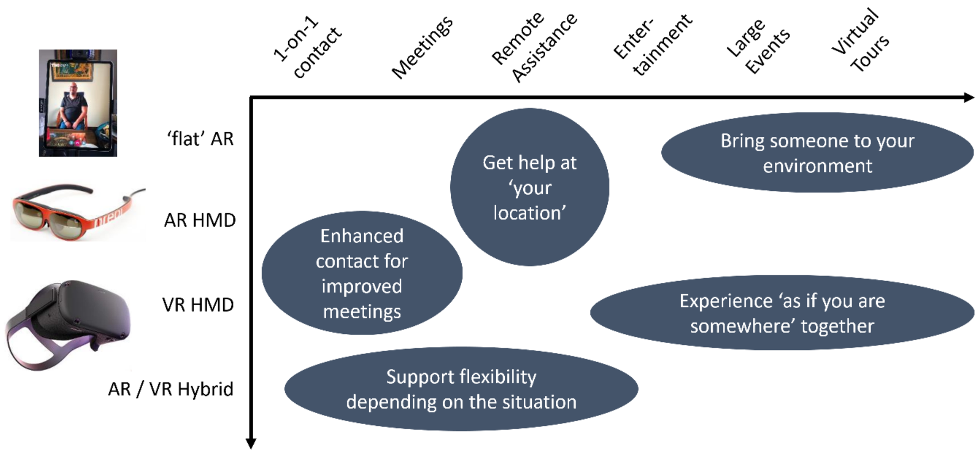


Figure 20: Different XR rendering modalities are suitable for various use cases

- **Research plan**

Current technologies for remote communication and collaboration face limitations with respect to capture, processing, transmission and rendering of multimodal media over mobile networks. In particular, the following three main research questions need to be addressed.

1. **Social and spatial presence:** in telepresence, we aim for the perceptual illusion of non-mediation. However, existing and emerging avatar-based telepresence solutions do not provide the feeling of being present in a mediated environment. Participants need not only be represented by avatars, but also represented through volumetric video. Perfect camera alignment for eye contact and volumetric video (e.g. point clouds, 3D meshes, light fields) is needed to create an illusion of the remote person's physical presence in the virtual and/or physical space, as well as a shared understanding of verbal and non-verbal cues.
2. **Social touch for multi-modal interaction:** despite the importance of social touch in co-located interpersonal communication, this form of communication is currently underexposed in modern communication technologies. Current communication tools, such as internet calling, video conferencing and telepresence, only send voice and a (partial) 2D image of the body. High-quality communication between users in remote locations should take into account all factors needed for humans to feel each other's presence. Mediated social communication including touch can contribute significantly to a feeling of social presence in the context of collaborative tasks performed in shared virtual environments.
3. **Seamless and scalable experience:** creating high-quality and immersive shared XR experiences between remote participants puts a significant demand on the communication infrastructure, especially when employing mobile networks. Networking infrastructure has to handle high-bandwidth streams, while keeping end-to-end latency low. Furthermore, the infrastructure should provide in-network processing, reducing the need for heavy computing devices at the client, thus increasing the clients' flexibility and mobility. Edge computing provides compute resources available at high bandwidth and with low latency by ensuring that processing, content collection and delivery are performed near the endpoints, allowing advanced in-network processing for data intensive applications while reducing the burden on the backhaul.

ERP Social XR consists of three research lines, integration, collaboration and project management activities.

- (RL1) *immersive technologies:* we aim to research and develop a full end-to-end immersive experience workflow, including volumetric video and tactile/haptic data, to address problems 1 and 2;
- (RL2) *empowered edge:* we aim to research and develop an adaptively tailored 'social XR' network slice for resource/cost-efficient and QoE-effective support of application scenarios, to address problem 3
- (RL3) *human factors:* we aim to identify and specify the key human factors that enable convincing and lifelike shared and social XR experiences, to address problems 1-3;
- (IL) *platform integration line:* we aim to demonstrate the application potential of the technology through iterative integration of research and development outputs of the individual research lines into a platform for XR-enabled networked communication and collaboration;
- (CL) *application and collaboration line*: we aim to set up long-term collaborations with key research partners and industry stakeholders.

The long-term roadmap of these topics is presented in Table 3, and with detailed results for 2021 presented in section 4 and plans for 2022 in section 5.

Table 3: Multi-year ERP Social Extended Reality roadmap, with achieved results for 2020-2021

Feature	Target > 2023	2020	2021	2022	2023
Usage scenarios	min. 2 usage scenarios, adopted by min. 3 units	business and informal **meetings** usage scenarios for units HL, ICT and T&T		**expertise at a distance** usage scenarios for units DSS, ET and ICT; business and informal hybrid meetings usage scenarios for units HL, ICT and T&T	
Platform modalities	Social XR platform for mixed reality applications	Social **AR** platform	Social **VR** platform	Social **XR** platform for mixed reality applications in **hybrid** settings	
Photorealistic representation (RL1)	6-degree of freedom for limited (~3m) movement	User eye gaze rays for better eye contact; dual-sensor capture of participants for 3DoF	E2E RGBD volumetric pipeline for capture, coding and representation of participants; static automated calibration; static HMD removal for increased eye gaze awareness	E2E RGBD volumetric pipeline for capture, coding and representation of environment; dynamic HMD removal for increased eye gaze awareness; increased visual quality of human representation with HMD removal and eye gaze awareness	
Social touch (RL1&3)	Social touch for min. 3 tactile displays	tactile proxy supporting different types of tactile displays	High-level tactile patterns for social touch	non-visual high-resolution hand and finger tracking through haptic proxy; high-level tactile pattern-generator; bidirectional- social touch interface for virtual visits	
Participants scale and device flexibility (RL1&2)	MCU @ resolution 8k framerate 60fps #streams 100 latency ~50ms	4K / 30 fps / 64 streams (simulated) ~400 ms	4K / 30 fps 12 real streams ~250 ms / VR	layered, tiled MCU design @ resolution 8k framerate 30-60 fps 24-48 real streams with split RGB-D coding latency ~100ms	
Network-based media processing and transmission (RL2)	blueprint for adaptively tailored Social XR network slice	GPU-accelerated media processing 5G RAN simulator; slice performance and capacity assessment for indoor office scenarios	Real time placement of processing functions among cloud, edge and user device Generic blockage model for use in 5G scenario assessments; simulations to derive feasibility, performance and resource needs of various small-scale social XR scenarios	slice adaptation based on cross layer aspects focusing on migrating processing between edges, triggered by user mobility; re-location strategies of slice deployment in federated edge-cloud infrastructure; PoC in TNO Research Cloud with two access points and two edge deployments	
Use case and HF-driven system requirements (RL3)	required social XR system capabilities for use cases	identification of use case classes	representative dimensions and social cues for use case classes; specification and validation of user requirements	required mediated social touch capabilities for virtual visits use case; required social XR system capabilities for people with difficulties in verbal communication	
Key factors for social presence in XR scenarios (RL3)	guidelines to how to implement social cues in social XR	value of photo-realistic volumetric human representation	influence of haptic communication on connectedness	identification of spatial cues for on-site and remote people in expertise at a distance scenario	

- **Targeted partnerships**

We aim to set up long-term collaborations with key research partners and industry stakeholders to co-develop social XR platforms and underlying technology modules. In particular, we seek academic knowledge partners, technology and platform (integration) partners and lead use case adoption partners.

Results 2021 and plan year 2022

3. Results 2021

- **Results achieved in previous Full ERP year(s)**

Research Line 1 – Immersive Technologies:

aims at designing a full end-to-end immersive experience transmission chain by focusing on capture, coding, transmission and rendering of volumetric video; and on tactile/haptic data for social touch. In 2021, research was conducted to improve eye gaze awareness in a multimodal experience, to enable multi-modal synchronization of haptic data in multi-modal experience and to enable real-time depth conversion/coding/transmission pipeline for volumetric video. Key results so far include i) a PoC for auto-calibration and auto-configuration of a dual-sensor configuration; ii) a PoC for HMD removal; iii) an updated MCU design; iv) an architecture for an end-to-end pipeline for multimodal media; and v) two draft invention disclosures on a tactile proxy and enabling system scalability through an MCU.

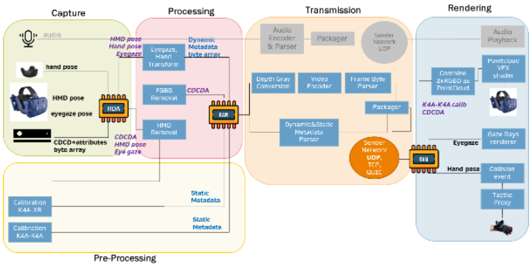


Figure 21: Detailed pipeline of Research Line 1

Research Line 2 – Empowered edge:

aims at developing of an adaptively tailored 'Social XR' network slice for the resource/cost-efficient and QoE-effective support of 'Social XR' scenarios. In 2021, research was conducted to optimize the distribution of accelerated media processing; to optimize radio network deployment /management; and to perform cross-layer optimization of application, processing and transmission layers. Key results so far include i) a PoC of distributed media processing using cross-layer orchestration on a real-world 5G radio infrastructure; ii) a generic blockage model for use in 5G scenario assessments; iii) extensive simulations to derive feasibility, performance and resource needs of various small-scale social XR scenarios; and iv) a draft invention disclosure on cross-layer adaptation.

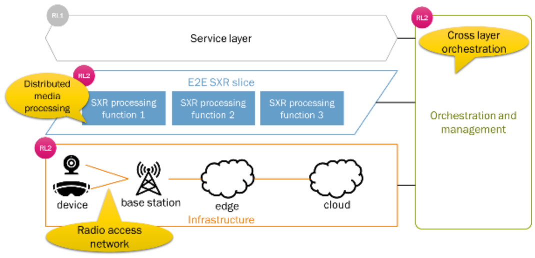


Figure 22: 1st version of an End-to-End Social XR Slice

Research Line 3 – Human factors in social XR: aims at validating the application potential of the technology, determining technical requirements and generate new knowledge on human factors. Key results so far include i) an investigation of influence of haptic communication on social connectedness; and ii) an initial validation of the newly developed Holistic Social Presence (HSP) questionnaire.


Figure 23: Initial validation of the HSP questionnaire

Platform Integration Line

We brings concrete results of the research lines from previous years together into instantiations of our social XR platform, evaluate the overall experience and validate use cases based on roadmap interests. A WebXR-based and cloud-native design facilitates portability of the demonstrator and reproducibility of the results. Key results so far include i) a specification of an XR-enabled business meeting scenario and its associated requirements on social presence; ii) a first-time technical integration of ERP 2020 outcomes into a social VR platform for interaction through spatial presence and touch; and iii) a preliminary validation of the user experience, demonstrating a significant increase compared to the Kiem ERP 2019 outcome.

Figure 24: (left) user experience test across 2 locations. (middle) 3-person business meeting in VR. (right) user experience results of Kiem ERP 2019 initial platform (VRDaysEU2019 survey) and ERP 2021 integration line outcome.

4. Plan year 2022

- **Focus Year 2022**

In 2022, we focus on generating knowledge and technologies needed for expertise at a distance use cases in hybrid situations (i.e. mix between real and virtual environments).

- **Activities Year 2022**

<u>Research Line 1: Advanced capture of environment:</u> for mixed reality application scenarios such as hybrid meetings and expertise at a distance, the real-world physical environment can play an import role in providing a sense of spatial presence. The real-time 3D mapping and modelling of the environment raises the following research questions: how can we best represent a real-world physical environment? How can we employ readily available RGBD sensors to capture and map a volumetric representation of the environment? Building upon existing research from ERP i-Botics we will design and implement a proof-of-concept of an environment capture model. The outcome will help us to develop a social XR platform catering for mixed reality application scenarios such as hybrid meetings and expertise at a distance.

<u>Research Line 1&3: Human representation and interaction:</u> in social XR, participants need not only be represented by avatars, but also represented through volumetric video. Moreover, multi-modal interaction is needed for social touch. Multi-modal human representation raises the following research questions: How can volumetric and model-based approaches be combined for human representation and cater for eye contact? How can we enable pragmatic, but generic and reusable kinesthetic input into the system through the Haptic Proxy? We will develop and evaluate human representation and interaction based on prioritized social cues. The outcome will help us to integrate human representation and interaction in our social XR platform.

<u>Research Lines 1&2: End-to-end real-time and scalable communication:</u> volumetric representation in networked communication comes with significant bandwidth and stringent latency requirements. Catering for real-time social XR raises the following research questions: What gain can we achieve by RGBD simulcast vs. tiled based prioritization of the depth part? What needs to change in our current architecture and implementation to scale for large (20+) user's groups in one communication session? With a complex distributed multi camera capture and tiled distribution end-to-end transmission chain what are new requirements on the synchronization? What changes are needed in the system to ensure these new requirements are being met? We will develop split encoding and

transmission schemes for RGBD-based volumetric video and implement a layered tile-based MCU. The outcome will provide us with real-time and scalable volumetric communication in our social XR platform.

Research Line 2: Slice adaptation based on cross-layer aspects: user mobility and/or device change may trigger a migration of processing between edges (or between device and edge). Such migration raises the following research questions: How do user mobility requirements in expertise at a distance use cases influence the deployment location of (edge) processing? What are optimal re-location strategies of the slice deployment in a (federated) edge-cloud infrastructure? We will develop a PoC in the TNO Research Cloud with two access points and two edge deployments. The outcome will allows us to cater for mobility and low-complexity rendering devices.

Research Line 3 Validation of HSP questionnaire and toolbox: to validate a previously developed a questionnaire that measures the quality of mediated social communication, we will investigate its (1) reliability, (2) sensitivity, and (3) convergent validity. This will be done by applying it to the same group of participants (1) on different occasions and for similar mediated social presence experiences, (2) for similar social presence experiences using different hardware and/or software, and (3) by comparing its performance to that of related questionnaires. The questionnaire will be applied to different social communication tools, primarily for expertise at a distance use cases in the Integration Line and collaboration projects PoN, Virtual Visits and Virtual Communication.

Platform Integration Line

We integrate research line results from 2021 into a first instantiation of a social XR platform, building upon the social VR platform developed in the 2021 integration line. The social XR platform innovations are demonstrated in accordance with 1-2 expertise at a distance use cases, defined by committed units DSS (aggression training) and ET (remote maintenance). We foresee the following integration activities:

- Research Line 1: Capture and rendering: we enable AR and HMD-less volumetric rendering of humans, increase hardware abstraction for vibro-tactile displays to support additional gloves and suits, and integrate basic (e.g. 360 streaming and offline 3D models) environment capture to enable situational awareness for remote experts.
- Research Line 2: Platform deployment on hybrid infrastructure: we extend our platform deployment on the TNO Research Cloud to external edge/cloud providers, as well as to the TNO Hi5 5G infrastructure. We aim to demonstrate a showcase where at least one user is connected over 5G.
- Research Lines 1 & 2: Moving local processing to edge: building upon the RL2 cross-layer orchestration PoC for moving media processing we select and prepare RL1 processing modules for deployment on Kubernetes, duplicate on-board client software components into edge cloud (e.g. Kubernetes cluster or equivalent) and design and implement the integration of the processing orchestrator into the integration line setup.

Application and collaboration Line

Social touch in Virtual Visits project: exchanging social touch can increase connectedness and the forming of social bonds. Adding mediated social touch to virtual visits raises the following research questions: what kind of social touch is suited for these kind of applications? What is the benefit of social touch with respect to social presence/connectedness and does this change over prolonged usage? We will design the -bidirectional- social touch interface, run longitudinal pilot studies and integrate the equipment, protocol, and test in the Virtual Visits project. The outcome will help us to qualify and quantify the benefit of mediated social touch.

Spatial awareness for expertise at a distance scenario in PoN project: experts at a distance need to quickly gain situation awareness of the remote environment, including functional (e.g. layout of the environment, location of key objects, etc.) and social spatial cues. The latter includes the location of people and their interpersonal distance, the personal space of individuals (including the remote expert!), the projection in 3D of the gaze direction (i.e. who is looking or pointing at what or whom). The key research question is: which spatial cues are important to on-site and remote people? We will run experiments within the use case PoN to identify the key spatial cues and how a social XR setup could address them.

NWA-ORC Virtual Communication project: people may experience difficulties in communication, for instance people who are hard of hearing, people with a brain injury, and non-native speakers. New social XR technologies may help overcome these difficulties and increase access to business and social meetings, remote learning and other services through enhancing (non-verbal) social cues. An important research question is how and to what extent this technology can benefit users in terms of better communication, collaboration, or social presence, what the specific user requirements are and how these translate to requirements for technology (development).

- **Deliverables Year 2022**

Table 4: Overview of expected ERP deliverables in 2022.

Activities	Deliverable
Research Line	
(RL1) Advanced capture of environment	Proof-of-concept of an environment capture model
(RL1/3) Human representation and interaction	Proof-of-concept for volumetric human representation and interaction based on prioritized social cues
(RL1/2) End-to-end real-time and scalable communication	Proof-of-concept of split encoding and transmission schemes for RGBD-based volumetric video and tile-based MCU
(RL2) Slice adaptation based on cross-layer aspects	Proof-of-principle for mobility-driven cross-layer optimization in the TNO Research Cloud
(RL3) Validation of HSP questionnaire and toolbox	Validated questionnaire applied to different social communication tools for expertise at a distance use cases
	Report on 2022 research line activities and results
Integration Line	
(RL1) Capture and rendering	Platform module for integrated basic environment capture to enable situational awareness for remote experts
(RL2) Platform deployment on hybrid infrastructure	Demonstrator for platfrom deployment where at least one user is connected over 5G
(RL1/RL2) Moving local processing to edge	Demonstrator for distributed processing for RL1 processing module movement to the edge
	Report on 2022 integration line activities and results
Application and Collaboration Line	
Social touch in Virtual Visits project	Report on the design of a social touch interface, longitudinal pilot studies and integration of the equipment, protocol, and test in the Virtual Visits project
Spatial awareness for expertise at a distance in PoN project	Report on the experiments within the PoN project to identify the key spatial cues and how a social XR setup could address them
NWA-ORC Virtual Communication project	Report on how and to what extent social XR technology can benefit users in terms of better communication, collaboration, or social presence, what the specific user requirements are and how these translate to requirements for technology (development)

11: Climate and Air Quality: Next generation model system for air quality and climate change applications

ERP Contacts: R. Dröge (Project Lead), M. Schaap (Lead Scientist), A. Dortmans (Science Director)
ERP Duration: 2021 – 2024

Overall program description

1. Context and Objectives

Problem definition

Every year around 7 million people die prematurely from exposure to polluted air. Global warming may lead to catastrophic sea level rise, droughts, and increases of wildfires and extreme weather. Critical loads for atmospheric nitrogen deposition are exceeded in 72% of the Dutch nature areas (55% in Europe), leading to significant biodiversity loss. All these pressing environmental challenges relate to anthropogenic emissions into the atmosphere and their negative impact on the environment. To curb these impacts the Dutch government has committed itself to reduce the adverse health impacts due to Dutch emissions by 30% and to reduce greenhouse gas emission by 49% in 2030, while nitrogen policies are currently under fierce societal debate. Many stakeholders have developed their own targets, e.g. climate neutral cities. These reduction targets will impact all economic sectors in the Netherlands, but the challenge is to decide which mitigation strategy to follow. Therefore, a strong demand exists for high quality and high-resolution information on the state of the environment, the origin of the pollution and independent assessment of the effectiveness of implemented or planned mitigation options. The high-resolution is required for emission monitoring on local instead of national level, the determination of more specific source-effect relations and personal exposure.

Two of the main challenges for providing such information are the need for high-resolution time-dependent emissions and the fact that the emissions and their impact are separated in time and place, influenced by complex processes such as atmospheric mixing and chemistry. At present, distinctly different model systems are used to describe these complex processes, each targeting specific spatial (urban to global) and temporal scales. However, there is a strong interaction between the different scales that needs to be considered when addressing above-mentioned environmental challenges. The main challenge, both conceptual and technical, is then to combine complementary models in one framework and to get those models to exchange information in a consistent and efficient manner.

Right now, the increasing resolution and quality of satellite and sensor data and the tremendously growing information on emitting activities through internet of things (e.g. real time traffic data) provides a driving force allowing a fundamentally different approach to detail the emissions and their environmental impact. To interpret these observations and provide high quality atmospheric information about the state of the environment and the impact of mitigation options to stakeholders, several fundamental challenges need to be resolved, which will be addressed in the ERP.

- **Expected impact to stakeholders**

Stakeholders face a challenge to decide which mitigation strategies to follow for reduction targets in climate change, nitrogen deposition and exposure to atmospheric pollution. For well-informed decision making one needs high quality and high-resolution information on the state of the environment, the origin of the pollution and impact of measures. An integrated knowledge base is required to optimally identify co-benefits.

2. Approach

- **Focus**

The overall goal is the development of a globally applicable, multi-scale atmospheric modelling system with resolution down to 25m to fully exploit the emerging observation capacity from satellites and sensors. In addition to the work packages devoted to develop and advance methodologies that enable to perform realistic simulations at this unprecedented resolution, a system integration approach is taken to ensure that a complete and flexible modelling system is obtained. The new system will be demonstrated for the greater Eindhoven area, motivated by the secured access to (sensor) data, commitment of local policy makers, collaboration with ERP ExpoSense and the presence of diverse emissions from transport modes, agriculture and households.

<u>A. Dynamic anthropogenic emissions</u> – The main objective is to develop spatially (25m) and temporally (hourly) highly resolved emission data for NRT and analysis purposes. The main developments include activity modelling based on big data (IoT, AI, data mining, agent modelling) and emission behaviour modelling including dependence on environmental conditions. Through these developments we will fundamentally transform the current top-down emission workflow into a bottom-up one. The emissions models will encompass air pollutants and greenhouse gases in one framework tailored to the requirements of the chemistry transport modelling systems to allow to address co-benefits.

A PhD position (ERP funding) will be created on dynamic transport emissions, with the Freie Universität Berlin.

<u>B. Hyper local air quality modelling –</u> The main goal is to develop the Dutch Atmospheric Large-Eddy Simulation model (DALES) away from idealized scientific case studies to realistic applications for atmospheric composition. We will research the impact of the urban and rural landscape on boundary layer dynamics and the resulting dispersion of reactive pollutants. This requires accounting for anthropogenic emissions, biogenic emissions, deposition processes, atmospheric chemistry, and building resolved flows.

<u>C. Assimilation of satellite and sensor data</u> – The main objective is to generate objective feedback on the quality of the models and emission information. We will develop new dynamic model evaluation methods to evaluate the impact of emission and meteorological variability using recent years including the COVID-19 period. For emission verification, we will develop methods to assimilate different types of observations (satellite, sensor, instrument) simultaneously in all transport models.

<u>D. System integration of multi-scale model system & demonstration –</u> The main objective is to connect all components of the model system to support fast and reliable calculations for re-analyses, nowcasting and scenario assessments. In practice, a specific IT-workflow needs to be constructed which takes place from data acquisition till the provision of the insights and results of the calculations. The data management component ensures the input and output data are FAIR – Findable, Accessible, Interoperable and Reusable. Flexible integration of new data types and calculation steps is crucial. A system integration approach will be followed to ensure efficient computing and exchange of data. The applicability of the model system will be demonstrated for the greater Eindhoven area.

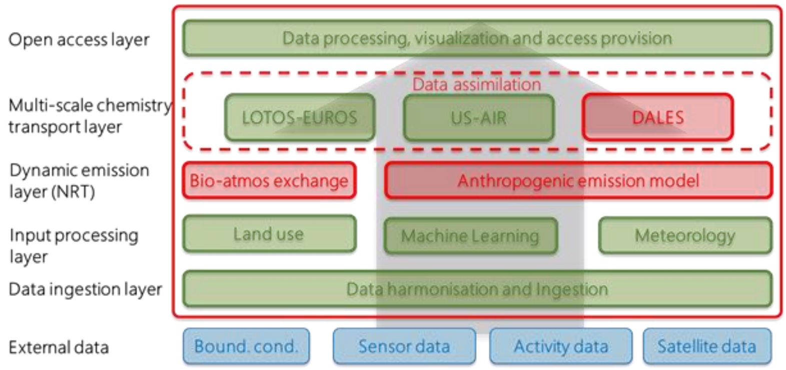


Figure 25: Design of the AQCCnext modelling system. The red boxes and lines will be developed with in the ERP Climate and Air Quality

- **Research plan**

The ERP aims to develop and advance methodologies that enable to perform realistic atmospheric composition simulations at an unprecedented resolution (25 m). The main research questions are:

- What are the main processes and mechanisms that induce the variability in anthropogenic emissions, concentrations and deposition of air pollutants, reactive nitrogen and greenhouse gases and how do they influence each other?
- How can we optimally use data driven methodologies to estimate and forecast high resolution emissions from traffic, households, agriculture and power production?
- What is the added value of artificial intelligence techniques to derive and forecast activity information?
- In how far is it possible to perform realistic, long term integrations using a Large Eddy Simulation model?
- How do the urban and rural landscapes influence boundary layer dynamics and the resulting dispersion of reactive pollutants?
- How to quantify the improvement of model skill using dynamic evaluation and data assimilation techniques using both in-situ and remote sensing observations?
- How do we optimally balance between the level of detail, functionality and computational demand?
- What is the uncertainty of the high resolution model results and which steps are required to lower these?

These research questions are addressed in the research lines described above and timed according to the schedule in Figure . Parallel activities are performed on emission modelling and LES modelling in which the main (sector wise and process wise) developments are performed in the subsequent ERP years.

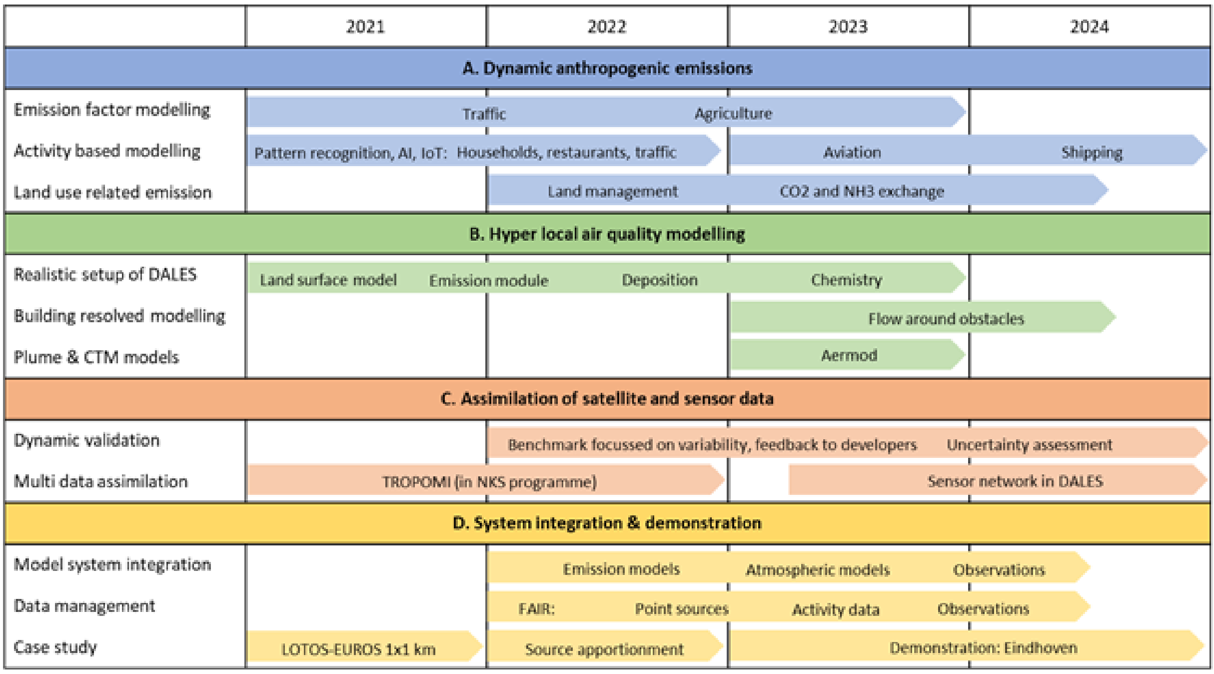


Figure 26: Timeline for the four work packages in the ERP Climate and Air Quality for the period 2021-2014

- **Targeted partnerships**

A. Dynamic anthropogenic emissions are key for assessing the importance of different sectors, identification of viable mitigation options and assessing the impact of transition scenarios or modal shifts. Modelling applications aimed at source apportionment, forecasting and emission monitoring rely critically on high quality emission data. We cooperate with (inter)national experts (e.g. WUR, RIVM, CBS, RWS, BSC, FMI, IIASA) on activity and emissions modelling. In 2021 we have submitted and won the EU-PAUL project with TNO contributions on high-resolution emission modelling. We aim to establish strategic collaboration within the upcoming emission monitoring initiatives (e.g. German ITMS consortium; CAMS and carbon tracker).

B. Hyper local air quality modelling with Large Eddy Simulation (LES) models will be applied to calculate high resolution air quality and urban climate studies, enabling to address also spatial planning and biobased solutions. Outside the environmental realm, high resolution atmospheric turbulence and composition can be applied to optical signal propagation for detection and communication purposes. The main partners are TUD, VU and WUR within the framework of Ruisdael and PIP (3 postdocs) as well as the Freie Universität Berlin (1 postdoc) and Leibniz Universität Hannover (LES developers). TNO will take the lead on applications and emission information in the DALES consortium.

C. Assimilation of satellite and sensor data can be applied for verification of regional air pollutant and greenhouse gas inventories and policies. Furthermore, the optimal estimates allow for nowcasting and short-term forecasting purposes. The main partners are CML, KNMI and TUD. Currently, a national knowledge program on using satellite data to evaluate and verify the emissions of nitrogen oxides and ammonia is under negotiation, and the knowledge developed in the national knowledge program will be applied in the model system. Collaboration with international colleagues at US-EPA and University of Toronto is established.

D. System integration & demonstration will result in a model system that can be applied for assessing integrated environmental issues. It can be used for assessing personal exposure, for studying the effect of mitigation options on hyperlocal air quality or for assessing the origin of nitrogen deposition.

For the latter a national knowledge program on modelling nitrogen deposition in collaboration with RIVM, CML, KNMI and WUR will start in is under negotiation and will most likely start in Q4 2021.

In 2022, we aim to provide source apportionment information for sensor networks in the Netherlands openly to attract a user community. Later, we envisage to provide the high-resolution maps openly to allow for industry to develop services on it. Other applications will become available when this model system is (partially) developed, such as air pollution-adapted routing for vehicles, early warning systems for hazardous chemicals, modal shift solutions and green labelling of the transport sectors like shipping, hereby supporting abatement measures on emissions and service spin-offs for companies.

From the start we will assemble a stakeholder group to take them along in the development of the model system and its applications. Envisioned stakeholders are (regional) governments (e.g. I&W, LNV, UBA, Noord-Brabant, DCMR), Research institutes (e.g. KNMI, RIVM, ESA), and NGOs (e.g. Longfonds; Natuur en Milieu, Urgenda). Other outreach to the envisioned user community is foreseen (e.g. NPoV). Where possible, additional funding (matching) will be attracted to strengthen the ERP.

Results 2021 and plan year 2022

3. Results 2021

- **Results achieved in previous Full ERP year(s)**

ERP Climate and Air Quality started in 2021. Hence, there is no heritage from earlier years, except for the ERP plan and the seed-ERP demonstrator results.
The activities in 2021 focussed on the development of data driven methodologies to specify emission variability, hyper local air quality modelling and model evaluation using sensor and satellite data.

A. Dynamic anthropogenic emissions

- A downscaling methodology for remapping 1x1 Km resolution data from the emission registration into a 25m resolution emission map was developed and used to provide a baseline emission map for Eindhoven domain. During the ERP the baseline will be replaced sector by sector by more detailed information.
- For road transport augmented emission maps (AEMs) describing the relation between the emission of NOx and CO2 as function of vehicle acceleration and speed were developed based on SEMS data. Analysis showed that cold-start emissions dominate the emissions of the newest cars, meaning a spatial emission distribution maximizing in areas where trips start whereas older cars emit largely on the main road network.
- After identification of relevant AI techniques, several approaches (clustering, TCN, LSTM) were implemented to explore the potential for forecasting activities on natural gas consumption. Activities on the more complex case of traffic flow data has started.
- The location and types of 800 restaurants in Eindhoven were mined from open-street-maps, which are currently combined with building information and delivery activity to estimate emissions.

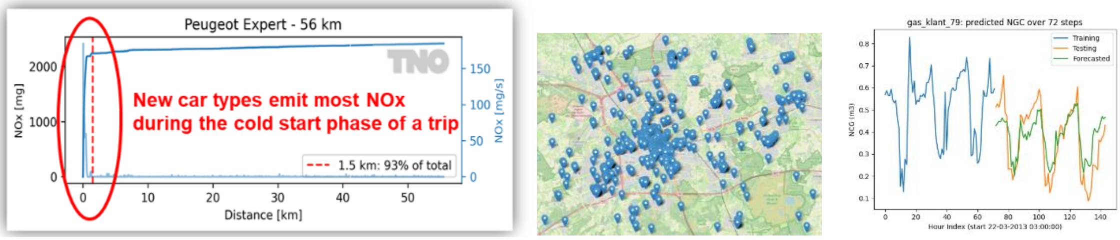


Figure 27: SEMS based cumulative NOx emission profile for a single trip (left); Restaurant locations mined from OpenStreetMap (middle); AI based forecast of natural gas use by a household (right)

B. Hyper local air quality modelling

- A module reading static emission data into DALES was developed based on annual average emissions per source sector modified by static time profiles.
- A module dealing with different types of land use was expanded and connected to TOPNL 10m land use maps
- The implementation of DALES was improved on a number of points including a shell of Python scripts to improve user friendliness and increase efficiency of compiling, configuring, running and post-processing DALES.
- The domain of the calculations was increased to cover 22.4 x 16 km^2, spanning the urban area of the city of Eindhoven and its periphery. First calculations of the dispersion of CO2 and NOx as passive tracers were performed for a summer day (August 17, 2016) with a resolution of 50 x 50 x 20 m^3. Different cases were modelled for both homogeneous and mixed land use with low vegetation, high vegetation, water surfaces, asphalt, and bare soil, and are currently used for evaluation.

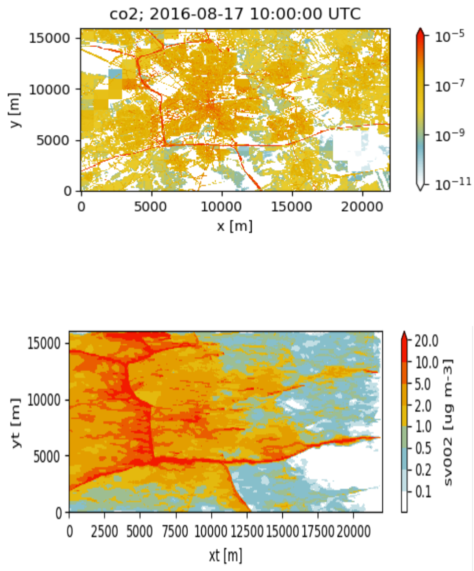


Figure 28. Static CO_2 emission (upper panel) and NOx concentration map (lower panel) for 10:00 a.m. on a typical summer day

C. Assimilation of satellite and sensor data

- A LOTOS-EUROS simulation over the Netherlands at 2x2 km resolution covering 2015-2017 was evaluated to quantify the base performance. Table 5 clearly illustrates that the explained temporal variability is especially low for primary components, such as NOx, NH3, SO2 and PM10. PM2.5 and NO2 show largest deviations during cold, stagnant conditions. Errors in ozone and PM10 show a different behaviour with maximum values during hot summer conditions. The different behaviour hints at specific shortcomings for the major source sectors for these pollutants.

Table 5. Evaluation results for a three year LOTOS-EUROS simulation in comparison to daily mean observations in the Dutch monitoring network

Pollutant	**Average concentration (µg/m^3)**	**Bias (µg/m^3)**	**R^2**
BC	0.68	-0.14	0.68
CO	199.0	-3.0	0.68
NH_3	11.1	-4.4	0.20
NO	3.3	1.6	0.46
NO_2	15.3	2.4	0.59
O_3	45.8	3.0	0.72
PM10	17.0	7.7	0.43
PM2.5	10.2	-0.73	0.61
SO_2	1.1	0.92	0.25

D. System integration of multi-scale model system & demonstration

- No activities in 2021

Publications

- Super, I., et al.: The impact of temporal variability in prior emissions on the optimization of urban anthropogenic emissions of CO2, CH4 and CO using in-situ observations, Atmos. Environ. X, 11, 100119
- Khan, B., et al.: Development of an atmospheric chemistry model coupled to the PALM model system 6.0: implementation and first applications, Geosci. Model Dev., 14, 1171–1193, 2021
- Ciais, et al.: Impact of lockdowns and winter temperatures on natural gas consumption in Europe, submitted to Earths future, 10.1002/essoar.10507326.1

4. Plan year 2022

- **Focus Year 2022**

The main foci in 2022 are i) on the development of emission models for traffic and agriculture (WP-A), ii) on the validation of these new emission components (WP-C) and iii) on the implementation of a prototype operational system (WP-D). The high resolution emission data for the region of Eindhoven will be fed into DALES, in which deposition and boundary conditions routines will be implemented to study nitrogen deposition patterns (WP-B).

- **Activities Year 2022**

A. Dynamic anthropogenic emissions

Road transport: Emission behaviour of modern cars differs largely from older models. It is therefore required to include more detail with regards to which vehicles are driving when and where, and how they're driven, to allow for a proper distribution of traffic emissions. This is especially challenging for urban centres as traffic monitoring is hardly available. In 2022 we will focus on:

- To infer likely starting points of vehicle trips for the relevant vehicle types from vehicle registration data.
- To infer different activity patterns for relevant vehicle types (old petrol vehicles used primarily for shopping trips in the afternoon or taking children to school, vs. newer vehicles commuting in peak hour traffic). This will be aggregated to average behaviour profiles for the four different urban road types defined in SRM-1. Where the available data is sufficient, this will also be done for roads with a specific maximum speed limit.
- We will use traffic monitoring data to investigate in how far rain and cold weather may lead to a different on-road fleet composition and higher congestion due to less use of alternative modes of transportation.
- For highways and main roads deep neural networks we will continue to analyse the traffic activity and develop 72 hour forecasting routines.
- Traffic activity patterns will be linked to the augmented emission maps (new & existing) to allow for localised emission estimates. Typical road link patterns will be derived as input to the urban emission mapping.

Investigations of the applicability and integration of various additional traffic data sources will continue. Obtaining floating car data and access to the Eindhoven traffic model will be pursued.

Agriculture: For agriculture we will introduce meteorological dependent timing of key activities and emissions:

- Integrate field based cropping information into the agricultural activity and emission timer (TIMELINES) for manure spreading (NH_3); harvesting (PM) and machinery use (PM, NO_x)). Validation of the module to in-situ activity information. Emission factors to be obtained from WUR.
- Connect the existing meteo-dependent emission parametrization for housing to the ER housing emission dataset (NH_3, PM) resulting in hourly, point based emission estimates.

B. Hyper local air quality modelling

The key objective for 2022 is to further enhance DALES in cooperation with the Ruisdael consortium and use the developments to quantify the impact of landscape architecture on ammonia deposition at a nature area in the demonstrator domain.

- To better incorporate the large scale meteorology and allow for longer simulations a scheme will be developed to use the meteorological fields from ECMWF as boundary conditions with turbulent spinup.
- Replace current constant chemical boundary condition profiles by 1) time and space dependent 3D fields originating from LOTOS-EUROS and 2) observations from a rural background station.
- Adapt the LOTOS-EUROS deposition modules to the land use classification in DALES and test the implementation in DALES.
- Ammonia emissions from animal housing as well as manure spreading will be taken (WP-A) to demonstrate the ability to perform process studies for nitrogen deposition. Different landscape structures will be modelled to quantify the impact of landscape architecture on the ammonia deposition over a nature area.

C. Assimilation of satellite and sensor data

WP-C will focus on the (continuous) validation of the model system:

- Quantify the impact of dynamic emissions from WP-A on the LOTOS-EUROS performance against LML data.
- First evaluation of the urban increments provided by the DALES simulations in comparison to LML station and sensor network data in Eindhoven
- Strategies to evaluate national emission distributions from NO_2 and NH_3 satellite data will be performed in the expected national knowledge program on remote sensing applications for nitrogen monitoring.

D. System integration of multi-scale model system & demonstration

The key objective is to start streamlining processes and build a first prototype of the operational NRT emission model. This consists of three important activities focused around the management of models and data:

- Development of an architecture for automatic data acquisition and storing based on the FAIR data principles, re-using existing open source tooling such as feature stores. The system will be demonstrated and tested on NRT production information from the power sector (ENTSO-E).
- Implement the emission modules of WP-A (residential combustion, restaurants and agriculture) in an operational emission model (v1.0). Sub modules will include the spatial allocation,

meteorological data, calendar, sector dependent activity timers and emission functions as well as plume rise to enable 4D emission forecasts (hourly).
- Incorporation of the 72h emissions into TOPAS and demonstration of the impact on air quality forecasts and PM source apportionment.

- **Deliverables Year 2022**

The key results in 2022 will be:

WP-A:
- Allocation algorithms for cold starts, road type dependent behaviour and emission profiles
- Detailed (urban) traffic activity patterns and a methodology to link these activity patterns to AEMs
- Crop dependent agricultural activity timer, housing emission routine

WP-B:
- DALES model version including 3D boundary conditions and deposition routines…
- Paper on influence of landscape architecture on ammonia deposition distribution over a nature area

WP-C:
- Paper on the impact of dynamic emissions on LOTOS-EUROS performance

WP-D:
- Technical documentation of the operational emission model including meteo-dependent emissions for households and agriculture and NRT emission predictions for road transport and large point sources
- An architecture and an initial implementation for collecting, processing and storing all data following the FAIR data principles
- Daily provision of 72hr emission and air quality forecasts for the Netherlands (hourly, 1x1 km2)

PM:
- Stakeholder workshop

12: Circular Structures

ERP Contacts: F. Cinquini (Program Manager), A. Bigaj-vanVliet, S. Valcke (Lead Scientists), A. Adriaanse (Science Director)
ERP Duration: 2018 – 2021

Overall program description

1. Context and Objectives

- **Problem definition**

Targets of 55% CO_2 and 50% primary material reduction by 2030 are set in the 2030 Climate Target Plan and the Green Deal highlights the construction sector as one of the 5 key industries to contribute to reaching these targets[7]. Enabling sustainable development is a complex, multi-disciplinary and multi-sectoral challenge with often contradicting objectives. As such, often arbitrarily chosen single aspects of the challenge are subject of innovations in the strongly fragmented Dutch construction sector. This is highly problematic as this sector is responsible for up to 10% of the total CO_2 and nearly half of the annual waste emission in the Netherlands. Hence, the construction sector faces a massive challenge to play a sizable role in achieving the 2030 climate ambitions. A material with foremost impact in the construction sector is concrete (3% of Dutch CO_2 emissions and >50% of annual waste). Therefore the construction sector and government launched the Concrete Agreement (Betonakkoord, 2018), declaring that by 2030 all construction and demolition waste (CDW) from existing concrete structures must be reused in new concrete. The quality and performance of CDW is currently unpredictable, so it is only used in limited percentages (only 2% of the 22 Mton/year of stony CDW, is reused in new concrete (33 Mton/year)). As a result, the concrete sector is seeking a breakthrough in (A) predictability of performance and risk of using CDW as well as (B) decision support in prioritizing solutions within the multi-objective context of sustainability, otherwise they are to fail in setting a cost-effective path to achieving their goals for 2030[8].

The overall goal of the ERP Circular Strutures is to develop methods, models and tools for sustainability-oriented and supply quality based, multi-objective design of structures. This will (A) allow using increased levels of CDW with predicted risks & gains and (B) support decision making for simultaneously reaching optimum in social wellbeing (incl safety), environmental impact (incl CO_2 & circularity) & economic performance (costs). As such we can support the whole chain in well-found prioritization of optimal cost-efficient sustainable solutions to reach 100% reuse and 50% CO_2 reduction in 2030, for various perspectives of stakeholders (recyclers, engineers, owners).

- **Expected impact to stakeholders**

Sustainable solutions for concrete structures have a vast <u>societal impact</u>, as the ERP approach can be used to optimize concrete structures <u>simultaneously</u> for safety, circularity, CO_2 emission and cost efficiency. In terms of circularity, CDW (22 Mton/year) is the one and only secondary resource that has sufficient volume to reduce more than 50% of primary materials in new concrete (33 Mton/year). In terms of environmental impact, 50% reduction of concrete CO_2 emissions will result in 20% of the emissions related to the construction sector, which is 2% of the total Dutch CO_2 emissions. And, last

[7] The European Green Deal. 2019. Communication from the commission to the European Parliament, the European Council, the Council, the European economic and social committee and the committee of the regions. Brussels, 11-12-2019
[8] Letter of Jaqueline Cramer on behalf of the 'Betonakkoord' to directors of Ministries IenW, BZK, EZK. d.d. 12-06-2020

but not least, 70% of the concrete produced is applied with a structural purpose, hence largely responsible for safety of structures. The concrete sector has repeatedly expressed their concerns that safety currently is ensured by higher cement contents (hence CO_2 emissions) to compensate for uncertainties in CDW quality (contrasting objectives of safety vs environment). In 2021 it was shown when using our ERP approach in which CDW quality is quantified and used in models, not only safety targets were obtained, but also at least 20% reductions in primary material and CO_2 could already be reached. As such, awareness is successfully raised about the potential of the ERP solution to contribute to societal impact proven by new partnerships and spin-off projects established throughout the entire chain.

Also, sustainable innovations in the concrete sector are <u>economically attractive</u> because the (investment) costs are much lower to reach a high societal impact (see above) compared to other sectors[9]. Nevertheless, because of low margins in the sector, cost-efficiency remains a barrier[9]. Our ERP approach helps stakeholders of the entire chain to optimize (conceptual to detailed) sustainable design of concrete structures to be cost-efficient because their value perspective can be entered prior to the multi-objective optimization. Because the ERP approach comes with simultaneous insight in quality, risks and gains, clients are more easily convinced and CO_2 taxes can be lowered. Also, new (collaborative) business models can be supported in which transparency and predictability of risks & gains for multiple objectives helps to overcome the current fragmentation of the chain, currently refraining the sector from progress in circularity. All in all, the Dutch frontrunner and export position in construction knowledge and industrialization (internationally renowned pre-cast industry) will be strengthened.

2. Approach

- **Focus**

This project aims to deliver a novel and transparent design framework for multi-objective optimization & decision support for design of sustainable structures made of CDW, in which the CDW quality serves as one of the design constraints. A range of non-traditional solutions based on CDW is being addressed incl. reuse of reclaimed elements, use of recycled concrete aggregates and use of binders based on CDW. The latter is supported by establishing technology for cement replacement with novel CDW-based binders (RL3). The multi-objective parametric design (RL1) will generate a set of optimized design alternatives, allowing engineers and decision makers to rapidly explore and optimize designs at various stages and to select the most preferable solution. To enable design with reclaimed materials, the set of design criteria, multi-parametric models and the evaluation framework (RL2) will be developed, accommodating all aspects of sustainable design. The approach contains short and long term objectives organized along three related research lines (RL) & a use case – stakeholders line (Figure):

- <u>*Research Line 1: multi-objective optimization of design and decision analysis for sustainable structures,*</u> aims to develop an algorithm-based design optimisation method and decision-support tool for concrete structures based on integration of supply quality and uncertainties treatment in parametric models (coming from RL2) and on optimized evaluation of conflicting objectives and requirements of social well-being (incl. structural safety), environmental impact, and economic performance (incl. life-cycle costs).
- <u>*Research Line 2: new generation parametric quality-based performance modelling (structural, environmental, economic),*</u> focuses on development of performance models that enable

[9] Macro-economische verkenning Betonakkoord. Zuidema, M., Saitua, R., Smit, N. Uitgegeven door Economisch Instituut voor de Bouw (EIB) in 2016.

integration of quality parameters of CDW and are fit for performance evaluation for circular solutions for concrete structures in life-cycle design. This is done for all levels of circularity, from reuse of entire structural components to reuse of all fractions of crushed rubble (incl. use of CDW-based binders based on results of RL3).

- *Research Line 3: quality & performance of secondary materials based on CDW,* focuses on supply quality enhancement: in order to get the maximum value out of CDW the low-CO_2 binders based on CDW are enabled, which is needed to accomplish >50% cement replacement by CDW. Solutions for activation & binder technology are based on principles of molecular dynamics in both inorganic and organic chemistry, solutions for alternative matrix composition will use principles of optimized packing and mix design. This is the input for Modelling of structural concrete with CDW-based binders in RL2.
- *Use Case & Stakeholders :* Although this is an *early* research project, it contains a use case line that is aimed at scoping, guiding and monitoring the research as well as ensuring a successful implementation and demonstration of the benefit of 100% CDW reuse, resulting in 50% CO_2 and primary material reduction. This track integrates RL1 - 3 and is executed in very close interaction with stakeholders (see partnerships).

- **Research plan**

In Figure , the 4-year plan is illustrated showing targeted goals in time per research line. Each of the target arrows is described in the text below as well as the relation between the RLs.

Research Line 1 : Multi-objective optimization:

The overall R&D aim of Research Line 1 (RL1) is equal to its focus described above. RL1 develops the tool to implement the models of RL2 and to perform the optimization for the design parameters and objectives and decision support framework as set in the use case & stakeholders line. Activities in the RL1 follow the targets in the roadmap:

- **implementing robust techniques for multi-objective optimization:** combining the EVEReST optimization technology with decision trees to create a decision support framework that incorporates domain expert knowledge and interactive visualization of multi-objective and multi-stage optimization results.
- **enabling decision analysis under uncertainties**, to include additional sources of information, uncertainties and learning from measurements over time, incl. extension towards a model-based decision support system with a more explicit uncertainty quantification component, allowing the multi-objective optimization methods to be used with risk objectives next to the performance objectives considered so far.
- **enabling sequential chain of optimization** incl. turning the sequential multi-stage (conceptual to detailed) optimization into a closed-loop framework that can account for the time aspect of decisions and the outcome of information gathering activities, which will enable practitioners to incorporate new data into the decision making process and support a broader class of more dynamic design problems.
- **enabling treatment of high complexity / high dimension problems** incl. case studies with increasing model and problem complexity for a convincing demonstration of the developed optimization capabilities.

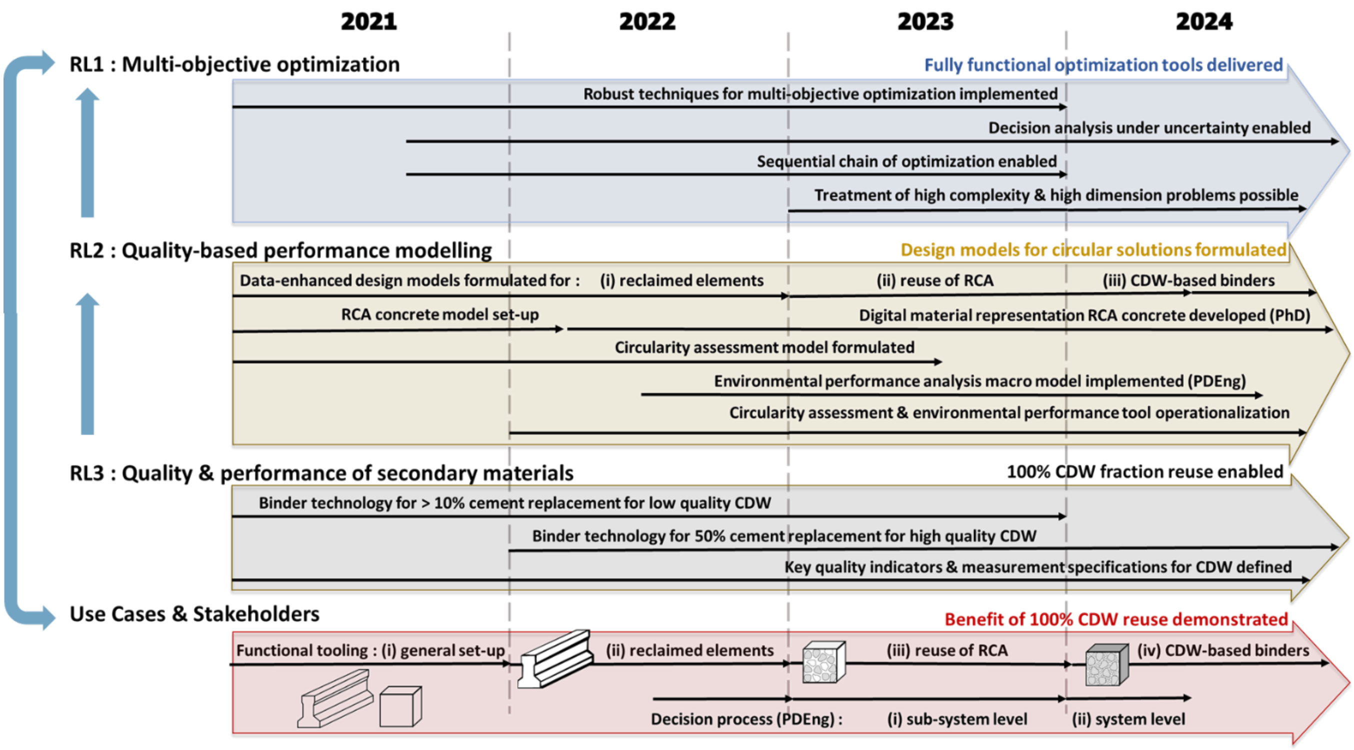


Figure 29: ERP Circular Structures Roadmap 2021-24 incl. research tracks, activities and timeline visualization

Research Line 2 : Quality-based performance modeling:

The overall R&D aim of Research Line 2 (RL2) is equal to its focus described in 2. RL2 develops the parametric models and risk & reliability framework to be implemented in RL1. The models are developed specifically for the relevant aspects of the use cases and notably RL3 supplies the key material parameters to be included. Activities in the RL2 follow the targets in the roadmap:

- **formulating data-enhanced structural design models for circular solutions** (reclaimed elements, structural applications of CDW-based aggregate and structural concrete with CDW-based binders) incl.: (i) uncertainty quantification and treatment, (ii) identification of key measurable parameters and quantification of relevant uncertainties in structural performance models, customization of safety analysis formats and partial safety factors, (iii) integration of quality data in determination of residual durability of reclaimed elements.
- **developing digital material representation of CDW-based concrete (PhD track TUDelft)** incl. (i) predicting constitutive behaviour of the concrete with up to 100% replacement with Recycled Concrete Aggregate (RCA) as a function of its mix design and the properties of the RCA, and based on variable concrete mix design parameters, (ii) integration into structural analysis of concrete structures and validation of design formulas (especially when higher replacements of RCA are used).
- **formulating new generation of environmental impact models for circular solutions** incl.: (i) formulation of circularity assessment model considering thermodynamic indicators, (ii) identification of the consequences of increased demand for secondary materials and development of environmental performance macro model (**PDEng UTwente**), (iii) operationalizing of the knowledge and implementation of the models in the tool (robustness of models, approaches and indicators) (**PDEng UTwente**)

Research Line 3 : Quality & performance of secondary materials :

The overall R&D aim of Research Line 3 (RL3) is equal to its focus described in 2. RL3 develops the theory behind the key quality characteristics to be used in the performance models in RL2 and be part of the input design parameters in RL1. Activities in the RL3 address:

- **development of binder technology for > 10% cement replacement for low quality CDW** and further developing this **for 50% cement replacement for high quality CDW** incl. molecular based (in)organic chemistry principles for deducing adequate additives and dosages
- **definition of key quality & measurement specifications for CDW** incl. development of a procedure for combining tailored in-house measurement tools to quantify fluctuations in CDW in relation to performance

Research Line: Use Case & Stakeholders :

Activities in the Use Case & Stakeholders line address:

- **demonstration of functional tooling** for design optimization, with progressive refinement of design complexity and scenarios of the use cases. After setting up **general format for study case** in 2021, in the following years effort is made to fully demonstrate capability of the tools and methods for: **reclaimed elements** (2022), **reuse of RCA** in structural applications (2023) and **use of CWD-based binders** as cement replacement (2024).
- **implementation framework for decision process** based on multi-objective design optimization, from the **'sub-system' level** (e.g., combination of concrete elements) to the entire **system-level** (e.g., concrete system of a bridge) incl. (i) development of a decision procedure for stakeholders to frame their *perspective of value and hierarchy* in the various sustainability indicators and (ii) the comparison of multi-objective optimization outputs with actual decisions leading to refinement of decision support framework (**PDEng**).

- **Targeted partnerships**

Co-developing knowledge partners: TU Delft Civil Engineering (Prof. M. Hendriks, dr. M. Lukovic) is involved in the planning of the intended PhD on parametric structural performance modelling (RL 2), with an option to apply for NWO funding[10]. University of Twente Faculty of Engineering Technology is partner for 2 PDEngs on modelling and quantifying circularity indicators (RL 2) and on decision-making process for circularity (RL1 & Use Case & Stakeholders line). Connection to national (e.g. BTIC and CB'23) and international (RILEM, fib, JSCC, JRC) knowledge platforms is done for all RLs. In particular, University of Barcelona (UPC) is our sparring partner in use case specific design & decision support processes.

Customers and other stakeholders involved in use case demonstration: Recycling company TweeR (ultrafine CDW separation) is involved to provide tailored CDW. Lagemaat (demolition and recycling company) and VBI (precast concrete floors) provide boundary conditions for scoping the use case of reclaimed slab elements and Nebest (concrete consultancy) for reclaimed beams. Antea (leading civil engineering company) and Consolis (designer and manufacturer of prefabricated concrete structures) have accepted to evaluate design tools developed in the project. RWS and Gemeente Rotterdam, infra and buildings stock owners, provide expert opinion on implementation of the multi-objective optimisation in decision processes and procurement.

[10] NWO call under Dutch Research Agenda Theme: Transition to a circular and emission-free building industry (2022)

Results 2021 and plan year 2022

3. Results 2021

- **Results achieved in 2021 (research 2021 ongoing - results until August 2021)**

Research Line 1 : Multi-objective optimization

In 2021, fully automated workflow of new multi-objective optimization methods was implemented for the first time in structural engineering using TNO's EVEReST optimization tool. The new methods follow a **hierarchical optimization method,** that enables the decision makers to specify a ranking of the objectives along with the acceptable compromise or desired increase in terms of the primary and secondary objectives. As such preferences can be expressed more directly instead of weighting factors that become less intuitive for multiple objectives. The new method is computationally faster than current multi-objective approaches. Results via the use case obtained with the hierarchical lexicographic methods also show additional technical benefits of the new approach: the Pareto front can be sampled in a more controlled manner, avoiding unnecessary calculations to be performed to map the set of optimized solutions for varying preferences of decision maker. Also, the basic principle was set to be implemented in EVEReST to follow a **sequence of optimizations with focus on different design variables,** using models with different levels of detail and accounting for different objectives and constraints. This enables more complex design problems to be addressed more realistically, which is useful to support decision making in various domains (also beyond the context of buildings and structures design).

Research Line 2 : Quality-based performance modeling

Data-enhanced structural design models: In 2021, listing and prioritization was done of the research and standardization needed to overcome issues arising from the application of the current design standards to non-traditional circular design solutions. A **position paper on the design of concrete structures with non-traditional circular solutions** is currently drafted, addressing the basic design principles (safety philosophy, execution and quality control), structural design provisions (assessment of material uncertainties in the limit state approach, end of service life considering durability-related information, partial factor and full probabilistic formats for safety assessment, design by avoidance, design assisted by testing or monitoring etc). In addition, the concept of the **design service life calculator for reclaimed elements** has been developed. This tool comprises the set of models, data and methods to be used in real cases.

Digital material representation of RCA-based concrete: In 2021, literature study was conducted on the reuse of old concrete in new structures. Main issues in predictive modelling are the complexity of mixture optimization of RAC due to the variability of recycled aggregates properties, e.g. density and old paste content. The major technological challenge is the formulation of a multiscale framework by a mathematical model describing the behaviour of interest at a given microscale, allowing the upscaling of the model to macro (structural) scale. Most suitable modelling options were analyzed incl. (un)coupled hierarchical multiscale models and concurrent models, giving basis to the PhD research concept.

N**ew generation of environmental impact models**: In 2021, state-of-the-art on circularity indicators has been reviewed and thermodynamic indicators were assessed for their suitability in multi-objective optimization for concrete structures. The most suitable thermodynamic indicator in our case is cumulative exergy demand as a measure for resource efficiency putting material and energy in relation to each other. As opposed to other thermodynamic indicators as (statistical) entropy, exergy data are readily available in Eco-Invent database, although gaps were identified for concrete. Statistical entropy was found to be less applicable as it reflects dilution steps that are too complex to define in case of heterogeneous concrete. In interaction with RL1, it was agreed that circularity does not need to be grasped in one single indicator. In that respect, in the coming years a macro- indicator will be developed zooming out of the Life Cycle Analysis (LCA) application boundaries to reflect the impact on material flows, e.g., pressure of secondary material use on transport distances or on other systems depending on the same resources etc.

Research Line 3 : Quality & performance of secondary materials for sustainable structures'
In 2021, a unique combination of **measurement tools** is tailored in-house to our needs: zeta-potentiometer tailored for highly concentrated pastes of CDW and additives, calorimetry for heterogenous samples, ICP-OES for high silica contents. By using this combination of techniques for 4 differently processed ultrafine CDW fractions and additives, the principle was shown that performance of CDW can be interpreted in relation to its key characteristics as well as its specific combination with additives. **Successful cement replacements up to 50% were achieved in 2020 while other qualities in 2021 would not allow more than 10% replacement.** It was found that **soluble Ca-content and left-over organic components from the old concrete are key characteristics** that determine the performance and as such in future can be key parameters in the optimization. The (adverse) effect of left-over organics could be understood based on the molecular theory as outlined in 2020 for this project.

Research Line: Use Case & Stakeholders
In 2021, the simplified use cases of 2020 (a reused floor slab and recycled concrete aggregate for a floor slab) were continued and refined on the following aspects: a higher number of environmental indicators as well as actual costs were implemented in the use case models (coding to follow). The two cases were de-bugged, compared and found to show robust outcomes using two different algorithmic approaches (jMetalpy & EverEST). Visualization of multi-objective optimization results showed to be crucial: the sampling of Pareto front plots with representation of respective optimized solutions allows optimization specialists to communicate more effectively and support decision processes. Major effort has been made to mobilize relevant stakeholders and establish collaboration for the coming years (see paragraph 2.4 Targeted partnership).

4. Plan year 2022

- **Focus, Activities and Deliverables year 2022**

The plan for 2022 consists of 4 strongly aligned Work Packages (WPs) and Project Management (PM).

WP1 -> RL1 : Multi-objective optimization

Focus **:** The 2022 aim is to consolidate and start leveraging the new multi-objective methods set up in 2021 by applying them to case studies with increasing complexity. The application of these methods in closer collaboration with end-user domain experts will help to guide further development of interactive visualization of multi-objective optimization results.

Activities 2022: The task related to multi-stage decision making will continue with further investigation of *sequential optimization approaches* supported by the decision analytics tools and decision trees to create a decision support framework. This is also the basis to start the research and development of *optimization approaches which can take into account additional sources of information*, uncertainties and learning from measurements over time, linking to other research lines of the ERP.

Deliverables 2022: (i) Basis of decision support framework by combining EVEReST optimisation technology with approaches of hierarchical decision trees and sequential chain of models, (ii) Proof of concept interactive visualization of multi-objective and multi-stage optimization results.

<u>WP2 -> RL2 : Quality-based performance modeling</u>

- **Data-enhanced structural design models**

Focus **:** The 2022 aim is to develop the safety framework at semi-probabilistic level for predicting performance & risks in design of new structures using reclaimed elements. The focus is on reclaimed prefabricated prestressed elements because of their relative easiness of dismantlement and reuse as loadbearing elements and the availability of a sufficiently high number of elements with the same nominal properties. The current rules of partial factors for the design of new traditional structures (Eurocodes) and for the assessment of existing structures do not fully address the design of new structures with reclaimed elements.

Activities 2022: (i) development of novel safety framework addressing the needs of standardization of asset owners, contractors and engineering companies, enabling the assessment of the design value of the loadbearing capacity of reclaimed elements at the end of their second life.

Deliverables 2022: (i) procedure for updating the partial factors for the partial factors on the resistance side and for the self-weight of the reclaimed element (the updated partial factors on the resistance side will account for the available information about the quality of CDW), (ii) Testing protocol for reclaimed elements and procedure for data-informed determination of service life and capacity for design (design documentation, assessing actual reinforcement & residual prestress level, carbonation and chloride tests, load tests, monitoring, ...).

- **Digital material representation of RCA-based concrete**

Focus **:** The 2022 aim is to set-up modelling and experimental validation plan for the PhD. Considering that state-of-the art research shows that recycled concrete aggregate (RCA) begins to have an appreciable effect on ultimate service life behaviour of structures at high replacement levels, focus of the PhD is on replacement above 50% and on the effect of the mix design on structural behaviour of reinforced concrete members.

Activities 2022: (i) starting PhD track with TU Delft , (ii) setting boundary conditions for numerical modelling of the constitutive behaviour of concrete with up to 100% primary aggregate replacement by RCA as a function of concrete mix design and RCA properties.

Deliverables 2022: (i) detailed PhD plan, (ii) set-up of multiscale model for digital material representation of RCA-based concrete (coarse and fine aggregate replacement), (iii) set-up of experimental investigation for model validation at material scale.

- **New generation of environmental impact models**

Focus **:** The 2022 aim is to further develop the circularity indicators selected in 2021 and implement them in the multi-objective assessment tool along with environmental impact indicators, this beyond state-of-the-art approach ***ensures*** that a higher material supply security (circularity) is coupled to better environmental performance. Furthermore, the consequences of introducing secondary materials to the supply chain, transport distances and secondary material processing will be mapped by broadening the scope of the analysis and zooming out to a macroeconomic level showing interactions between the construction sector and other sectors of the economy.

Activities 2022: (i) further formulation of environmental and circularity assessment focussed on exergy, (ii) setting-up PDEng track with the Univ. of Twente and initiation of detailed Micro to Macro overview and (iii) operationalizing the knowledge in strong connection with the use case line.

Deliverables 2022: (i) Validation of cumulative exergy demand (eco-efficiency) as a circularity indicator ready to be implemented in the optimization tool and calculation of exergy demand for two types of cement, (ii) Proof of Concept of a macro-indicator on supply & demand 'balance' to be implemented as additional circularity indicator, (iii) PDEng plan incl. literature.

<u>*WP3 -> RL3 : Quality & performance of secondary materials*</u>

Focus **:**. In 2022 CDW research focus continues on the CDW quality improvement and mix design to enable above 10% cement replacement. Particular attention hereby is paid to reproducibility in relation to quality variations and mix design based on CDW characteristics, smart packing, appropriate additives and mix design experience gained in 2021. Also, the origin of the discovered differences in key quality characteristics of CDW (organic components and soluble Ca) will be investigated in relation to the recycling process and input concrete.

Activities 2022: (i) Further development of the measurement procedures as tailored in 2021 in relation with two experimental validation activities: (ii) determination of performance of different CDW qualities in optimised binder & mortar combinations and (iii) investigation of the origin and influence of fluctuations in organic and soluble Ca-compounds in the CDW.

Deliverables 2022: (i) Optimised performance of CDW combinations at mortar level in relation to CDW characteristics; (ii) validated hypothesis on the origin and influence of fluctuations in organic and soluble Ca-compounds in the CDW to be used for modelling in RL2 and for optimisation and quality control of recycling techniques.

<u>*WP4 -> Use Case & Stakeholders*</u>

Focus For 2022 a use case will focus on reuse of reclaimed elements, while decision support process investigation will target sub-system level decisions. This shall lead to strengthening of 2021 partnership with Nebest, Antea, VBI and other stakeholders for input design use cases & decision processes***.***

Activities 2022: (i) inventory of possible new materials and reused material components for a selected use case incl. relevant engineering model, design parametrization, selection of indicators and decision hierarchy, (ii) comparison of optimised use case with a current traditional approach, (iii) stakeholder survey on decision processes & value.

Deliverables 2022 (i) demonstration of complex design optimization for reuse of reclaimed elements, (ii) mock-up of interactive visualisation of optimisation results, (iii) described use case on sub-system level for decision support framework, (iv) stakeholder position on decision processes & value

13: Auto ADAPT

ERP Contacts: R. Corbeij (Project Lead), F. Willems (Lead Scientist), M. Martens (Science Director)
ERP Duration: 2022 – 2025

Overall program description

1. Context and Objectives

- **Problem definition**

Industry is facing a turning point in control development for modern, increasingly complex and connected systems. With traditional engineering methods, the development time and costs reach unacceptable levels. Guaranteeing robust, optimal performance is becoming less feasible and, as a result, large safety margins are introduced to deal with system deviations. This compromises overall system performance. In addition, traditional systems are not well-prepared for unforeseen conditions for which no solutions can be provided at design time, as they lack the flexibility to deal with internal (e.g., aging) or external change (e.g., tasks, environment) at run-time.
If future systems are to contribute to a sustainable society and drive a competitive industry, they must operate at optimal performance for the maximum of their potential lifetime. This requires adaptivity at run-time and thus innovative methods that optimize system performance by automatically tuning the system's control: truly **self-adaptive systems**. Based on discussions with industry, we foresee self-adaptive methods to have a strong impact in a wide range of application areas and markets.

- **Expected impact to stakeholders**

1. Accelerated introduction of climate neutral solutions by self-learning energy management in transportation, electric grids, and heat power applications. We maximize efficiency, availability and uptime. In infrastructure systems, like electric charging stations and micro electric grids, where it is crucial to handle unknown, long-term dynamics' system conduct, this minimizes CO_2 emissions and the added performance robustness supports the use of local energy production. In electrified on-road transportation, it guarantees sufficient driving range and allows to meet pollutant emission targets around Zero Emission zones.
2. Maximal system availability, profitability, and up-time through extended system's useful life by smart system usage and self-reconfiguration and -healing based on knowledge of long-term component behavior and system capability. For expensive and durable systems, e.g., ships, space-based instruments, and manufacturing systems, self-adaptive methods keep systems performant over an extended useful life. For batteries, lifetime cost reductions of 20% are foreseen by smart charging strategies and their extended useful life directly contributes to minimal usage of precious materials and energy in production.
3. Strengthen industry competitiveness by reducing time-to-market and system costs with self-adaptive systems with their minimized integration needs. The automotive industry foresees up to 80% reduction in development time and costs, which will enhance the market position of partners, incl. VDL, Lightyear, and DAF, while, the Free-Space Optics (FSO)-consortium targets reduced time-to-market and cost prices to gain the edge over international competition, creating a new multi-million business.
4. Reduced operational costs by guaranteeing high performance over a wider range of conditions**.** For vehicle energy management, 30% reduction of operational costs are expected compared to conventional strategies. Total-costs-of-ownership is further reduced by maximized availability.

2. Approach

• Focus

This new Full ERP aims to develop self-adaptive methods to optimize overall system performance with minimal efforts by changing the controlled system's behavior and configuration. We envision to fuse computational science and physical modelling with data-based learning for self-learned adaptation and optimization of system control:

1) Awareness**:** characterize environmental and operational impact factors on system performance to estimate and predict system's capabilities given its context. We integrate hybrid data-driven and physics-based modelling with probabilistic reasoning, which deals with system and observation uncertainties.
2) Optimization**:** develop a scalable, multi-objective optimization method based on constraint mechanisms. This method links system characteristics data from the awareness with control parameters, allowing for performance optimization with further uses for integration and novel test cycles, and verification and validation, which are important for final acceptance by industry or legislator.
3) Adaptation**:** development of online self-adaptive methods that guarantee stable and optimal performance of the overall system under a wide range of conditions. We concentrate on self-optimization and self-configuration techniques embedded in risk-aware decision processes.

In this full ERP project, we will follow a use case-centered approach for which access to data and a development platform is essential. In addition, we considered industry interest and support to select two leading cases:

- Vehicle energy management concentrates on battery life-optimal eco-driving for electrified vehicles, aiming for self-optimization while dealing with varying demands, battery health and operating conditions, including route, pay load, or traffic flow. End target: lab-scale demonstration of self-adaptive algorithm for a (simulated) open, low risk environment (TRL 4-6).
- Space-based optical communication terminals focuses on self-configuration and auto-calibration to compensate for production variations. This will directly shorten time-to-market and enables reduced production costs of TNO-developed free-space optical terminals and instruments. End target: lab-scale demonstration on an actual FSO terminal (TRL 5-6).

For both use cases, spin-off to closely related application areas are foreseen, as illustrated in this Figure

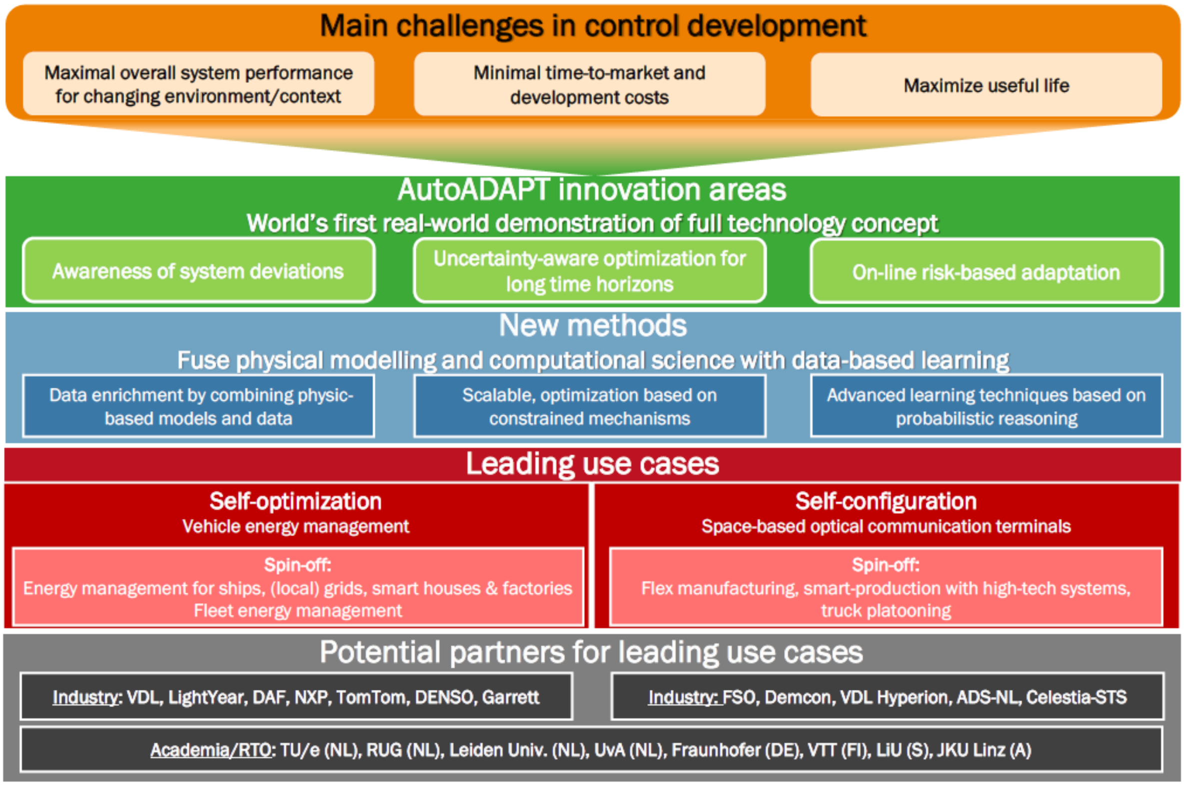


Figure 30: Overview of proposed approach for Full ERP project Auto ADAPT

- **Research plan**

The ambition of the full ERP is to develop and demonstrate self-learning adaptive methods that optimize overall system performance with minimal efforts by changing the controlled system's behavior and configuration.

To do so, the following key research questions are addressed:
- How to compute awareness of system performance and capabilities suitable for operations and control optimization under varying context and with uncertainty of the system state?
- How to learn control parameters by using awareness and to guarantee stable and optimal performance under changing operating conditions?
- How to continuously self-optimize a control system using awareness and guarantee safe and optimal performance under unforeseen short and long-term conditions?

Table 6: Research plan for research lines and connected use cases. Used abbreviation: UC (Use Case); CPA (Coarse Pointing Assembly); FSM (Fine Steering Mirror); FSO (Free-Space Optics)

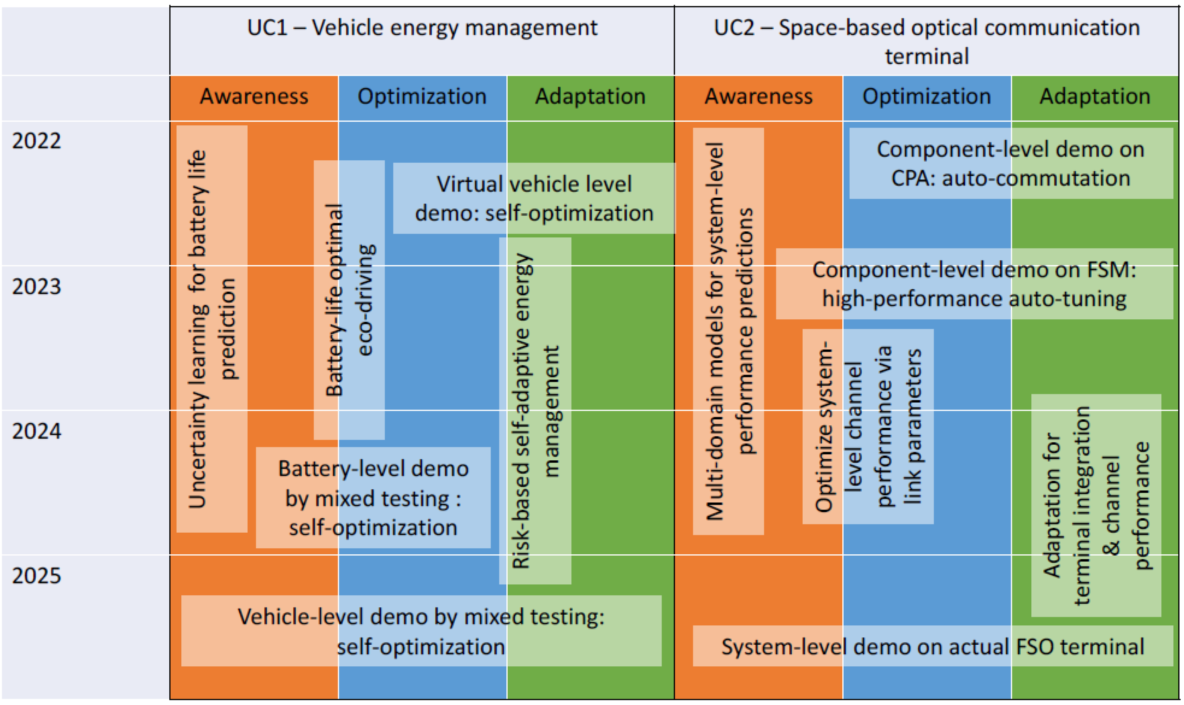


Table 6 summarizes the high-level research plan with activities and time planning. Key in this approach is the synergy between the two leading use cases within three research lines:

- RL1 – Awareness of system capabilities;
- RL2 – Scalable, multi-objective optimization;
- RL3 – On-line adaptation based on risk assessment

The research lines develop the methods to realize the essential functionality. For demonstration, we foresee different technology readiness levels as well as various testing methodologies, ranging from virtual testing (digital twins), via mixed reality testing (hardware-in-the-loop), towards experiments.

- **Targeted partnerships and external collaboration**

Collaboration with external parties will form an important aspect of the full ERP activities. With the growing maturity of practical application of the researched technologies, the contributions from external partners will gain importance; with priority given to Dutch partners.
Collaboration with industry: strategic partnerships will be built to secure necessary data and hardware support. Focus is on parties linked to the selected use cases. By collaborative research, application expert knowledge will supplement our in-house expertise and development platforms will be realized. Industry engagement and steering of development direction will also be realized by an Advisory Board.
Collaboration with academia/RTO: we already have a very strong link with Dutch universities via professorships and PhD positions of six project team members at TU/e, RUG and Leiden University. On strategic areas, we aim to collaborate with Fraunhofer (data systems, communication technologies), Linköping University (data-driven diagnostics).

Results 2021 and plan year 2022

3. Results 2021

- **Results achieved in Seed ERP (2021)**

In the SEED ERP project, the main objective was to define the full technology concept and architecture for self-adaptive systems. This is essential input to create the Full ERP project plan. We followed a use case-centered approach with focus on vehicle energy management for eco-driving. For this use case, the potential performance benefit for off-line optimization of operating conditions was assessed. The resulting demonstration is seen as a first step towards self-optimization.
The project team consists of 13 members from five units (ICT, T&T, ET, DSS, IND). The team started-up quickly and established an efficient way of working. For this SEED phase, the main results are:
- Definition of full technology concept for self-adaptive systems (TRL 2). The envisaged methods, system requirements and software architecture are described in detail in a TNO internal report. This work was also input to the Appl.AI Research Strategy discussions;
- Selection of two leading use cases; starting from the proposed, relevant use cases from various domains (incl. energy production, defense, industry process), the leading use cases were selected for the Full ERP project. All proposed use cases and the selection are documented in the report.
- Proof-of-concept simulation off-line optimization (TRL 3): combining a method to extract key characteristics from data and a scalable, numerical optimization method. This method is successfully integrated in a virtual development environment, with its potential shown for energy management of a hybrid-electric vehicle for battery ageing and for unforeseen route changes.
- Scientific output: conference paper on off-line optimization for vehicle energy management is accepted for presentation at 2022 SAE World Congress Experience (WCX), Detroit, US.
- Knowledge transfer: workshop/webinar for TNO experts and potential partners is planned for Q4.
- Collaboration with industry and universities: several parties have already confirmed their interest by a letter of support: VDL, TomTom, and LightYear. Also, contacts have been initiated to understand challenges and align on potential partnerships (see also Appendix): Durapower, Eleo, Garrett (CZ), Fraunhofer (DE) and VTT (FI). Besides existing collaborations with TU/e and RUG via professorships and PhD position of four project team members (Emilia Silvas, Steven Wilkins, Gert Witvoet, Elena Lazovik), the full professorship of Frank Willems (TU/e chair Self-learning powertrains) is extended to 0.4 FTE.

5. Plan year 2022

- **Focus year 2022**

In this first year of the ERP project, the main focal area is the development of essential methods for the full technology concept in the three research lines. In this early project phase, the development direction is guided by the anticipated integration levels and requirements set by the two leading use cases. For vehicle energy management (UC1), this information is already available from the SEED ERP project. We will follow a similar approach for UC2. Secondly, early demonstration of the full technology concept is considered to be essential. This will not only give feedback for methodology development, but also generates important evidence of the concept's potential. This is seen as important input for the third focus area; engagement of industry partners and realization of a collaborative research program with relevant industry and academic partners.

- **Activities and deliverables year 2022**

The activities in the three research lines and leading use cases are organized in individual work packages. Also, work packages for dissemination and collaboration are included to highlight the importance of these activities. For each work package, the planned activities and deliverables are listed in Table 7.

Table 7: Project overview: work package structure, planned activities and corresponding deliverables (Used abbreviations: UC – use case; POC – proof of concept; CPA - Coarse Pointing Assembly)

Activities	Deliverables
WP1 - Awareness	
Develop a situation and inner-system awareness model for UC1, UC2, which estimates and predicts capabilities and allows to deal with uncertainty coming from the unknown state of the system.	- Minimizing uncertainty awareness concept based on learning - Architecture of the awareness concept - Multi-domain awareness model report
WP2 - Optimization	
Make a self-configuration and optimization model, which given the uncertainties, can find at least suboptimal solution for UC1, UC2 on subsystem (component) level.	- Overview of optimization objectives report - Classification model for risks report - Methodology for scalable distributed multi-objective optimization
WP3 - Adaptation	
Create a self-adaptation mechanism methodology, which allows to have a closed-loop including control of the system	- Methodology for adaptation loop for use cases - Architecture v.1.0 for the overall self-adaptation solution - Overview of mechanisms to connect to the physical controls of the system for the use cases
WP4 – Vehicle energy management	
Demonstrate feasibility of self-optimization concept	- POC simulation - battery life predictor with learning capabilities using historic and fleet data - POC simulation – self-optimization for eco-driving
WP5 – Space-based optical communication terminal	
Initiate system-level requirements and modeling for awareness, and demonstrate feasibility of auto-adaptation	- First version of multi-domain model (optics, mechanics, dynamics, communication) – continued in 2023 - Early demonstrator: auto-commutation algorithm for cost-effective CPA
WP6 – Coordination & Dissemination	
Project coordination, knowledge transfer and increasing visibility	- Scientific output: 3 papers (1 method, 2 use cases) - Patent search to identify the ERP's IP strengths - Two talks at relevant conference/forum - Knowledge transfer - workshop with TNO experts and potential partners

WP7 - Collaboration	
Initiate and establish a stakeholder eco-system around the full ERP	- Realize Industry Advisory Board - Arrange in-kind support for use case demonstrators (hardware, data) - Explore funding opportunities for collaborative research and select approach - Submission of collaborative research program proposal with academia/industry (incl. 2 PhDs)

14: Digital Health Measures

ERP Contacts: M. van Erk (Project Lead), S. Wopereis (Lead Scientist), P. Bongers (Science Director)
ERP Duration: 2022 – 2025

Overall program description

1. Context and Objectives

- **Problem definition**

ERP Digital Health Measures will develop tools and methodologies for meaningful, inclusive, digital health measurements, which are a cornerstone in the upcoming transitions of healthcare. Digital Health technologies offer solutions to current and especially future challenges in healthcare. According to a recent report of Deloitte about the future of the Dutch Healthcare, upcoming health care transitions include a shift from disease based care towards health focused care with a clear aim at prevention, early diagnostics and remote accessibility. Data from sensors and wearables enable personal health feedback and can support the user during interventions. Future sensors and wearables will enable digital therapeutics, where personal health insights are directly coupled to the intervention in one sensor system. These developments will contribute to a care system that is truly patient-centered unlike the current system that is centered around the healthcare professional. These upcoming health care transitions are strongly driven by digital health innovations and more specifically by the development of new digital health measurements that facilitate remote patient monitoring, early diagnosis and interception. Innovative health measurements are fueled by new sensor technologies that measure health continuously with a low burden for the user, e.g. by application in wearables, plasters and clothing.

Societal health impact of new sensor technology and digital health measurements depends on adoption by stakeholders and users. Thus, this requires not only technological (sensor) innovation, but also social innovation, with involvement of all stakeholders and addressing essential requirements in an early (technology) development stage. Combining relevant expertise in a multidisciplinary program is essential for the development of meaningful and inclusive digital health measurements.

Meaningful, inclusive digital health measurements are accepted by users, fit-for-purpose, meaningful, scientifically validated, medical grade, privacy respecting and actionable. Combined these attributes will allow for seamless incorporation in health care processes and, more importantly, will make these measurements future-proof and accelerate the medical-to-healthcare and patient-centered-care transition. This topic calls for an (eco)systems approach that transcends individual expertise of each involved research group or institute. In this ERP, TNO unit Healthy Living and TNO unit Industry will uniquely collaborate to integrate expertise on sensor technology, social innovations and measuring health by focusing on resilience.

The ERP will focus on the development of a multiple-domain, or holistic, digital health measure for cardiovascular resilience integrated with sleep and chronobiology. This will be based on the resilience concept invented by TNO that could deliver a new type of innovative digital measure that promises to diagnose and monitor early health derailment allowing for preventative interception (van den Brink 2021). The combination of a biology based measure, i.e. cardiovascular resilience, with a contextual based measure, i.e. sleep, will lead to actionable measurements allowing for health interception (right care for the right person, at the right place, at the right time) and will be applied for the prevention of

Cardio Vascular Disease (CVD), an important non-communicable disease (NCD). The outcome of the ERP will be a Digital Health Measurement Lab that offers generic technologies, methodologies and services, including algorithms and guidance tools, for identification of technical and social acceptance requirements of digital health measurements. Specifically, TNO will contribute to digital health measurements that truly monitor the relevant biological and contextual determinants that predict early stage CVD in a way that is meaningful for health care and user, which would be a major technological breakthrough. A real 'innovation for life' as the longer term impact would be a healthier society with more quality of live for all.

- **Expected impact to stakeholders**

The most important impact of this ERP is to accelerate digital health innovation in the medical-to-healthcare and patient-centered-care transition. The proposed approach will lead to an easier adoption of new non-invasive sensing technologies by all stakeholders. Healthcare cost and quality of life are strongly affected by NCDs with CVD being the biggest contributor to lost healthy years of life, the biggest burden of disease and one of the most expensive diseases in the Netherlands. In addition, the prevention potential of CVD is about 80%, hence the focus on CVD in this ERP. Sleep apnea, the other focus point, is an important risk factor for NCD and in particular for CVD. Sleep apnea affects at least 200.000 people (costs 176 million, annual basis), which is most probably an underrepresentation. Therefore, the Dutch healthcare authority (ZIN) advised in 2021 to improve the diagnosis (accessibility) and treatment of (obstructive) sleep apnea. Meaningful digital health measurements can contribute to better monitoring of sleep(apnea). The digital health measure lab is expected to strengthen the current position of Dutch start-ups in emerging technologies. This ERP will thus benefit Dutch earning capacity. A recent Techleap report identified HealthTech one of the most promising investment areas with photonics as a potential winner. Both (medical) photonics and digital technologies are key enabling technologies in the Knowledge and Innovation agenda of Topsector Life Sciences and Health (LSH) and the proposal fits seamless in the LSH central mission as well as in mission I and II.

2. Approach

- **Research focus**

The interplay between sleep problems, circadian clock desynchronization, and CVD, in combination with the high and still growing number of people with CVD and/or sleep problems, dictates the leading use case for this ERP: the prevention of Cardio Vascular Disease. Development of CVD is characterized by a complex overlapping pathology, including oxidative stress, insulin resistance, microvascular remodeling, high blood pressure, and activation of the sympathetic nervous system. Interestingly, vascular pathological processes are an early culprit for CVD (Labazi 2017) and are negatively influenced by sleep disorders (Büchner 2011). Therefore we focus the research on sleep as a contextual factor and cardiovascular resilience as biological factor.

The focus for Research Line A (RL-A) will be on the development of meaningful digital measurements of cardiovascular resilience for persons at risk for CVD. The focus for Research Line B (RL-B) will be on the development of meaningful digital measurements of sleep and chronobiology for persons with sleep problems, including obstructive sleep apnea and circadian clock desynchronization. Diagnosis of sleep disorders is typically late, since the threshold for sleep analysis in a clinic is high. Home monitoring of sleep quality will allow increased and earlier accessibility of care. Furthermore, as CVD is an important comorbidity in persons with sleep problems, additional application of the developed digital measurements of cardiovascular resilience will facilitate preventive actions targeted at this comorbidity. A broader application perspective is secured in Research Line C (RL-C), where the methodological knowledge is embedded in TNO's Digital Health Measure Lab. In connection to RL-A, focusing on technology readiness level and social readiness level (TRL/SRL) 1-5, and RL-B, focusing on TRL/SRL 4-7, TNO's Digital Health Measure Lab methodology and services will be applied in different phases of meaningful and inclusive digital health measure development useful for different contexts.

Technologies/methodologies/facilities to be developed include:
- Modular photonic sensor platform (RL-A, RL-C): the ambition is to extent the existing photonic patch with algorithms for microvascular characteristics, hydration & subcutaneous fat determination, monitoring of blood pressure, SpO2 and pulse wave velocity to allow for the development of meaningful and actionable digital measurements of cardiovascular resilience;
- Modular vital sign sensor platform (RL-C): the existing Health Patch and non-contact sensor mat will be further extended with measurements for e.g. core body temperature to allow for the development of meaningful and actionable digital health markers of sleep (apnea), chronobiology and cardiovascular resilience;
- (Composite) digital measurements (RL-A, RL-B): explainable AI-based hybrid algorithms that integrate multiple sensor signals to a medical grade composite digital measure of sleep (apnea), chronobiology, and cardiovascular resilience based on abovementioned modular sensor platforms and other wearables;
- Digital tissue simulation platform (RL-C): Monte-Carlo simulations for evaluation of inclusivity and validity aspects of photonic sensor technology, such as skin colour, gender, and age;
- Digital health standards & clinical facilities (RL-C): Vocabulary, standards and performance criteria of clinical validity, usability, inclusivity, etc. that currently do not exist for digital measurements;
- Social Innovation methodologies (RL-C): Behavioural Health Design methods for social innovation, meaningful aspects of health, and concepts of Societal Readiness Level (SRL);
- TRL & SRL assessment (RL-C): integrated assessment- and guidance tool for Technological Readiness Level (TRL) and Societal Readiness Level (SRL) of digital health measurements.

- **Research plan**

The core of the research is on sensor technology integration and holistic health, referring to integrating multiple aspects of health into meaningful integrated composite measurements. In the 4-year program of Digital Health Measures we will differentiate three different research lines (RL):
RL-A will develop meaningful digital measurements of cardiovascular resilience. The key research question (RQ) here is: How to develop meaningful, inclusive, and actionable digital measurements of cardiovascular resilience with medical-grade validity, allowing for early detection of CVD development? Activities include:
- Based on social innovation methodology (RL-C), meaningful aspects of health (e.g., prevention of medication use), and the associated digital measurements (e.g., microvascular resilience) will be defined together with end-users and healthcare professionals with a specific focus on prevention of CVD. [Year 1].
- Stakeholders and end-users will be identified and involved in iterative co-development, testing and implementation of digital measurements of cardiovascular resilience, focused on health monitoring in daily life. Ethical, regulatory, and usability requirements will be identified using social innovation methodology from RL-C. [Year 1-4]
- Using different combinations of multiple signals from Wearables and Invisibles digital measurements of cardiovascular resilience will be developed and validated in volunteers under controlled conditions, based on validation performance criteria from RL-C. [Year 2-3]

RL-B will develop meaningful digital measurements of sleep and chronobiology that further elaborates and extends the 2021 results and additionally moves towards digital measurements for chronobiology, providing insights in biological timing of care (right care at the right time). The key-RQ in RL-B is: Can we develop explainable digital measurements of sleep and can these be integrated with cardiovascular resilience measurements to create a meaningful, inclusive and actionable holistic digital health measure that allows for effective implementation in health care and can be utilized in an at-home context? Activities include:

- Algorithm development for digital measurements of sleep and chronobiology with multiple sensor inputs integrated into measurements that can determine sleep quality and sleep problems. The algorithms will be designed to allow for explainable AI. [Year 1]
- Iterative extension of the Digital measurements of sleep and chronobiology, based on the requirements from the stakeholder and user inputs from two application contexts generated in 2021, with further validation in volunteers, both under clinical conditions and under remote care conditions [Year 1-3]
- Real-world clinical study for technology testing (estimated TRL and SRL 5-7) with focus on technological and societal effectiveness of digital measurements of sleep integrated with digital measure of cardiovascular resilience. Integration of biological and contextual digital health measurements in algorithms to provide users a holistic insight on cardiovascular health taking into account sleep problems as important contextual factor for development of CVD and interception option to reduce risk for CVD [Year 3-4].

RL-C will set-up the Digital health measure lab where existing TNO capabilities will be combined, further innovated and exploited. The key-RQ in RL-C is: What is an effective functional design of a digital health measure lab to facilitate fit-for-purpose development of inclusive, meaningful digital measurements with medical-grade validity in different application contexts? Activities include:

- Definition of the integrated TRL/SRL meta-framework of the digital health measure development process to allow for effective exploitation of the Digital Health Measure Lab. This will be based on the measure-technology-operations framework from the DiMe Society [playbook DiMe]. This will be evaluated in an iterative process with RL-A and -B. [Year 1-3]
- Algorithm development to measure microvascular characteristics, hydration & subcutaneous fat, and pulse wave velocity with the photonic health patch for SpO2 monitoring in development. [Year 1-2]
- Algorithm development for processing raw signals from the non-contact sensor mat to calculate vital signs including heart rate, respiratory rate, and body position. [Year 1]
- Application of existing concepts of explainable AI to time-series data collected from the modular sensor platforms and other wearables from RL-A and -B, targeted at acceptance by end-users. [Year 3-4]
- Development and application of Ethical AI methodology for inclusivity testing as part of sensor development. This will include utilization of the digital tissue simulation facility to evaluate inclusivity aspects such as skin colour, gender, and age. [Year 1-4]
- Development and adoption of performance criteria for validation (verification, analytical validation, clinical validation). [Year 2-4]

- **Targeted partnerships**

Besides broad involvement of unit Healthy Living and Industry, we foresee co-developing internal partnerships with ICT (data science and AI); SA&P (orchestrating innovation, inclusivity, ethics) and DSS (digital measurement of sleep). External partnerships for co-development are Lifestyle4Health, CIRO, Sevagram, DiMe Society, Erasmus MC Cardiology, LUMC Hart Long Centrum Leiden and the Netherlands Obesity Clinic. Digital Health Measurements will contribute to the development of applications of interest for various external stakeholders, namely (integrated) sensors, algorithms and measurements (MedTech, e.g. Philips, Sanmina); health care delivery (UMCs and Insurers), prevention (e.g. TATA steel, ASML), clinical trials (Pharma, e.g. Novartis, Roche).

Results 2021 and plan year 2022

3. **Results 2021**

- **Results achieved in year 2021**

The seed ERP Digital Health Measurements (DHM) aimed to develop a generic framework for validation, security, data governance and utility of digital health measurements, that was applied to a single dedicated measure of health as demonstrator, i.e. sleep. We set out to marry technical and systems biology innovation with social innovation at an early stage of sensor development. Social innovation includes early involvement of citizens, patients and professionals for the co-development of digital health measurements depending on the application area of the sensor. Technical innovation involves development of trust-by-design infrastructure in the sensor technology and data integration platform.

The 2021 results from the seedERP DHM confirmed our expectation that societal as well as functional requirements of digital health measurements are highly dependent on the context, i.e. medical or non-medical, indicating that **integrated social and technical innovation** is essential in the development of digital health measurements. In addition, proof of principle for the Health Patch and the non-contact sensor mat as modular sensor platforms to develop medical grade digital measurements of sleep was acquired.

- ***Social innovation: Stakeholders, meaningful aspects of health, Societal Readiness***

Two field labs were developed; one together with CIRO in the clinical research/health care context (end-user: patients with sleep apnea) and one together with Sevagram in the workers wellness/elderly care context (end-user: shift workers), where for both field labs the key stakeholders and ecosystem were defined. Stakeholder meetings and mixed-method workshops were held to generate perspectives on application of the modular sensor platforms in the respective settings, and identify preconditions with respect to innovation, impact and implementation (see Figure 31).

Innovation:	Impact:	Implementation:
- Quality, safety, functionality - Use, usability, user friendliness - Maturity, stability, operational reliability	- Reach, size of targetgroup - Productivity, effectiveness - Target, short or long term goals/aims	- Capability, knowing how and being able to - Opportunity, being enabled, equipped - Motivation, knowing why, being convinced

Figure 31: Toolbox for co-design of meaningful digital health measurements in an ecosystem

Social innovation resulted in large differences in needs and preferences between stakeholders and contexts of use, indicating the need for a fit-for-purpose approach in the development of digital health measurements. This concerned context-dependent meaningful aspects of health, as well as functional and social design requirements of digital health measurements, including ethical and legal concerns (data governance, privacy and data management) with regard to remote monitoring. In addition, the need for the development of an ecosystem was found in both field labs in order to drive implementation and adoption of digital health measurements, requiring organizational changes and definition of the roles, tasks and relationships of user and other stakeholders. Moreover, it was found to be important to intertwine social innovation with technological innovation as part of the development process in order to 1) adapt technology to user needs and context in the Sevagram use case, e.g. shift workers were not aware of the adverse effects of poor sleep, but expressed the need for general (non-medical) insights in own healthy sleeping patterns, and 2) to adapt the context to the usage of the technology, and orchestrate implementation and ecosystem development in the CIRO use case, e.g. stakeholders expressed the potential for home care, self-management, early diagnostics, and cost reduction, requiring organizational change in order to reach potential of these opportunities.

- ***Technological innovation: sleep monitoring and work performance***

Two professional networks have been developed during the Seed ERP Digital Health Measures for execution of technological innovation field labs in the clinical care (CIRO sleep clinic) and the work health context (Sevagram – shift work in elderly care). A proof-of-principle has been acquired for (multi-day) application of the Health Patch for sleep algorithm development. Initial algorithms showed comparable performance with the benchmarks from the Fitbit and a sleep diary. Further optimization of these algorithms against clinical standard polysomnography, and under at-home monitoring conditions is warranted to allow reliable prediction of individual sleep patterns. Furthermore, objective sleep monitoring outperformed subjective sleep monitoring (diary) in predicting health indicators, such as exhaustion after work, showing the utility of modular sensor platforms to study the integration of context and biology for holistic insight.
From the social innovation stakeholder analysis and user experience evaluation, the need was identified for less-intrusive, yet valid sleep monitoring technology. Particularly in the preventive health context. Further optimization of the Health Patch instructions and possibly materials is needed to ensure non-intrusive, long-term usability in multi-day at-home settings. Also, a proof-of-principle was generated for a non-contact sensor mat to detect body position when placed under the bedsheet. Further development of this technology to reliably detect body position, as well as heart and breathing rate, is promising to allow its application in a clinical setting.

4. Plan year 2022

- **Focus**

The ERP Digital Health Measures focus of 2022 is to set the stage for and initiate the development of meaningful digital measurements of cardiovascular resilience under RL-A and to elaborate on the development of meaningful digital measurements of sleep and chronobiology under RL-B that was initiated during the seedERP. Additionally, generic technologies/methodologies/facilities for the development of valid digital health measurements will be (further) developed under RL-C as part of the Digital Health Measure Lab to allow exploitation in years 2023 – 2025 of ERP Digital Health Measures.

- **Activities and deliverables 2022**

The 2022 activities and deliverables for RL-A 'meaningful digital measurements of cardiovascular resilience' are:

- A.1. Workshop series to define an ecosystem, including infrastructure, stakeholders and end-users, around a population at risk for CVD for iterative co-development. *Deliverable A.1: Report on workshop outcomes defining ecosystem around population at risk for CVD.*
- A.2. Based on the outcomes of the simulations under activity C.3, an algorithm will be developed to extract microvascular characteristics from the photonic health patch identified as relevant for cardiovascular resilience such as SpO2 and pulse wave velocity to come to inclusive digital cardiovascular resilience measurements. *Deliverable A.2: algorithm to extract microvascular information from photonic sensor.*
- A.3. Workshop series to identify, categorize and prioritize the meaningful aspects of cardiovascular health, as well as social and functional requirements to home-monitoring sensor technology, in a cardiovascular risk population. Together with activity A.2, this will form the basis for further development/selection of modular sensor platforms in 2023 towards development of meaningful digital measurements in 2024/25. *Deliverable A.3: Report on workshop outcomes of social innovation requirements to home-monitoring sensor technology in a cardiovascular risk population.*

The 2022 activities and deliverables for RL-B 'meaningful digital measurements of sleep and chronobiology' are:

- B.1. Workshop series to identify, categorize and prioritize the meaningful aspects of health, as well as social and functional requirements to home-monitoring sensor technology, in a population with sleep disorders. Health aspects of chronobiology and cardiovascular risk will be included as topics, to prepare for the holistic approach in the real-world volunteer study of 2024/25. Stakeholders and end-users from the clinical care ecosystem around sleep disorders, as identified during the seedERP, will be involved. *Deliverable B.1: Report on workshop outcomes of social innovation requirements to home-monitoring sensor technology in a sleep disorder population.*
- B.2. Execution of a clinical validation study, designed and approved during the seedERP, to develop and validate algorithms for medical-grade predictions of sleep (apnea) in a clinical care/research setting covering the Health Patch and the sensor mat. *Deliverable B.2: scientific publication on medical-grade algorithms for sleep (apnea) prediction in a sleep apnea population.*
- B.3. Design and medical ethical protocol (METC) submission for home-monitoring of sleep (apnea) and chronobiology using modular sensor platforms, based on the outcomes of activity B.1 and B.2. *Deliverable B.3: clinical protocol submitted to METC for at-home monitoring field lab of sleep (apnea) using modular sensor platforms.*

The activities and deliverables in 2022 for *RL-C: Digital Health Measure Lab* are:

- C.1. Identification and definition of concepts and criteria of Societal Readiness Level (SRL) and Behavioral Health Design (BHD) methods for determining social innovation and meaningful and inclusive aspects of digital (preventive) health measurements to come to the integrated TRL/SRL meta-framework. *Deliverable C.1: report describing SRL and BHD methods verified for the Digital Health Measure Lab.*
- C.2. Based on activity C.1, design of the integrated TRL/SRL meta-framework and a fit-for-purpose decision support tool along the lines of the 'Measure-Technology-Operations' (MTO) framework from the Digital Medicine Society. The integrated TRL/SRL meta-framework will cover the technologies/methodologies/facilities of the digital health measure lab to ensure effective

utilization. The design will be iteratively evaluated after workshops, field labs and simulations from RL-A and RL-B, to deliver a prototype method at the end of 2022. Further optimization will be performed in 2023-25. *Deliverable C.2: prototype of the integrated TRL/SRL meta-framework and decision support tool to utilize the digital health measure lab.*

- C.3. Literature study on skin composition variations, and subsequent digital tissue simulations of photonic sensor sensitivity to body location, BMI, gender, age and ethnicity as start for ethical AI methodology development for inclusivity. *Deliverable C.3: submission of scientific publication on photonic sensor sensitivity to aspects of inclusivity such as body location, BMI, gender, age and ethnicity.*
- C.4. Optimization of the Health Patch for long-term wear and integration of photonics technology in the health patch to create the photonic health patch for measuring SpO2 and microvascular characteristics. Health Patch instructions for use will be updated and verified, as well as other patch materials will be tested for improved usability. In parallel, optimal body positioning of the photonic health patch will be determined based on the simulations under activity C.3. *Deliverable C.4: Modular Health Patch for long-term wear with integrated photonic sensor technology where sensor outputs adapt based on inclusivity aspects such as BMI, gender, age, ethnicity.*
- C.5. Using data from the clinical validation study executed under activity B.2, algorithms will be developed for the non-contact sensor mat to predict body position, heart rate and breathing rate against clinical standards in a sleep apnea population. *Deliverable C.5: Algorithms to measure body position, heart rate and breathing rate with the non-contact sensor mat.*

15: OPTO-ACOUSTICS

ERP Contacts: R. Jansen (Project Lead), P. van Neer (Lead Scientist), C. Hooijer (Science Director)
ERP Duration: 2022 – 2025

Overall program description

1. Context and Objectives

- **Problem definition**

The Early Research Program (ERP) Opto-Acoustics will create a revolution in acoustic measurement technology by using optical, rather than electrical means, to generate and receive acoustic waves. Acoustic-based measurement systems are used for a large variety of applications such as sonar, seismics, non-destructive testing and medical imaging. These systems use mechanical waves and are ideal to extract information on mechanical parameters such as its stiffness, density and viscosity. Acoustic-based measurement equipment is safe (no ionizing radiation is used) and relatively inexpensive. Most acoustic sensors use piezoelectric materials to generate and receive acoustic waves. These materials have existed for over a century and have been the subject of continuous research, although the pace of their improvement has been slow. The accuracy/image quality of acoustic measurement equipment is ultimately linked to the efficiency and sensitivity limits of acoustic transducers and thus to the piezoelectric material properties.

In the last 10 years scientific developments at the interface between acoustics and optics have accelerated. The field of Opto-Acoustics is starting to yield promising sensor concepts (TRL 1 to 2) for further development. The ERP Opto-Acoustics aims to enable a breakthrough in acoustic measurement technology. An Opto-Acoustic technology platform will be created to develop new Photonic Ultrasound Transducers (PUT) principles and novel Opto-Acoustic measurement systems. With this Opto-Acoustic technology platform we will be able to:

- Radically outperform existing measurement systems in terms of accuracy or image quality.
- Create sensor systems with a much larger/denser coverage area compared to the state-of-the-art and
- Seamlessly integrate them into composite structures.

- **Expected impact to stakeholders**

The revolutionary solutions enabled by the Opto-Acoustic technology platform promise to impact a large number of application domains relevant for TNO, e.g. medical, composite structures, semicon and defence (see Figure 3). For this ERP, 2 application areas have been identified where the immediate impact of Opto-Acoustics is expected to be the largest: 1) medical ultrasonic imaging and 2) large area sensor networks in smart composite structures.

Medical ultrasonic imaging

During the last 60 years there has been a continuous drive to improve the quality of images obtained by medical Ultrasound hardware. Higher quality images result in earlier, better and more specific diagnoses and therefore lead to increased patient health and well-being and lower health-care costs. Figure shows the increasing quality of medical ultrasound images from 1985-2015.

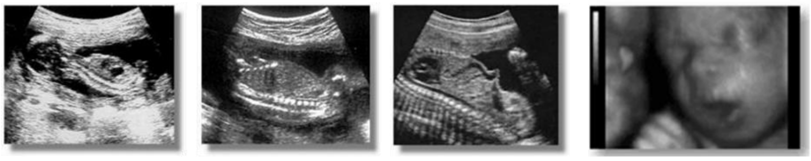


Figure 32: Improvements over the years of typical medical US images.

Important factors for image quality are: ultrasonic image resolution (frequency) and Signal-to-Noise-Ratio (SNR). To generate a high quality image, a certain SNR is needed at the penetration depth determined by the application (e.g. carotid imaging 5 cm, liver imaging 15 cm). However, at higher frequencies (resolutions) the SNR becomes lower due to sound attenuation in tissues. Thus, medical ultrasound companies are constantly researching ever more sensitive ultrasonic transducers to increase the frequency and thus the image resolution/quality.

The scientific literature[11,12,13]shows that Photonic Ultrasound Transducers (PUTs) can be up to 100 times more sensitive than traditional piezo-based sensors at equal sensor surface area. This was confirmed by the work performed in the SEED ERP Opto-acoustics in 2021. This increased sensitivity would enable medical ultrasonic transducer designs featuring a frequency 2 times higher than is currently available, leading to a resolution enhancement of more than a factor 2 in all directions (x, y and z). This factor of 10 reduction in image voxel size is game changing. After discussions in 2021 with industry, academic and clinical healthcare, the TNO team identified the following medical instrumentation development opportunities with high level economic and societal impact, for the proposed Opto-Acoustic technology platform:

1. Increasing medical ultrasound image resolution. Almost every medical ultrasound application will benefit from a higher resolution enabled by PUT technology. Better images will result in more specific diagnostics and should reduce the need for more costly medical imaging approaches (MRI, CT) or collection of tissue biopsies which requires an invasive procedure by a medical specialist.
2. Replacing invasive ultrasound (trans-esophageal, trans-rectal, trans-vaginal) scans by non-invasive ones. This increases patient comfort and reduces procedure time (=cost). The increased SNR and resolution enabled by PUTs could make invasive scans superfluous.

The size of the medical ultrasonic sensing market was US$4.6 billion in 2019[14]. The industry is expected to grow to US$6.2 billion at 2025 with a 5.1% compound annual growth rate. Dutch industrial presence is significant in this market (Philips, Oldelft Ultrasound, Lumina Solutions, ITheraMedical, Kaminari, Esaote, etc.).

<u>*Large area sensor networks for smart composite structures*</u>

Glass or carbon reinforced composites have a high strength to weight ratio, and thanks to their superior properties over conventional materials they are used in different markets ranging from renewable energy to maritime, automotive, aerospace and defence. The global composites market is projected to grow from US$74 billion in 2020 to US$112.8 billion in 2025[15]. In the renewable energy domain, the size of the wind turbine composites market will reach to US$ 12.31 billion[16], which is about 10% of the global composite market. The main technology trends that are shaping the composites industry are complete digitization, increasing use of automation and the use of recyclable thermoplastic resins in order to reduce costs and carbon footprint and increase consistency and

[11] Leinders et al., Nature Scientific Reports, https://doi.org/10.1038/srep14328
[12] Westerveld et al., Nature Photonics, https://doi.org/10.1038/s41566-021-00776-0
[13] Ouyang et al., SPIE OPTO, https://doi.org/10.1117/12.2539573
[14] Yole market report (2019): 'Ultrasound Sensing Technologies for Medical Industrial and Consumer Applications'
[15] Composites Market Global Forecast to 2025 | MarketsandMarkets
[16] Wind Turbine Composites Material Market | Size, Share, Growth | 2021 - 2026 (marketdataforecast.com)

manufacturing volume. The Opto-Acoustics sensor system proposed will accelerate these developments in the following ways:

1. Complete digitization means monitoring of the structure from manufacturing until the end-of-life. To design leaner and lighter structures, whilst maintaining current safety margins, monitoring of the material properties is required. The Opto-Acoustic sensor system will measure both strain and stiffness to calculate the stress distribution. Today only strain is measured and only at discrete locations which requires regular inspection of the structure, or model assumptions, to ensure reliability.
2. The large coverage area sensor network proposed will allow for measurement of strain and stiffness at each sensor location and in between sensors for the specific areas of interest.
3. Because Opto-Acoustics is based on glass fibers, it promises seamless integration into composite structures, fully automated, with minimal effect on mechanical properties, featuring cradle to grave monitoring.

The composite industry is very diverse, and the Netherlands has many companies serving applications in different markets. In the SEED ERP Opto-Acoustics (Offshore) wind turbine blades have been identified as a high level economic opportunity for the Opto-Acoustic technology platform. It is estimated that 4.6 kg of polymer and 7.7 kg of (re-in forced) fiber material are needed for every kW of energy produced by wind energy[17]. To speed up the clean energy revolution, costs per unit energy need to be reduced by extending the lifetime of the structure to increase the total energy yield. Continuous monitoring of the structural health of the wind turbine blade from fabrication, to transport and operation is the first step to complete digitization. This requires the incorporation of large area structural health monitoring systems. PUTs are ideal for this since they can measure stiffness and strain, and can be seamlessly integrated. In addition, they are resistant to lightning strikes, which is a significant problem for electrical sensors.

2. Approach

- **Focus**

Acoustic transducers based on light are called Photonic Ultrasound Transducers (PUTs). PUTs encompass both acoustic transmitters and receivers. PUTs based on integrated nano-photonics are called Integrated Photonic Ultrasound Transducers (IPUTs), and on fibers, Fiber Optic Photonic Ultrasound Transducers (FOPUTs). PUTs for the transmission of sound operate as follows: light pulses are guided to a specially designed absorbing layer and absorbed. The absorber heats up locally, expands and creates a traveling acoustic wave. This mechanism can be used on photonic chips (IPUT) or combined with optical fibers (FOPUT). PUTs for the reception of sound are based on the fact that the passing of an acoustic wave alters the refractive index or shape of optical waveguides. Two read-out options are available: 1) an optical resonance is created and the wavelength shift of this resonance as a function of pressure is monitored or 2) an interferometric approach, where the phase difference between a path affected by the acoustic wave and a reference path is measured. We expect this technology platform to provide solutions for a variety of markets but the focus of work in this ERP will be on ‘medical imaging’ and ‘smart composite structures’ (see Figure 3).

[17] rms_for_wind_and_solar_published_v2.pdf (eitrawmaterials.eu)

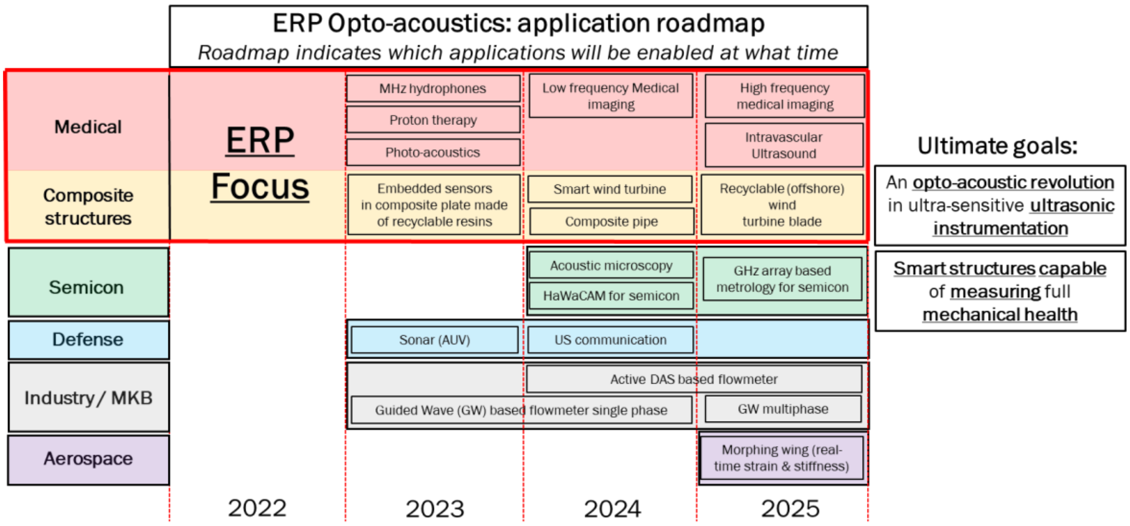


Figure 33: Application roadmap of the ERP detailing which applications will be enabled at what time.

- **Research plan**

After the execution of this 4 year research plan TNO will have: a unique design capability including associated predictive models, a patent portfolio to protect its right-to-play, demonstrators and prototypes and on-going cooperation with academic and industry partners to bring the technology to market.

- **Targeted partnerships**

A key academic partner for this ERP is TU Delft. Currently, a joint TNO-TU Delft NWA project is ongoing entitled 'Optoacoustic sensor and ultrasonic microbubbles for dosimetry in proton therapy'. Sensors based on integrated photonic waveguides are an active area of research at TU Delft. Fabrication of IPUTs has so far been outsourced by TNO. We expect to continue this collaboration, as well as exploring potential new IPUT manufacturers. During the SEED ERP, FOPUT development has benefitted from the strategic partnership with University of Massachusetts Lowell who fabricated the FOPUTs. We intend to continue this collaboration. Regarding industrial partners, we are in contact with a number of application specific partners and component and/or system manufacturing partners.

Results 2021 and plan year 2022

3. Results 2021

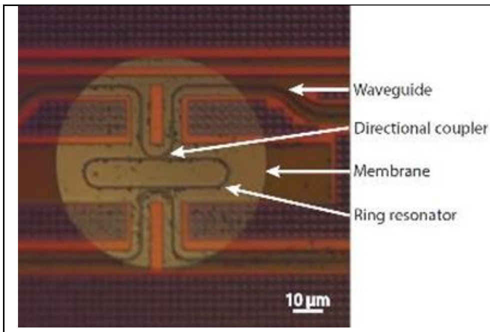
- **Results achieved in previous SEED ERP year**

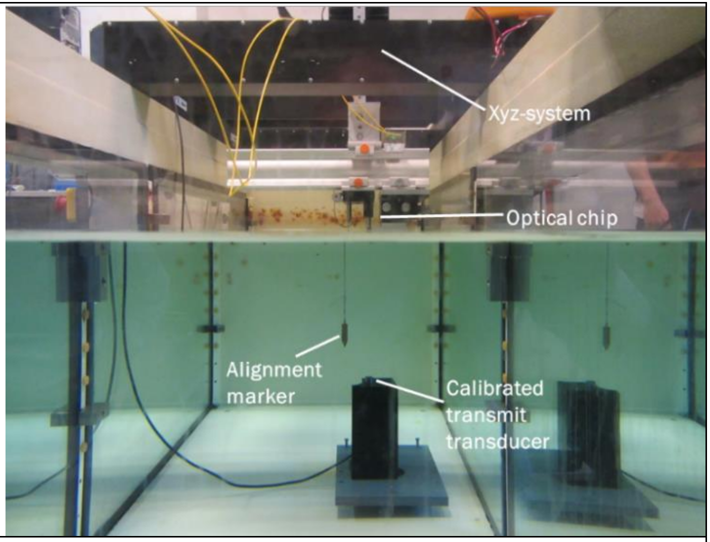
In the SEED ERP we established our right-to-play by determining our IP position, proof-of-principle experiments, performing stakeholder mapping and preparing technical and application roadmaps.

Right-to-Play – Intellectual Property (IP)
A landscape IP search was conducted and no blocking IP was found for IPUT or FOPUT. Regarding FOPUTs, there is little on the active acoustic measurement systems as proposed in this ERP.

Right-to-Play – Proof-of-Principle experiments
Feasibility experiments (Figure) were conducted with acoustic receiver IPUTs sourced from the joint TNO-TU Delft NWA project. IPUTs resonating at 250 kHz and 1 MHz were shown in experiments to

have a lower (=better) Noise Equivalent Pressure (NEP) than competing state-of-the-art (piezo) transducers at equal sensor surface area. It was also shown experimentally that the receive transfer function increased by 6-8 dB when going from 2 to 4 IPUTs (6 dB was expected), providing clear evidence of the performance potential of IPUT arrays for each individual transducer element.

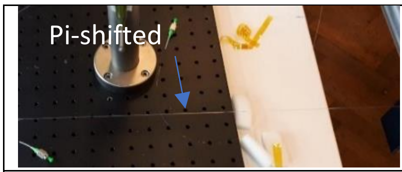


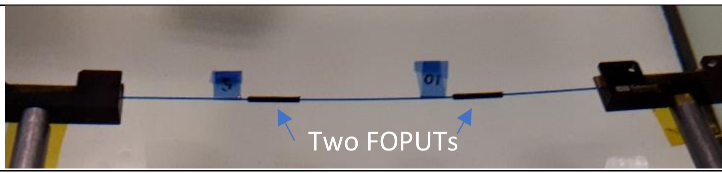


IPUT using the ring resonator concept	IPUT performance test

Figure 34: SEED ERP Proof of Principle experiments with Integrated Photonic Ultrasound Transducers (IPUTs)

Further feasibility experiments (Figure) were performed with acoustic receiver and transmitter FOPUTs. FOPUT receivers based on Pi-shifted Fiber Bragg Gratings (FBGs) were experimentally shown to be 5+ times more sensitive than regular FBG based FOPUTs, whilst maintaining a very high bandwidth. Transmitter FOPUTs were sourced through our cooperation with the University of Massachusetts Lowell. The transmitted acoustic wavefield was successfully measured, the pulses showed an extremely large bandwidth of 0.1 - 10 MHz, although the produced acoustic pressures were rather low. The knowledge and experience gained with these experiments has led us to believe that considerably more efficient transmitter FOPUT concepts could be possible than those of University of Massachusetts Lowell . The experience gained in the IPUT and FOPUT experiments has sparked new ideas for improved PUT and optical read-out system design. In the coming months we will expand on these ideas and file new IP.





FOPUT receiver using Pi-shifted FBG Diameter of the FBG = 0,1 mm	FOPUT emitter array (provided by UMASS Lowell) Diameter of the emitter (the two black sensors) = 3,0 mm

Figure 35: SEED ERP Proof of Principle experiments with Fiber Optic Photonic Ultrasound Transducers (FOPUTs).

Right-to-Play – Stakeholder mapping

We mapped the main stakeholders in the field by conducting an extensive literature search, by means of the landscape IP search, and by interacting with our contacts. Besides the current cooperation with the Medical Imaging group of TU Delft, also a large number of relevant academic groups were contacted for feedback. Also, a large number of companies were contacted. The responses from both academia and industry were very positive, further validating the identified benefits and business opportunities offered by the Opto-Acoustics technology platform. Fraunhofer IEG, for example stated that they found the proposed concepts really novel and that they would be interested in a collaboration to run tests on geothermal wells that are difficult to access and where such a sensor provides a cost effective solution.

Technical and application roadmaps
The outcomes of the proof-of-principle experiments, patent scan, literature research and extensive discussions with external parties (both companies and academic parties) have led to detailed application and technical roadmaps. It also resulted in an overview of interested/committed academic and industrial partners .

4. Plan year 2022

- **Focus Year 2022**

The focus for year 2022 will be on establishing the ERP Opto-Acoustics as a research program, that includes:

- Research on single PUT design, packaging and integration.
- Design of PUT arrays and parallel read-out concepts, and (fibre-coupled) light source designs.
- Strengthening our right to play through the filing of key IP.
- Sharpening the commercial and application outlook.
- Expand TNO's value proposition and network via relevant national and European initiatives.

- **Activities Year 2022**

In 2022 the activities will address 4 technical developments (WP 1-4). Alongside this there will be application research (WP 5) and management activities (WP 6).

WP 1: Single PUT development

This work package focuses on the research of new PUT designs to boost PUT efficiency and sensitivity.

At the end of 2022 we will have established an overview of promising design, modelling results and test results to rank performance, manufacturability and first insight in cost of goods for a single PUT, both IPUT & FOPUT.

WP2: Optical system development on excitation & read-out

We focus on the development of novel optical excitation (transmitters) and read-out systems (receivers) with the aim of improving the linearity, dynamic range, stability and of reducing noise levels.
This WP will result in the basic design needed to transmit and receive acoustic waves, an overview of cost of equipment and an inventory of the building blocks, critical components required to run Proof of Concept test for the medical applications. The main focus is on reading-out a number of IPUT's in parallel.

WP3: PUT array development

This work package focuses on researching how to develop efficient PUT arrays and networks.
In order to scale up to cover large areas, multiplexing capabilities will be researched for both IPUTs and FOPUTs.

WP4: Packaging and embedding

Here we will research advanced methods to package PUTs for robustness, yield and cost effectiveness. The overall aim of this WP is to have an overview of PUT packaging and an overview of acoustic coupling (not embedded but mounted on surface, coupling media) for the specific ERP application targeted for such as water, (soft) tissue and (solid) resin.

WP5: Application research with the TNO units HL, BIM, ET & DSS | further strengthening IP

In this work package activities will take place to further sharpen the commercial and application outlook.

WP6: Project Management

Activities related to steering the development and establishing and maintaining collaborations. In addition to search for new prospects such as participation in EU and nationally funded R&D projects. It also includes progress meetings with the team and reporting and presenting to CSO.

- **Deliverables Year 2022**

Internal reports
- Status update single PUT and optical read-out design (TNO report, M6)
- Application research: market and application requirements (TNO report, M9)
- Status update PUT embedding and packaging (TNO report, M9)
- Status update multi PUT & parallel read-out design (TNO report, M12)

Demonstrators/proof-of-concept
- Design, realization and characterization of improved single IPUT design (M6) and number of single IPUT in parallel (M9)
- Design, realization and characterization of multiplexed FOPUT transmitter & receiver (M12)

Conferences & IP
- 2+ contributions to scientific conferences
- > 1 journal articles
- > 5 patent intakes

16: PANDEMIC PREPAREDNESS

ERP Contacts: J. Kieboom (Project Lead), B. Keijser, D. Noort (Lead Scientists), P. Bongers (Science Director)
ERP Duration: 2022 – 2025

Overall program description

1. Context and Objectives

- **Problem definition**

The Corona crisis showed the tremendous disruptive impact of a pandemic outbreak on our society and revealed shortfalls in our lack of preparedness. History learns that every 50 to 100 years a (viral) pandemic outbreak occurs (*e.g.* yellow fever, Spanish flu, HIV). Regional outbreaks of potential pandemic pathogens have occurred more frequently, including SARS-1, MERS, Zika, and Ebola. Fortunately, these could be contained regionally and did not reach a global pandemic status. Pandemic pathogens can emerge as a result of random genetic mutations, allowing viral pathogens to switch hosts (*e.g.* from bats to humans, called zoonosis), and/or to escape existing immune defences (*e.g.* flu). It is therefore certain a next pandemic will occur again.

Modern society has become extremely vulnerable to emerging infectious diseases. Human encroachment on wild habitats, deforestation and increased livestock have helped to circulate animal-borne diseases and increased the risk for emergence of novel pathogens. Urbanization, global travel, and demographic changes increases the speed and efficiency of spreading, making it more difficult to control an outbreak. It is thus of importance that our society becomes better prepared for a next emerging pandemic.

One of the most striking shortcomings in the Corona crisis was the inability to establish adequate testing capacity. Testing is an essential strategy to rapidly assess whether or not individuals have been infected and subsequently to prevent further spreading of the infection. It thereby aims to reduce economic burden of a lockdown and the societal costs of social distancing measures. The diagnostic approach deployed during the Corona crisis was based on routine medical practice and was shown to be ill-suited. In medical practice, testing is focused on therapeutic care, but proved to be too slow to enable efficient tracing of infected individuals, too inefficient and costly to be deployed for population-level screening. While attempts were made to implement novel and more efficient diagnostic procedures during the pandemic (*e.g.* breath test, SERS-RAMAN, MS and RT-LAMP), most of these attempts failed due to legal obstructions, premature and hastily introduction and a lack of support from the medical professionals.

In order to better cope with future pandemic outbreaks, we need to develop a scalable and multilevel testing strategy, optimally aligned with the needs during different phases of an pandemic outbreak. These are:

1. A bio-surveillance system for non-targeted ('agnostic') identification of pathogens at pandemic hotspots (*e.g.* airports).
2. A cost-efficient and simple to use platform for on-site detection of infected individuals during contact tracing.
3. A pandemic targeted diagnostic mass screening platform for efficient detection of infected individuals at population level.

- **Expected impact to stakeholders**

Little is needed to express the tremendous impact of a pandemic crisis at both a societal and economic level. The Netherlands Institute for Social Research (SCP) reported that the Corona pandemic impacted all layers in society in terms of physical, and mental health, education, and employment (1). It led to severe social unrest and decline in social coherence. A negative impact on public health over the longer term is expected, as a result of delayed treatment of diseases and inefficient prevention. The Dutch economy showed the strongest decline since the WW2. The Dutch governmental balance showed a 56 billion (7.2%) deficit, of which 24 billion can be attributed directly to Corona measures (2). Over 16 billion euro was required for direct financial support for businesses to avoiding bankruptcy. Despite the rapid recovery in some sectors the loss in productivity, consumer trust and disturbed distribution are expected to have a long-lasting effect in the Dutch economy in other sectors.

In a future pandemic crises, the immediate availability of an efficient and innovative diagnostic testing strategy, will enable national authorities to better control the pandemic infection and to limit the economic burden of a lockdown and the societal impact of the distancing measures.

Our stakeholders require validated, robust and operational diagnostic tools to achieve their goals. The CRISPR and LAMP-based methodologies that will be developed during this ERP have unique and generic properties that can revolutionize molecular diagnostics. New molecular tools and workflows will be established that allow molecular target detection to be faster, more flexible and less demanding with regard to the technological infrastructure and be less dependent on the availability of specific reagents. Diagnostic tests with PCR level sensitivity can be performed on site, at home or in high volumes in fully continuous labs for screening and surveillance purposes. Since techniques are generic and able to cope with any genetic biomarker, it can bring significant changes to our routine medical diagnostic test strategy providing faster and on-site detection of infections, and allowing treatment to be initiated more rapidly and efficiently. The technology can also be applied for analysis of liquid biopsies, where circulating genetic markers in blood replace invasive tissue sampling and allowing population level surveillance. Making molecular diagnostics more flexible and more broadly available offers a myriad of opportunities for (medical) diagnostic companies, pharma, biotechnology, and agri-food industry.

2. Approach

- **Focus**

During this ERP innovative diagnostic tools will be developed that are optimized for use in emerging pandemic outbreaks. A distinction is made in *early phase* detection of novel pandemic pathogens (Research line A: *in search of the unknown*), and *middle and late* phase detection of known pandemic pathogens (Research line B: *in pursuit of the known*).

<u>*Research line A: in search of the unknown*</u>
To serve the earliest phase of an emerging pandemic, during which the causative agent is not known, a system will be established enabling detection of virtually all possible infectious agents on the basis of biomolecule mass fingerprints. This biothreat surveillance technology will be deployed at travel hotspots (airports), serving as an early warning system, leading to initiation of track and trace measures. Bioaerosol samples collected in air filters or wastewater samples will be analysed in a novel hybrid mass spectrometry (MS) based technique, combining untargeted proteome analysis (shotgun MS) with targeted MS (Parallel Reaction Monitoring MS (PRM MS)). This procedure generates high

volume of random peptide mass fingerprints, which are subsequently processed by a machine-learning based algorithm with the purpose to detect emergent pandemic pathogens and variants thereof.
Unique in this approach is its ability not only to detect known pandemic pathogens but also variants (mutations) thereof as well as synthetic viruses, created by gene editing techniques and released through an accident or even as an act of terror. For this, the Pandemic Proteomics algorithm will not only rely on existing viruses, but will also infer evolutionary mutations, use metagenomic surveillance and integrate emerging diseases and outbreak reports, such that of the Program for Monitoring Emerging Diseases (ProMED). In a later stage, the technology will be extended to human samples and integrate pathogen detection with human inflammatory fingerprints allowing detection of pathogen carriage as well as infection risk.

Research line B: in pursuit of the known
Efficient tracking and tracing of outbreaks, point of care detection, and population-level testing are essential in later stages of an emerging pandemic. For this, we will build further on TNO's expertise on LAMP and CRISPR/CAS based detection. Key focus is to establish a generic end-to-end workflow that can be rapidly deployed. Minimized sample handling protocols will be defined to allow for different sample types of relevance for a next pandemic (*e.g.* oral, blood, faeces, insects, wastewater). We will introduce and characterise novel DNA/RNA manipulating enzymes, with unique properties, better suited for pandemic testing. Enzymes that are more efficient, robust and allow for multi target detection as well as instrument free detection (point of care). As molecular assays are driven by target-specific primers (synthetic DNA fragments), a pipeline is established for optimized LAMP / CRISPR DNA primers design. In this, structural and kinetic information is included allowing an optimal assay design and avoiding the current time-consuming trial and error approach. Subsequently this pipeline is then used to establish protocols for detection of ten pathogens that pose the highest risk to emerge to a pandemic. To facilitate point of care detection and efficient tracking and tracing, the CRISPR/LAMP protocols established are implemented in a sample-to-result workflow, ensuring minimized sample pre-treatment isothermal target amplification and visual detection. Electricity-free detection techniques are explored, possibly also allowing for use of the methodology in deprived countries. To facilitate high volume testing at population level, we aim to implement our pandemic diagnostic protocol in microfluidic generated artificial cells. This eliminates the use of a major part of the plastic labware and increases the throughput. For this, existing platform technologies are modified to enable isothermal high throughput detection. Protocols will be implemented in a high-throughput drug screening facility (Pivot Park Screening Centre), establishing a national pandemic emergency testing lab.

- **Research plan**

The PANPREP program has 2 interlinked research lines, each with multi-year objectives.
The main objective for *Research line A "In search of the unknown"* is to establish a mass spectrometry-based tool and supportive machine learning based algorithm for *de novo* detection and identification of (viral) pathogens in environmental samples at travel hotspots. To meet this main objective, the following activities have been defined.

- A.1: Establish protocols for efficient sample collection, enrichment and handling for shotgun mass spectrometry. Environmental samples include bioaerosol, filter, and wastewater. Extensions are made for the collection of human (*e.g.* respiratory, blood, faeces), and animal (incl. main viral vectors mosquito, ticks) samples.
- A.2: Establish a machine learning-based algorithm for identification of pathogenic viruses based on mass fragments.
- A.3: Embed machine learning pandemic pathogen identification tool for pandemic risk estimation
- A.4: Validation of TNO's (P4PP) Proteomics 4 Pandemic Protection Platform for bioaerosol/wastewater pathogen detection

- A.5: Enhance the machine learning algorithm to detect pandemic viral mutants/variants and evaluate its performance.
- A.6: Simulation / stress test for pandemic use of shotgun mass spectrometry surveillance (TNO pandemic field lab)
- A.7: Establish a machine learning-based algorithm for identification and characterization of human inflammatory responses based on mass fragments.
- A.8: Explore the potential use of metamaterials/RAMAN for direct optical detection of viruses (support FastBioScan, the proposed successor of the VirusScan project)

Main objective for Research line B *"in pursuit of the known"* is a diagnostic surveillance platform for mass screening of samples based on isothermal amplification and/or detection of pandemic pathogens. To meet this main objective, the following activities have been defined.
- B.1: Establish minimized protocols for pre-processing of human (*e.g.* respiratory, blood, faeces), animal (incl. main viral vectors mosquito, tics) and environmental samples.
- B.2: Characterisation and optimization of novel tools (enzymes/reagents) for isothermal amplification and / or detection of pandemic pathogens
- B.3: Establish protocol for lyophilized reagent storage and handling
- B.4: Establish bioinformatic pipeline for automated determination of optimal DNA primers (LAMP/CRISPR) for detection of novel pandemic pathogens (support to the EDF proposal BioCR DIM).
- B.5: Establish minimalized technology for sample collection, handling and reagent processing.
- B.6: Establish and experimentally validate integrated protocol for point of care pathogen detection for 10 pathogens with the highest pandemic potential
- B.7: Establish and experimentally validate integrated protocol for high volume diagnostic testing for 10 pathogens with the highest pandemic potential
- B.8: Simulation / stress test experiment of population-level testing in TNO pandemic fieldlab (with partners, separate funding)
- B.9: CE-IVD marking of established methods (with co-investing partner)

- **Targeted partnerships**

The recent COVID pandemic has stimulated TNO to converge available expertise in the field of microbial detection and identification for novel diagnostic tools, suitable for testing under pandemic crisis. It allowed TNO to establish itself as innovation partner and broker between government, academia, health care organisations and companies enabling to speed up innovations. With a foothold in the field of innovative testing, and having established a strong ecosystem consortium with both very relevant public partners (*e.g.* GGD Amsterdam, RIVM, Antonius Hospital, TOM-i), private partners (*e.g.* Sanquin) and academic groups (*e.g.* LUMC, UMCG, WUR, ERASMUS MC, Robert Koch Institute), TNO now has a unique window of opportunity to develop to a forefront partner in the field of innovative diagnostics and early biothreat detection.
In the ERP with stakeholders, we will establish a pandemic diagnostic preparedness plan (advisory and visionary document) and also explore and discuss opportunities for application of these novel diagnostic approaches for improved regular medical diagnostics to expand the ERP ecosystem. Potentially this will drastically transform current regular diagnostic testing by medical professionals and labs in a much more flexible, diverse, low cost, quick, on site and even do it yourself diagnostics

Results 2021 and plan year 2022 (max. 3 Pages)

3. Results 2021

- **Results achieved in Seed ERP (2021)**

In order to generate proof-of-concept for Mass Spectrometry (MS) based pathogen identification, we established a virus specific sample preparation method, a data library and analysis pipeline enabling the identification of 46 different pathogenic virus species. Filter capturing experiments were performed and correctly identified two different Coronaviruses (SARS-CoV-2, 229E). Bacteriophage captured from a bioaerosol cabinet could be identified in one occasion, suggesting more improvement is needed. In collaboration with Erasmus MC, gastrointestinal viruses could be directly identified from clinical faecal samples.
There is an increasing demand for easily accessible self-tests to perform diagnostic tests outside the lab with sufficient sensitivity, preferentially with results within the hour, without electricity. In this way, dangerous pathogens can be quickly detected, and the origin of the contamination traced. Our goal was to demonstrate a proof-of-concept of CRISPR-Cas LFA assays. For this purpose, a lateral flow (immunochromatographic) assay was developed based on CRISPR-crRNA pathogen recognition either pre-amplified using LAMP or post-amplified using TdT (Terminal deoxynucleotidyl transferase (3, 4). Using this approach we could demonstrate that both methods are easy implemented and recognize the programmed pathogens (SARS-CoV2 and Anthrax).
In summary, lateral flow sticks are cheap, easy and quick in use, but still miss sensitivity compared to the PCR method. Our aim is to bridge this gap in sensitivity. In parallel to the work in the SEED-ERP, the team has been able to establish and patent a novel CRISPR signal amplification technique, allowing sensitive detection of molecular targets.
We have been able to establish, LAMP test-protocols for 4 common respiratory viruses (RSV, Influenza A/B, Human metapneumovirus and Adenovirus) underlining the potential of the LAMP technology for a broad spectrum of infectious agents. In collaboration with the Antonius Hospital, clinical samples were obtained and successfully tested. At the same time, it also showed the peculiarity of the LAMP assay, where optimized conditions for one target were not working well for other targets.
In collaboration with the Wageningen University and Research, a novel CRISPR detection system has been established. Results were published in the very prestigious journal Nature Communications (5). The novel CRISPR-LAMP systems enable efficient detection of molecular targets also opens novel diagnostic opportunities. We also established a electricity-free LAMP detection method (6). Furthermore, in collaboration with the Pivot-Park Screening Centre (PPSC), the RT-LAMP protocol was converted for use in a fully robotized high throughput setting. The facility and LAMP based methodology has been proposed to be part of the national pandemic preparedness infrastructure. Novel isothermal assays established during this ERP can be embedded withing this very high-throughput infrastructure.

4. Plan year 2022

- **Focus year 2022**

For Research line A: we aim 1) to establish bioaerosol capturing technology suitable for efficient proteomic virus detection, and 2) to create and evaluate version 1 of our Pandemic Proteomics identification pipeline. For Research line B: we aim 1) to establish technology for efficient pre-treatment of samples (human/environmental) for LAMP and CRISPR detection, 2) to determine key mechanistic factors for efficient detection by LAMP and CRISPR, and 3) to evaluate novel strategies for multiplex detection by LAMP and CRISPR.

A key focus in 2022 is on establishing and strengthening our partnerships with both national and international stakeholders spanning the whole diagnostic chain. We will establish an advisory board of academic, public and private parties relevant for pandemic testing. More active collaborations will be initiated with academia (PhD research collaborations), health organisations (*e.g*. GGD Amsterdam), and companies (e.g. SHERLOCK). We will further attract interest and solidify collaborations with leading companies in diagnostic testing.

- **Activities year 2022**

Research line A

We will evaluate different methods for bioaerosol capturing and sample pre-treatment for proteome analysis of samples representative for those available at travel hotspots. Bioaerosol sampling of viruses is challenging due to the small size. We will evaluate different virus capturing strategies, such as impactor, cyclone, filter, impinger, electrostatic precipitator and a water-based growth tube collector. Following desk study evaluation, comparative bioaerosol experiments will be carried out with virus analogues in order to determine performance of these capturing techniques for bioaerosol proteome detection. Initially, latex nanoparticles of different sizes are tested for capturing efficiency, subsequent experiments are performed with virus analogues determining quantitative capturing efficiency is determined, as well as suitability for proteome analysis.

In parallel, a full proteomic database will be established for pandemic viruses and other pandemic agents. A bioinformatic routine will be established for automated selection of viral proteome biomarkers. Next, Version 1.0 of our Pandemic Proteomics pipeline will be created and evaluated *in silico* using data from bioaerosol experiments.

Research line B

Representative clinical and environmental samples will be collected, and different methods for pre-treatment will be evaluated through in spike-in experiments. In this, we will further build on our work using modified cellulose capturing, deploy thermal virus extraction strategies, and use size exclusion spin filter strategies. All techniques aim to reduce the time required to prepare samples for analysis from 30 minutes to 2 minutes or less.

In previous work, test conditions for RT-LAMP required extensive experimental optimization. Significant differences were observed in test sensitivity and reliability depending on choice in enzymes, DNA primers and reaction buffer. The unpredictable performance hampers RT-LAMP to be established in routine diagnostics. To resolve this, we will perform time-resolved molecular analysis of the LAMP assays, performed under different (experimental) conditions , using a DNA fragment analysis, nanopore sequence and cryo-electron microscopy. Next, we will integrate the data and establish a kinetic and mechanistic model, allowing to predict optimal and robust assay conditions.

Detecting multiple targets by LAMP and CRISPR is difficult and inefficient. Besides evaluation of some existing molecular strategies, we will also explore the use CRISPR III activation of downstream effector proteins (5, 7). As part of the natural defence, CRISPR III generates signalling molecules, activating different enzymes. This not only includes DNA modifying enzymes but also proteases, allowing novel strategies for multiplex signal amplification.

- **Deliverables year 2022**

Research line A

- D.A1: Methodology for efficient bioaerosol sample collection, enrichment and handling for shotgun mass spectrometry.
- D.A2: Version 1.0 of a machine learning-based algorithm for identification of pathogenic viruses based on mass fragments.

Research line B

- D.A1: Methodology for efficient pre-treatment of human samples relevant for pandemic molecular testing

- D.A2: A predictive kinetic and mechanistic model of the LAMP assay
- D.A.3: Publication on molecular properties of LAMP kinetics, describing different stages of the assay, primer and reagent properties at molecular resolution.
- D.A3: A report on the evaluation of multiplex detection on the basis of CRISPR III signalling.

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17: Subsidence and Building Damage

ERP Contacts: R. Li (Project Lead), T. Candela, C. Geurts (Lead Scientists), A. Adriaanse (Science Director)
ERP Duration: 2022 – 2025

Overall program description

1. Context and Objectives

- **Problem definition**

Subsidence-induced damage to the built environment is a worldwide issue, especially in low-lying urbanized deltas: some known hotspots are Venice, New Orleans, Jakarta, and urban conglomerates in India and Nigeria, as well as the Netherlands.

In the Netherlands, anthropogenic causes of subsidence are estimated to lead to over €20 billion worth of building damage in the coming decades[18]. Besides damage to buildings, subsidence can compromise the integrity of critical infrastructures, such as dikes, (rail)roads, pipelines, and underground cables. The built environment can be damaged by subsurface activities ranging from groundwater level management to deep resource extraction. Besides existing subsurface activities, there are multiple anticipated changes that can exacerbate subsidence-induced structural damage: (i) housing shortage, forcing to build in our most subsidence prone areas; (ii) the transition to renewable energies (geothermal and Aquifer Thermal Energy Storage, ATES) which can lead to additional subsidence; (iii) the closing of the Groningen gas field, forcing gas production at other locations; and (iv) increased drinking water extraction accelerating local subsidence processes. With the recent alarming report on climate change[19], now more than ever it is time to proactively anticipate subsidence-related issues. Drought episodes, which lead to subsidence, are expected to be more frequent and severe in the future. Also, greenhouse gases are released during subsidence, which accelerate climate change.

Multiple actors are involved in subsidence-induced damage to the built environment; however, there is no overarching political responsibility to coherently address the problem upfront. The recent resolutions filed in the Dutch House of Representatives[20] increased the awareness among policy makers and the society. Nevertheless, at present, damage induced to the built environment is dealt with only after its occurrence. This reactive approach stems from the lack of knowledge and lack of tools to accurately assess the causal relationship between subsidence and damage. We are confident that building up this knowledge and related tools (the model chain, see section **Focus**) helps to transform the current reactive approach to a proactive one and this is what we propose to accomplish in this ERP.

- **Expected impact on stakeholders**

The prime impact of the model chain is to reduce the estimated huge costs for building repair in the coming decades while enabling the safe continuation of pre-existing and future subsurface activities.

[18] PBL (2016), Dalende bodems, stijgende kosten
[19] IPCC (2021) Summary for Policymakers.
[20] Van Nieuwenhuizen (2019), Kamerbrief rijksbrede inzet op bodemdaling & Bromet (2020), Motie aanpak van bodemdaling versnellen, 34682-65

Governments and large assets owners will take well-informed decisions on subsurface activities (e.g. gas extraction, salt mining, groundwater levels, ATES) and land use.

The impact in terms of social well-being of inhabitants is potentially large. The current experience from earthquake induced damage in Groningen demonstrates that the trust in government can be very low, and it takes a long time to repair the "moral damage[21]". Using the model chain to assess the subsidence-related damage with unambiguous outcomes will help to gain confidence in the public sector.

In contrast with the earthquake induced damage in Groningen, where actions took place relatively late, there is still time to implement impactful prevention and mitigation scenarios for subsidence induced damage and ultimately to save billions of euros in the coming decades in the Netherlands.

2. Approach

- **Focus**

The core of our research is to develop the know-how necessary to develop the model chain for subsidence induced damage to the built environment. The key scientific breakthrough is to establish the causal relationship between the sources of subsidence and damage to the built environment. Six research lines are defined, see Figure 36: research lines (RL) 1-3 constitute the three pillars of the model chain. RL 4-6 create the cohesion between the first three pillars, and they are tailored for the integration of the modelling components. RL1 to 3 are dedicated to the development of predictive models that are probabilistic to enable risk-based decision making. The aim is to develop fast yet accurate alternatives of computationally expensive models, which are physics-based, empirical, based on Artificial-Intelligence (AI) algorithms, or their combination. In RL4, we will validate the models of RL1-3 against field and laboratory observations making use of ensemble-based data assimilation procedure and conformance methodology. The newly developed models will be integrated into a dedicated software tool as part of RL5, that is *the model chain from subsidence to structural damage*. The application of this model chain to assist decision making in terms of land use planning, urban development, water management or mining activities, will be tested within RL6 in selected use cases with the involvement of relevant stakeholders.

During the first two years we will focus on structural damage to masonry buildings induced by a selected subset of shallow and deep sources of subsidence, see section ***Plan year 2022***. In the second part of the ERP, other civil engineering structures (e.g. road and hydraulic infrastructure) will be considered as well as other subsidence sources (e.g. geothermal, ATES, local excavations).

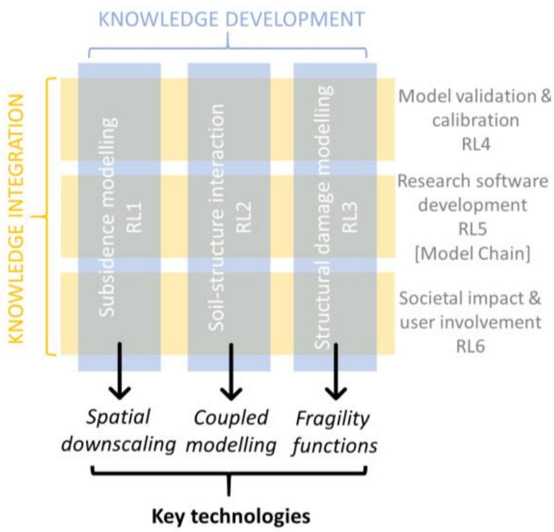


Figure 36 Research lines (RL)

[21] www.sociaalplanbureaugroningen.nl/aardbevingen-en-leefbaarheid/

- **Research plan**

RL1: Subsidence modelling
This research line answers the research question (1): *How to disentangle multiple sources of subsidence and downscale our subsidence predictions to the building-scale?* Physics-based models fed by laboratory-derived constitutive equations and coupled with AI algorithms will be developed to disentangle the contribution of each superposed source of subsidence and to downscale our subsidence predictions.

RL2: Soil-structure interaction
This research line answers the research question (2): *What is the influence of soil-structure interaction on the subsidence induced damage of the built environment?* To provide answer(s) first we will develop physics-based coupled models of the soil-structural interaction (finite element models). Ultimately the goal is to create accurate and computationally cheap models (i.e. surrogate models) that will be used as components in the structural modelling of civil engineering assets and their damage (see RL3).

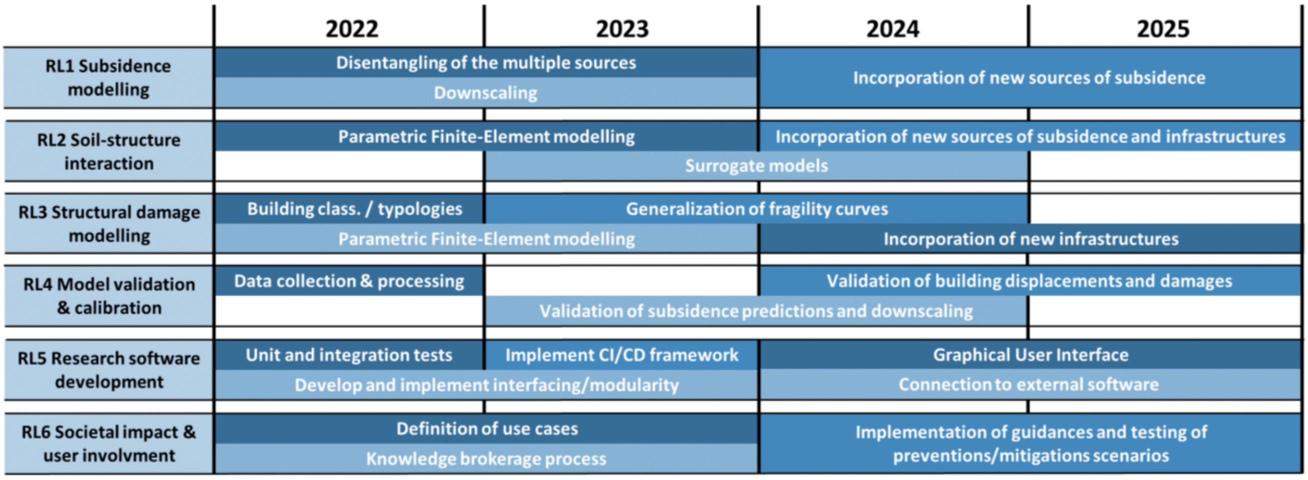
RL3: Structural damage modelling
To assess the risk of damage, research question (3) is formulated: *How to derive fragility functions that predict structural damage under subsidence?* To answer this question, we will develop physics-based structural models (finite element models) fed by the subsidence predictions of RL1. The nonlinear finite element models will be parametric, which allows to programmatically vary parameters and to couple them with probabilistic models that represent uncertainties in material properties, loading, dimensions, etc. Finally, we will devise novel methodologies to derive fragility functions.

RL4: Model validation and calibration
To trust models, they must be validated against real world observations. This validation/calibration step will be performed for each model component and the entire model chain as well. The main research question (4) is: *How to satisfactorily validate a model when existing observations can be scarce and/or attached to a low signal-noise ratio and collecting new observations can be time consuming?*
A combination of diverse type of data (satellite-based such as InSAR; cone penetration tests; damage assessments by experts; etc.) coupled with adapted data assimilation procedures and conformance methodology will be developed. We will collaborate with our academic and industrial partners to leverage their existing datasets and expertise.

RL5: Research software development
Within this research line we will develop software that implements the model chain. The research question (5) is: *How to effectively link models which describe different physical processes, and how to account for uncertainties, to allow for model calibration, to be maintainable and expandable when new knowledge is obtained?* The software should be fast enough to allow scenario studies, sensitivity studies, and probabilistic forecasts.

RL6: Societal impact and user involvement
The objective of this RL is to answer the research question (6): *How to increase the societal impact of the model chain and to connect it to the relevant users and their contexts*? A knowledge brokerage process will be set up between potential users of the model chain and researchers who are involved in its development (in RL 1-5). AI learning capabilities to assist planning and decision making will be explored. The objective is to enhance the understanding and use of the model in the selected user contexts. Finally, guidance will be developed for different user groups, such as policy makers, banks, insurance companies, and house owners.

The timeline/planning of the main activities per research question is displayed in Figure 37.



CI: Continuous Integration. CD: Continuous Delivery.

Figure 37 Timeline / planning of ERP Subsidence and building damage

- **Targeted partnerships**

Research institutes: Fundamental knowledge input is ensured by linking the ERP to NWO's LOSS program[22] and setting up two PhDs: (i) one with Padova University (IT) on subsidence modelling (RL1) and (ii) one with TU Delft (NL) on damage modelling and soil-structure interaction (RL2 and RL3). TU Delft has a world leading track record in modelling of masonry structures and has a broad experience in assessing damage initiation and progression in structures, whereas Padova University is world renowned for subsidence modelling in urbanized coastal areas in Europe (in particular Venice, IT) and Asia. We will also use the strong connection between TNO-ET and Utrecht University for subsidence modelling and its link to subsurface management and land planning. Research institute GEO (DK) will contribute, based on Danish use-cases, to the validation of our models with geotechnical data and incorporation of the results on their online portal for geo-information (RL4).
Industry: Fugro (NL) and Sweco (SWE), among the largest civil engineering companies in the world, are partners in providing data, expertise, and cases regarding foundation engineering, soil mechanics and soil structure interaction (RL2, RL4). This also accounts for Sixense (FR) and Sensar (NL), two worldwide operating monitoring companies that will provide multi-annual measurements of structure- and land movements in subsiding areas (RL4).
Government: The Ministry of the Interior and Kingdom Relations (BZK) and the province of Overijssel as asset owners and decision makers, will help us to define use-cases and scenarios of prevention and mitigation (RL6). Attached to our industry partners, these two government stakeholders will also serve as the first end-users of our products. Use cases relevant for the province of Overijssel include new salt mining activities near urban centers, damage predictions to houses and cultural heritage due to drought induced subsidence, and subsidence by ATES deployment. Dissemination of our results is ensured by the partnership with ‘Coalitie Stevige Steden’, a platform of decentralized governments, housing corporations and insurance companies with a focus on the Green Heart area.

[22] NWO-NWA ‘Living on soft soils’

3. Results 2021

- **Results achieved in 2021**

We successfully designed, implemented, and tested a proof-of-concept model chain in a Python software package. We demonstrated that it is feasible to model subsidence, perform downscaling and conversion of subsidence to damage-related intensity measures, and to calculate probabilities of damage for existing masonry buildings. The model chain has the potential for future (more sophisticated) models to be integrated while maintaining our probabilistic approach.
Although not all uncertainties and complexities were accounted for, as for example only a single source of subsidence (groundwater level lowering) was considered, this proof-of-concept has shown its value: we are able to couple our subsurface and structural modelling capabilities with the potential to model the causal relationship between subsidence and building damage. Our results highlighted a clear dichotomy between (1) the subsidence and (2) its spatial difference at the building scale; this last being one of the damage-related intensity measures. Indeed, our results showed that geographical locations with high subsidence are not necessarily the ones with high differential subsidence at the building scale (see Figure 38). The naïve approach consisting in correlating high subsidence with high damage is thus erroneous and the local spatial variability in the subsidence is the key ingredient which much be properly captured by the downscaling procedure.
The development of the current model chain has also highlighted modelling assumptions and research questions (see section ***Research plan***) that will be addressed in the ERP.

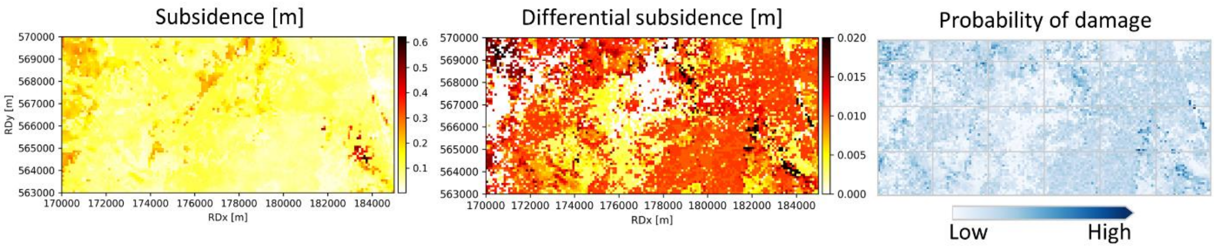


Figure 38 Illustration of the results achieved during the SEED-ERP

4. Plan year 2022

- **Focus year 2022**

For year 2022, on the subsidence side, we will focus on selected deep and shallow sources of subsidence: (1) groundwater level lowering (hereafter referred as shallow source), and (2) gas extraction or salt mining activities (hereafter referred as deep source). On the damage side, in this first year, only existing masonry buildings will be considered.

Each research line of the ERP (Figure 37) corresponds to a distinct work package. The six work-packages (with same title as the research lines) will run simultaneously from the start of 2022. The overall focus of this first year is to establish the scientific foundations to ultimately solve at the end of the ERP the scientific challenges defined in the section ***Research plan***. This will require a close interaction with our stakeholders from the start of the ERP to define the two PhDs and to screen our available datasets.

For each work package, a specific focus for 2022 is defined:

WP1	Establishing a strong scientific foundation and the modelling components for (1) the disentangling of the multiple sources of subsidence and (2) downscaling procedure.
WP2	Development of parametric finite-element models for soil-structure interaction.
WP3	Development of coupled physics-based and probabilistic models for subsidence-induced building damage.
WP4	Screening of existing datasets with our stakeholders and development of the data assimilation procedures.
WP5	Software implementation of the models and approaches developed in WP1-4 with special emphasis on maintainability, extendibility, and interoperability.
WP6	Establishing a co-creation/brokerage process between model developers and stakeholders.

- **Activities year 2022**

WP1: Subsidence modelling

Large-scale subsidence modelling – disentanglement of the two sources: shallow and deep: The first modelling step consists in computing large-scale (~100m resolution) subsidence predictions and disentangling the relative contribution of both shallow and deep sources. Semi-analytical physics-based models for deep sources will be newly implemented and the existing shallow sources modelling components will be upgraded to honour uncertainties at each sub-modelling steps (i.e. geological-, flow-, geomechanical models). Within this WP1, we will also define the PhD proposal on subsidence modelling with Padova University (IT).

Small-scale subsidence modelling: This activity is about downscaling our large-scale subsidence predictions to the building metric-scale (~10m resolution). The newly developed probabilistic downscaling procedure during the SEED-ERP will be strengthened to relax the assumed simplifications, with an emphasize on honouring uncertainties in the groundwater simulations.

WP2: Soil-structure interaction

To understand the coupling between soil and building movement, we will develop physics-based soil-structural interaction coupled models (finite-element models) which take as input the subsidence predictions of WP1. In 2022, we will further develop models of the soil-structure interaction. These parametric finite-element models will be surrogated in 2023. Within this WP2, we will define the PhD proposal on soil-structure interaction and building damage (WP2 and WP3) with TU Delft (NL) and aim for a start of the PhD project in the first half of 2022.

WP3: Structural damage modelling

The goal by the end of 2023 is to derive fragility functions for typical existing masonry buildings in the Netherlands. To this end, in 2022 we will categorize Dutch masonry buildings into structural typologies based on their predicted susceptibility to subsidence induced damage. Using the developed structural typologies and damage quantification metrics, we will build nonlinear finite element models to accurately simulate the behavior of masonry buildings and their damage under subsidence. These models and their components are going to be validated against laboratory and field measurements (see WP4 on validation). We will combine the soil-structure interaction finite element models of WP2 with the structural models developed in this work package.

WP4: Model validation and calibration

In the first year we will connect to our stakeholders to gather existing datasets and to jointly process them. The missing key datasets will be identified, and measurement campaigns will be defined.

During the first year, the data assimilation procedure to calibrate and ultimately validate our predictive models will be elaborated. For our subsidence predictions and the disentangling of the multiple sources, this data assimilation procedure will leverage existing workflows based on Bayesian statistics and deep learning. In 2022, our large-scale subsidence predictions, disentangling and downscaling procedure will be verified with synthetic data and real observations will be used after the first year.

WP5: Research software implementation

We will support the software implementation of the scientific developments in WP1-3 work packages, ensure that they will be seamlessly coupled and form a robust chain of models. We will develop reusable and thoroughly tested codes following state of the art software development practices and ensure that the results are reproducible. We will also perform sensitivity analysis of the entire model chain and its components to provide valuable feedback to researchers working in other work packages.

WP6: Societal impact and user involvement

In 2022, a desk study of potential users of the model chain and their contexts of use will be conducted. An inventory of policies and existing governance structures that are relevant for the model chain is made. Interviews are set up with relevant users and policy makers to create a deeper insight into the user context. Main questions to be asked are: “what is the need for the model chain and the information that will be produced?”, “what are their requirements for the produced information?”, and “would they be willing to participate in the knowledge brokerage process and under what conditions?”. We will also explore the role of AI based models for planning and decision making to further integrate the model chain outcomes in future policy making and develop an outline of a co-creation process with selected stakeholders.

- **Deliverables year 2022**

WP1: Subsidence modelling

- PhD plan on subsidence modelling with University of Padova (IT) and start of the PhD.
- Modelling components (and report describing their scientific foundations) for deep and shallow sources of subsidence and their disentanglement with uncertainties honoured.
- Modelling components (and report describing their scientific foundations) for the downscaling of our subsidence predictions.

WP2: Soil-structure interaction

- PhD plan on soil-structure interaction (WP2) and building damage modelling (WP3) with TU Delft (NL) and start of the PhD.
- Report on strengths and weaknesses of existing approaches for soil-structure interaction (together with PhD student).
- First implementation (and report describing its scientific foundations) of the physics-based coupled model of the soil-structure interaction.

WP3: Structural damage modelling

- First definition of masonry building typologies.
- For each typology: finite element models that are controlled programmatically, integrated with the finite element models developed in WP2, and coupled with probabilistic models.

WP4: Model validation and calibration

- Data collection and inventory from field and laboratory.
- Validation approach for the disentangling procedure (with geodetic-type observations).
- Validation approach for cases where the data collection is expensive and time consuming, e.g. for the downscaling procedure and building damage prediction.

WP5: Research software implementation

- Version v0.1 of the model chain with description of the software architecture and user documentation.

WP6: Societal impact and user involvement

- Report on the stakeholder/user analysis and AI-based model, including: relevant policies, the interview results, the user selection and the outline of the knowledge brokerage process.

18: QuTech

ERP Contacts: C.J.M.Eijkel (Project Lead), D. Brousse, R. Versluis, E.J. van Zwet (Lead Scientists), C. Hooijer (Science Director)
ERP Duration: 2022 – 2025

Overall program description

1. Context and Objectives

- **Problem definition**

In 2015, recent breakthroughs in nanofabrication, cryogenic technology and high-frequency electronics opened the avenue from quantum-mechanical concepts to systems large enough to be usable to humans. Exploitation of the concepts of 'superposition' and 'entanglement' is now available to an elite set of scientific and industrial labs worldwide, among which QuTech: the collaboration between TUDelft and TNO. The path is open to applications like the Quantum Computer with unprecedented computing powers for specific problems, and Quantum Communication which is inherently safe from eavesdropping. This will result in considerable economic value. QuTech develops scalable prototypes of Quantum Internet and Quantum Computing, in a world-unique organization with the best scientists, engineers and industry. Technology leadership and economic footprint are prime targets in that endeavor.

By joining forces between TUDelft and TNO, QuTech realizes a unique position in the international field. Both organizations, supported by EZK, OCW, TKI and NWO, bring together the core funding on which the institute is built. This core funding enables a continued strength and leadership position of QuTech, allowing it to play a leading role in the international field of quantum technology, play a leading role in national and international agenda's and attract private funding. ERP is a key element in creating that strong core.

- **Expected impact to stakeholders**

Quantum computing promises exponential improvements in calculation power for relevant problems that are hard to solve using conventional computers. This encompasses areas like simulation, chemical modeling, machine learning and optimization problems. The application areas that will profit from this sharp increase in calculation power are expected to be chemistry, catalysis, logistics, materials development and many more. Some of the critical problems that could be solved via quantum computing are improving the nitrogen-fixation process for creating ammonia-based fertilizer, creating a room-temperature superconductor, removing carbon dioxide for a better climate and creating solid-state batteries. As a result, quantum computing is expected to create value towards the Sustainable Development goals as defined by the United Nations.

Encryption and secure quantum communication are also of great interest to security-sensitive areas like critical infrastructure, banking, health and defense organizations, as the downside of the quantum computer is that security measures founded in classical computing can be breached with a quantum computer.

Besides these societal and economical motives for application of quantum technologies, a new supply chain/industry has to be set up for manufacturing of the quantum computer and secure internet, leading to opportunity for economic footprint.

This vision is backed up by multi-million-euro investments by companies (Intel, Microsoft, IBM, Google, Fujitsu) and nations (Netherlands, USA, China, UK). The European parliament chose quantum technologies as the third (and so far final) Flagship with a 1 billion budget over a 10-year run-time. Within the Netherlands, the National Agenda Quantum Technology underlines the societal and economic relevance of quantum technology, and this was awarded a 615 million euro grant from the national Groeifonds.

2. Approach

- **Focus**

Driven by the technological roadmaps of QuTech and the need for a tighter integration of research and engineering, QuTech is organized in three divisions, along the research lines as defined below. Each division is managed by a division research lead (DRL, default from TU Delft) and a division engineering lead (DEL, default from TNO). The overall multi-year objective of the program - to develop a scalable prototype quantum computer and a multi-node prototype quantum internet – will remain the same and needs a joint effort from both partners forming QuTech. Technology leadership and economic footprint are the ultimate goals of the QuTech endeavor.

In the divisions Quantum Computing and Quantum Internet, we combine all efforts on specific qubit systems, control systems, software stacks and system architectures, focused at arriving at scalable prototypes for Computing and Internet. The most relevant technologies are integrated in our demonstrators. Due to the limited maturity of the technology, QuTech uses a constant optimization between top-down design and bottom-up options and ideas. This allows us to constantly search for new and better solutions for every level in the stack and the maturing of the best solutions to higher TRL. Our new governance and the yearly budgeting and evaluation cycles are used to achieve that.

The Qubit Research division has a different role in the QuTech system. Here, promising but very early stage technologies are being pursued, such as Majorana's and fluxoniums. This division also houses a strong legacy and capability in nanofabrication, theory and materials development. In that way, this division will provide future options for the Quantum Computing and Quantum Internet divisions with relevant technology and the underpinning scientific understanding.

- **Research plan**

ERP Research Line A "Quantum Computing"

The ultimate QuTech objective for this research line was to develop a prototype fault tolerant quantum computer: The Fault-Tolerant Quantum Computing (FTQC) roadmap aims for a full-stack scalable quantum computing system, including the qubit circuits, the control electronics, and the software layers such as compilers. The approach to achieve fault tolerance is based on quantum error correction, in which information is encoded redundantly, enabling error detection without destroying quantum data. The qubit hardware systems are electron spins in quantum dots and superconducting quantum circuits.

This goal requires a level of technological maturity that will probably not be reached in 5 years. However, the power of quantum computers can also be used in a different way, formulated as NISQ computing (Noisy Intermediate Scale Quantum computer). In a NISQ computer quantum error correction is not included. Normally error correction restricts the computational space to a very small sub-space of the quantum-mechanical Hilbert space that is theoretically available. The biggest part of the Hilbert space is used for redundancy (which is how most error correction methods work). In classical computing the redundancy factor is usually small so only a small fraction (<<1) of the data bandwidth is used for correction (e.g. one parity bit per many bits). In quantum computing the redundancy factor is very large (>1000), meaning only a fraction (<0.001) is available for actual computation. NISQ uses the full data space for computation to solve problems in a way that cannot be done classically. NISQ machines require another paradigm of programming and control. The main differences are the user interaction and the amount of user interference with the machine (which is higher and more complex than with fault tolerant machines) and the diversity of control signals (variations) which is increased. In 2021 we started determining the full requirements for NISQ machines. In 2022-2025 we will develop such a machine, most probably on the basis of spin qubits in Silicon or Germanium. The research, which up to now was focused a lot on the interaction between control hardware and quantum chips will shift more in the 2022-2025 period towards the quantum chips themselves. This shift is driven by the following observations:

- The control hardware has gone through big developments the recent years and is no longer a system bottleneck. We have seen an increase in performance of these systems from the major commercial players in this field and strong take-off of start-up companies in this field, such as QBblox, with starting IP licensed from TNO and TUDelft.
- The development of quantum chips at QuTech has been slow compared to some major global players (IBM, Google, Alibaba). Each of those companies are now producing quantum chips with tens of *superconducting* qubits, while QuTech still only has systems with less than ten qubits available (both superconducting and spin qubits). In the domain of superconducting qubits there are now also several (start-up) commercial companies (like QuantWare from The Netherlands, again based on QuTech IP) offering commercial QPU's with up to ten superconducting qubits. Superconducting qubits are still an important topic for Qutech, but the focus of the TNO involvement will be on Spin qubits in the coming years.
- In the domain of spin qubits QuTech is still at the top of academic knowledge, but the chip development depends a lot on devices made by PhD students and lacks a good development strategy. We will put more TNO effort in the development of spin qubit devices, not only on the material side and pre-fab, but also on the design side and the engineering of fully functional chips and PCBs. Spin qubit devices are seen as the most attractive devices from a scaling point of view. One of the aspects here is the footprint of the qubits. Only Spin qubits have a small enough footprint to enable FTQC, which will require billions of qubits on one chip.

One of the main bottlenecks in NISQ is spin readout. The current methods are destructive (they destroy the qubit after measuring it or leave it in an undetermined state. Error correction methods (and potentially NISQ based algorithms as well, but this is not really clear yet) require the qubits to remain in a definite state after readout. Therefore . Therefore we will put more research and engineering focus on non-demolition readout, , using microwave photons. Since electron/hole spin only has a weak coupling with (microwave) photons, we will also put focus on developing cryogenic amplifiers to optimize the Signal-to-Noise ratio of the readout. Mastering cryogenic amplifier technology is also important geo-politically, because these devices are crucial for quantum computing.

The *ambition* is to have a 25-qubit system in 2025, based on spin qubits in Si or Ge, online via Quantum Inspire, with low-level user interaction with the qubit control, to exploit the noisy qubit devices for actual real-life use cases. This will further position Quantum Inspire within the European and global arena. The NISQ approach is in line with the recommendations of the Dijkgraaf committee of the QuTech mid-term review.

On the superconducting qubit side at QuTech we expect a steady growth in qubit numbers, going from 7 qubits in 2021 to 17 qubits in 2022 and 49 qubits in 2024. This work is part of Quantum Inspire, but not part of the ERP program

On all systems we expect a strong increase in the co-operation with external (Dutch) companies, through TKI projects, NAQT projects, EU projects and other types of co-development, IP transfer or licensing.

Planning:

- Direct spin readout, proof of principle	2022
- TWPA prototype, based on Nb tri-layer technology	2022
- 6-qubit NISQ system online, limited functionality, no direct spin readout	2023
- TWPA final version	2023
- Direct spin readout, high fidelity (>80%)	2024
- 10-qubit NISQ system online, full functionality for NISQ algo's with direct spin readout	2024
- 25- qubit NISQ system online, full functionality	2025

<u>ERP Research Line B "Quantum Internet"</u>

The goal of this research line is to build an optically-connected network of many (small) quantum processors. Such a network enables the exchange of quantum bits between any of the connected quantum processors in order to solve problems that are intractable classically.

A quantum network in which the processors are located at different geographical locations is called a Quantum Internet. Our goal is to develop the technology to enable quantum communication between any two places on earth. One application of such a quantum internet is to provide a fundamentally secure way of communication in which privacy is guaranteed by the laws of physics.

Quantum processors can also be connected into a quantum network in order to assemble a large quantum computing cluster. This approach is called networked quantum computing and offers a natural path towards scalability. Combining a quantum internet and a networked quantum computer finally allows remote users/providers to perform secure quantum computing "in the cloud".

For many years the Nitrogen Vacancy (NV) center in diamond has been the most promising qubit for Quantum internet applications, due to its optical interface, long coherence times and lifetime limited linewidths. Scalability towards applications is however limited by the fact that coherence times and linewidths are extremely sensitive to surface effects, prohibiting the integration of NV centers in optical nanocavities or integrated photonic structures. The next generation of quantum processors with an optical interface will most likely be based on group-IV color centers in diamond, like Tin vacancies. These color centers are compatible with integrated photonics. It is our goal to make engineering steps towards scalable quantum processors, using integrated photonics.

Planning:

- First long-distance entanglement generation between Delft and The Hague	2022
- Realization of a 3^{rd} node, with control of an additional qubit based on ^{13}C	2022
- Two NV based nodes accessible for experimenting by the public via a web interface	2023
- First samples based on integrated photonics with embedded color centers ready	2024
- Functional device with integrated photonics and embedded group IV color centers	2025

<u>ERP Research Line C "Qubit Research"</u>

One approach to demonstrate a quantum computer is to scale up quantum bits with given fidelities and use error corrections to perform algorithms. The goal of this research line is to come up with quantum bits with fidelities that will challenge the already existing quantum bits. So far, our efforts have focused on Majorana topological quantum bits. For the coming years our attention will also be given to fluxonium quantum bits.

We will continue our efforts in combining material science, theory, and novel device design to obtain more control of the underlying constituents of protected qubits. The material possibilities and fabrication processes are at the moment the limitation to further development. Most of the resources will be used to achieve pristine interfaces between the materials, defect free layers and testing new possible combinations of insulators/metals/superconductors.

Every breakthrough will be transferred to the other research lines when applicable.

- **Targeted partnerships**

In this challenging and internationally very dynamic environment, TNO is well positioned due to the partnership with TU Delft in QuTech. TNO's investment into QuTech leverages approximately 230 fte scientific personnel (including PhD's and post docs), technical and support staff. In addition we play a central role in the NAQT. All in all there is a lot going on around QuTech, and for a full list of the partnerships (running and targeted), we refer to the appendix. Nevertheless, the key foundation for all these efforts is the continued base funding from TNO through the ERP.

Results 2021 and plan year 2022

3. Results 2021 and Plan year 2022

ERP Research Line A "Quantum Computing"

Focus 2022: prepare for NISQ devices based on Spin qubits. This will require R&D on control systems and software but main focus will be on the device development, to bring the current spin qubits chip from an academic R&D environment (with lots of trial and error) to a higher development level (both in terms of development process and in performance).

Key objectives and deliverables 2022:

A1. Direct spin readout – Proof of principle
A2. 6-qubit Spin device integrated in Quantum Inspire, partly operational
A3. 10- 25-qubit Spin device – Architecture study and requirements defined
A4. 10- 25-qubit Spin device – Devices Under Test
A5. Dip stick test facility at TNO (1.5 Kelvin) to increase turnover time chip development
A6. 2nd Spin qubit set-up connected to Quantum Inspire for NISQ devices

Activities 2022:
All ERP activities are integrated in a much larger set of activities that have multiple funding schemes (ERP, TKI, EU, NAQT). Great care is taken to harmonize these activities. ERP activities are mainly focused around chip development, such as material analysis, gate design.

ERP Research Line B "Quantum Internet"

Key results so far:

- Two NV based nodes and a measurement station have been realized and first scientific experiments are being conducted in the lab as part of a sequence of tests, before moving one of the nodes to The Hague and the measurement station to Rijswijk.

- Phase locking between lasers has been demonstrated under operational conditions (low power, limited duty cycle), as preparation for a future upgrade of the existing nodes.
- An improved production process of Solid Immersion Lenses (SILs) has been engineered and the first NV sample with SIL has been delivered.

Key objectives and expected results 2022

B1. First long-distance entanglement generation between Delft and The Hague (using the key components that were developed up to now).
B2. Realization of a 3rd node, with control of an additional qubit based on ^{13}C.
B3. Production of NV based samples based on SILs: one sample for the new 3rd node and samples with improved performance intended for the existing 2 nodes.
B4. Start with the design and process development of integrated photonic structures for color centers in diamond.

ERP Research Line C "Qubit research"

Key results so far:

- Fabrication of superconducting islands and observation of zero bias peaks (possible signature of Majoranas)
- Development of a low temperature deposition process for gate oxide
- Design and fabrication of a multiplexer chip consisting of 3 resonators for Qubit reading
- Transformation of sputter tool into an evaporator (needed for superconductor depostion)
- First steps towards decreasing the quasi particle poisoning using various phonon traps designs

Key objectives and expected results 2022:

C1. Reproducible fabrication process for hybrid devices
C2. Demonstrated design for fluxionium qubit
C3. Reproducible fabrication process for fluxonium qubit
C4. Reproducible process on newly transformed evaporator (including cleaning and deposition process)
C5. Demonstration of RF multiplexing using 6 non superconductor resonators

19: MICROPLASTICS

ERP Contacts: S. Henke (Project Lead), J.H. Urbanus (Lead Scientist), A. Dortmans (Science Director)
ERP Duration: 2022 – 2025

Overall program description

1. Context and Objectives

- **Problem definition**

Plastic pollution is considered one of the "most pressing environmental and social issues of the 21st century"[23,24]. Microplastics (MPs), plastic particles smaller than 5 mm, are formed during degradation of plastics[25] and have been detected in water, food and air. Ingestion and inhalation of these MPs lead to human exposure[26]. MPs have been shown to invade the human system and accumulate in various tissues and organs[27]. Although the hazardousness of MPs is still largely unknown, ongoing research (with TNO involvement through amongst others a ZonMW-project) shows that MP exposure can cause adverse health effects.

The attitude of industry, government and citizens towards potential adverse health and wellbeing effects caused by environmental pollution is changing. Traditionally, risk assessments were employed in which risk is expressed as exposure times hazard. However, the hazard is often unknown making these assessments difficult to apply. Nowadays, maximum precaution with a zero-emission approach of particles and substances is preferred ("***the precautionary principle"***): "better safe than sorry". Policies are being modified accordingly which drive industries towards mitigation[28]. Exemplary is the intentional use of MPs in products (e.g. cosmetics), which has been forbidden recently, while further steps have been announced by the European Commission to reduce the unintentional release of MPs to the environment[29].

Wear and tear, UV- and thermal instability are known to be the main causes (stressors) for the formation of MPs during degradation of plastics. Besides from plastic pollution, MP formation and release can occur during production of plastics (industrial emissions –), use of plastics (rubber from tyres, textile, food packaging – estimates mention a consumption of 5 gram of plastic per week[30], of which a significant part originates from food packaging) and recycling of plastics (up to 30% losses reported[31]). The MPs formed are both water- and airborne, leading to a global flow of MPs, eventually entering our water and food systems and resulting in human exposure.

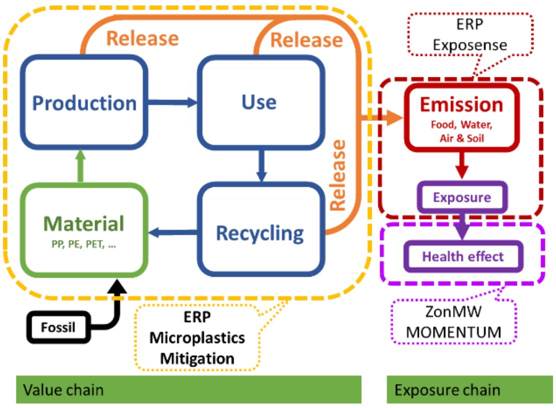


Figure 39: Plastic value chain with positioning of ERP Microplastics, ERP Exposense & ZonMW Momentum (MPs & health).

[23] https://www.pnas.org/content/118/16/e2020719118 [PNAS, **2021**, https://doi.org/10.1073/pnas.2020719118]
[24] https://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/34948/MPN.pdf
[25] Understanding plastic degradation and microplastic formation in the environment: A review - ScienceDirect
[26] https://www.sciencedirect.com/science/article/pii/S0048969720374039#bb0545
[27] Plasticenta: First evidence of microplastics in human placenta - ScienceDirect
[28] https://www.nature.com/articles/s41467-020-19069-1
[29] https://ec.europa.eu/environment/topics/plastics/microplastics_en
[30] https://www.consumerreports.org/health-wellness/how-to-eat-less-plastic-microplastics-in-food-water/
[31] conversation with stakeholder

Maximum precaution (or zero exposure) requires mitigation of MP-emissions through reduced MP formation and/or release to the environment. In order to develop effective mitigation strategies, a systems perspective is required which comprises understanding how microplastics are formed, where they are formed predominantly and how they are released. Internationally, research has been focused on detecting microplastics in various places (oceans, rivers, north pole), on assessing dominant sources (litter, recycling, tyres, coatings & textile) and on removing plastic pollution from oceans and rivers. Not much is known yet about formation mechanisms nor microplastics mitigation options. Therefore, the overall objective of this ERP is to lay the foundation for the development of effective mitigation strategies, based on knowledge generated on the formation and release of microplastics. This new knowledge will be used to develop solutions for the zero-emission approach, as such enabling governmental and industrial stakeholders to tackle this societal challenge.

According to European and Dutch policies, plastics should become fully circular by 2050. Here, the plastic material ideally runs through the production, use and recycling loop infinitely (see Figure), thereby eliminating the need for fossil feedstocks. Currently, only 30% of our domestic plastics is being recycled (mechanically) and often only once. Because of a decrease in quality, the material is then used in less challenging products (downcycling) or is simply incinerated. The decreasing material quality results from the stress it experiences during production, use and, most significantly, mechanical recycling. This stress can potentially also lead to MP-formation in the entire value chain. Hence, plastics circularity could ironically become a major source of MPs through the multiple production-use-recycling loops the material needs to undergo. Thus, true circularity requires innovations on *materials*, *production, use* and *recycling* of plastic products. This will lead to safer products (safe-by-design) and less losses, an important bonus in view of scarcity of raw materials. Therefore, plastics in a circular economy, and in particular circular packaging, is selected as the leading use case of this “ERP Microplastics”.

- **Expected impact to stakeholders**

Important stakeholders are the polymer and recycling industry that will be forced to reduce their MP emissions; brand owners that need to ensure MP free products and national and EU governments that need to ensure quality of environment, water and food. Through adopting the envisioned mitigation strategies accompanied with appropriate policy and legislative frameworks, these stakeholders will achieve *societal impact* through intrinsically safer products, less pollution and improved quality of life. On top of that, negative perception about plastics is alleviated, enabling its role as sustainable solution provider. Furthermore, mitigation leads to *economic impact* through averting the threat of losing the licence-to-operate and reducing the loss of valuable raw materials along the manufacturing chain. In addition, it will create business opportunities for equipment suppliers.

2. Approach

- **Focus**

The scope of this ERP is the development of mitigation strategies that reduce formation and/or release of MPs, towards zero-emissions in the circular plastics industry as leading use case. Although MPs are defined as plastic particles <5 mm, (nano)particles much smaller than 100 µm are most relevant with respect to technological challenges and potential adverse health effects. Therefore, this ERP focuses on such small MPs. The strategies can be implemented at various points in the value chain (see Figure): in the material properties themselves, in the production, during use and in the recycling process. This ERP focuses on three key research areas: 1) the *formation* of MPs in relation to material properties and external stressors, 2*)* the *release* of MPs across the plastics value chain and 3) the development of appropriate *mitigation* strategies for design (materials & products), processing (production & recycling), and product use. Additionally focus is on 4) *valorisation*: the application of generated knowledge to the packaging and other sectors prone to MP-emissions, such as textile, conveyer belts in food/medical processing, semicon (clean rooms, sterilization), etc.

In this ERP we plan to develop and apply innovative methods and instruments correlating material properties to MP formation (e.g. new chemical and physical characterization methods on MP particle level), lab facilities (tools) to assess the impact of polymer processing and recycling on the formation and release of MPs (e.g. new equipment to simulate recycling steps), analytical technologies to study the release of microplastics during production, recycling and use and, finally, a methodology to quickly assess various mitigation strategies.

- **Research plan**

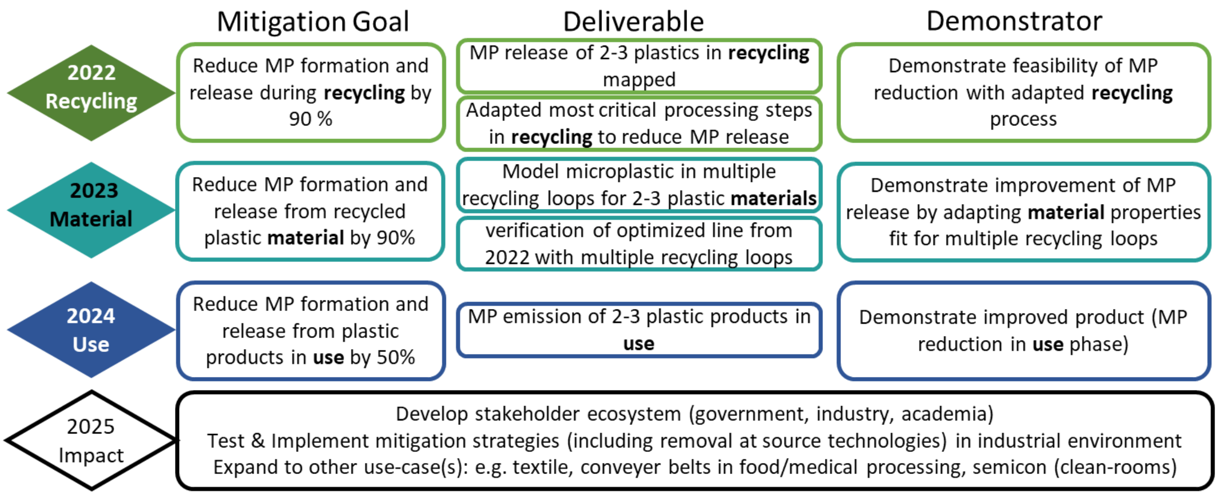


Figure 40: Summary of main mitigation goals over the years, concretized in key deliverables and related demonstrators.

With the objective as described above (laying the foundation for mitigation based on knowledge generated on formation and release of MPs), the main research questions are as follows:

- Q1. <u>How are MPs mechanistically formed?</u> What is the influence of polymer type, morphology and formulation (in a packaging product) and how do different stressors influence the formation?
- Q2. <u>Where in the circular plastics value chain are MPs released?</u> Where do we need to intervene?
- Q3. What is the influence of <u>multiple recycling cycles</u> on MP formation potential of materials?
- Q4. How should a recycling processes <u>be adapted</u> to generate less MPs?
- Q5. How should plastic (packaging) products <u>be designed</u> to generate less MPs?
- Q6. How to <u>separate & destruct</u> MPs in waste streams (air, water) of processes?

These research questions are addressed in the research areas above (formation, release and mitigation) and will lead together to the demonstrators as scheduled in Figure 40 , during the full ERP.

- **Activities & targeted partnerships**

The activities for the full ERP all contribute to the development and implementation of effective mitigation strategies, based on the knowledge generated on the formation and release of MPs.

<u>1. Formation.</u> The activities to understand MP formation will be aimed at the detailed mechanical and chemical characterization of 5-6 polymers (or -grades) and the related mechanisms involved in MP creation (Q1). A tool (e.g. tribometer or shredder) will be developed to create a reproducible MP formation process on small scale that can be used to differentiate between polymer types and grades. Special attention will be put on the impact of multiple recycling steps for these 5-6 polymers on the change of polymer properties (Q3). We will also include the change in release due to degradation (e.g. oxidation) and use of the plastics. For this, we will build a tool that will execute a defined external stressor to the plastics (Q3). The targeted partners for this universities.

<u>2. Release.</u> Release of MP’s can occur during processing, recycling and use. An inventory will be made of the value chain for the defined use case to assess the conditions of highest MP release for the 5-6

polymers selected (Q2). This also includes the MP release during the use phase of these polymers. Furthermore we will assess the 3 most relevant processing steps and identify the critical parameters associated with MP release. This involves development and optimization of in-line or real-time sampling and analytical techniques of MPs. We will build and deploy a new tool for such real-time particle characterization to directly correlate the particle release to hardware settings and material properties. Intended partnerships to reach our goals are universities, a research organization and a governmental organization.

3. Mitigation. Based on the technological developments of formation and release, we will start with adapting critical processing steps in recycling to mitigate direct MP release in a demonstrator (Q4). The next step will be to mitigate future MP release by changing the recycling conditions in a multiple recycling loops scenario in collaboration with process technology partners at a university. (Q5), In cases where MP formation cannot be mitigated we will initiate research on removal at source strategies, together with one or more research institutes for removal of MPs from process water (Q6). We will improve the fraction of plastics that will be retained during recycling as compared to the current 30% that is lost as so called "fines" (microplastic) from state-of-the-art recycling processes.

4. Valorisation. An integral approach will be defined for the implementation of the mitigation measures in the existing and anticipated ecosystem: running: MOMENTUM, LEON-T, in development: 'Groeifonds Materialen', HEurope), TTW perspectief. This also includes the validation of the microplastic reduction concept with at least three industrial polymer partners, and three packaging or branch organizations. We will also investigate how this approach will relate to legislation and EU regulations. Due to TNO's unique position in the field of microplastics, we will act as system integrator and orchestrator of eco-system broad mitigations toward plastics without (hazardous) microplastics. This ERP will expand our scientific eco-system (see Figure 41) through new and reinforced collaborations with several partners incl. universities and an industrial pilot scale facility.

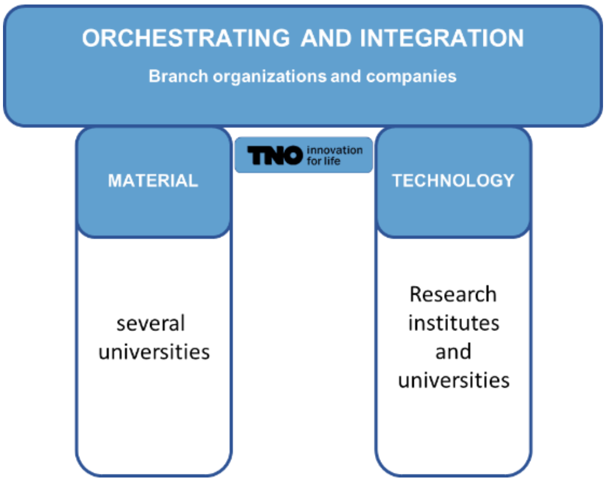


Figure 41: Knowledge T-profile (modified) for MPs. Role & position TNO (in blue): orchestrating and knowledge integration (materials & technology).

Results 2021 and plan year 2022

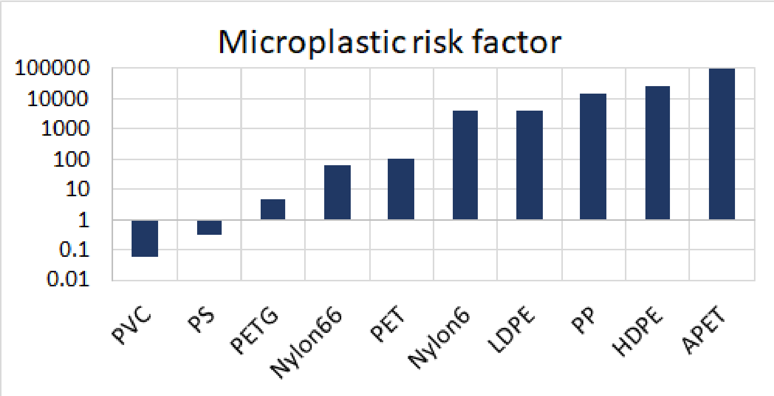
3. Results 2021

- **Results achieved in 2021**

The topic of MPs was only recently identified as being extremely relevant in relation with environment and health. Most academic research on this topic relates to the presence of MPs in various environmental compartments (water, sediments, air, etc.) and on the potential health impact. However, very limited knowledge is available on the actual formation mechanisms, and how to intervene on a material and processing level. Therefore, we started the seed-ERP phase from almost zero to build a promising approach towards MPs mitigation, and found that the understanding of physical properties and chemical characteristics in combination with the degradation of plastic is essential in order to define proper mitigation strategies.

Correlation formation MPs with physical properties

A preliminary correlation between the formation of MPs and physical properties of polymers was set up. The size of particles formed by mechanical stresses occurring in polymer processing and use was predicted from polymer properties. We assessed the risks of polymers to form microparticles, using a risk factor that ranges between 0.01 and 1000000. An example is given in Figure 42 (left), in which the risk factor is calculated for several polymers (based on literature properties). This graph shows that PVC has the highest risk to form MPs and APET the smallest.



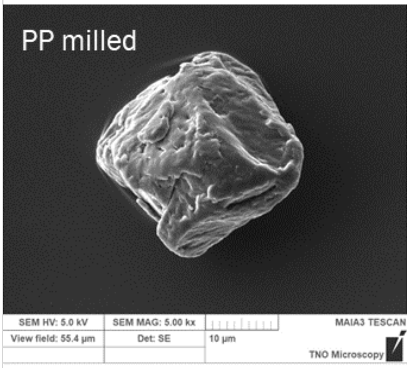


Figure 42: (left) Microplastic risk of virgin polymers; (right) SEM picture of PP particle.

Characterization

An initial understanding of the mechanisms during polymer degradation and subsequent microparticle formation was obtained by the implementation of new analytical techniques. These are able to characterize the chemistry of MPs at particle level (< 10 mm), which is very important for understanding the chemical changes during formation of MPs. The size and shape of particles generated from degrading samples (obtained by SEM), was combined with information on the chemistry (CathodoLuminescence (CL) and AFM-IR). For example, oxidation of PP exposed to UV light was detected by CL on a micrometre scale.

For a circular economy, the impact of multiple recycling loops on the polymer properties and subsequent tendency for the generation of particles becomes extremely relevant. Recycling changes material properties, and introduces material losses when MPs are formed and lost.

4. Plan year 2022

- **Focus year 2022**

The leading use case in 2022 and 2023 is food packaging in a circular economy, with an initial focus on PP. The goal is to understand the relation between the polymer material, (multiple) recycling steps, degradation and the nature of formed MPs, as a foundation for the development of effective mitigation strategies. The effects of the use phase on MP formation will be investigated from 2024 onwards.

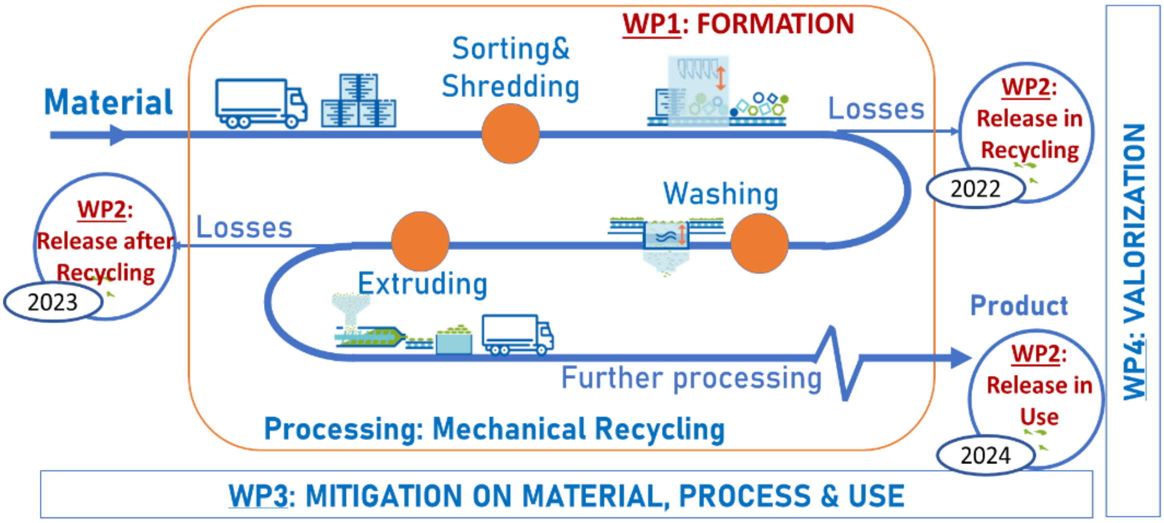


Figure 43: Schematic representation of mechanical recycling, leading use case for this ERP. The process of mechanical recycling consists of sorting, shredding, washing and extruding and turns plastic waste into (recycled) products. The orange circles indicate suspected hotspots for MP formation. The WP-numbers refer to the work packages of the full ERP.

- **Activities year 2022**

The goal of 2022 is to demonstrate the feasibility in reducing the release of MPs during a typical recycling process by 90% by changing processing conditions and with removal-at-source of microplastics. For this we foresee the following activities for 2022:

WP1: *Understanding the formation of MPs in relation to material characteristics and processing steps.*
We will build a new tool that applies a controlled mechanical stress to the polymers, mimicking some of the processing steps during recycling. This will result in more in depth understanding of failure mechanisms for 2-3 polymer (grades). We will extend the ability of targeted chemical analytical steps on single particle level, using SEM-CL, AFM-IR, and introduce microindentation as a small scale mechanical characterization tool to analyze MP formation.

WP2: *Understanding the release of microplastics to the environment (water, air, soil, food).*
We will develop a methodology to measure the release of MPs in a recycling process for 2-3 polymer (grades). After an inventory of all individual steps in the whole recycling chain, the steps that are expected to generate the most MPs will be assessed into further detail. For this we will combine 2 technologies:

- In-line particle collection and characterization that will be implemented to real-time measure the hotspots of particle release from several processing steps. This will be done using an adapted ERP-Exposense analyzer for particulate matter, that will be able to measure the chemistry of particles
- On-site particle sampling followed by lab characterization of size, chemistry, etc. to correlate to the in-line detector results.

Furthermore, in cooperation with 1-2 stakeholders, a first step will be taken to convert MP release from sorting and recycling plants into emission sources that can be implemented in occupational and environmental source modelling.

WP3: *Definition and assessment of mitigation measures to reduce the release of MPs to the environment.*
The mitigation steps taken in the first year of the ERP will be focused on the adaptation of processing conditions in a recycling process. 2-3 polymers (grades) will be exposed to (semi)industrial sorting, shredding and washing experiments. The production of MPs (amount, particle size distribution, release rate) will be analyzed. The methodology of WP2 will be used to identify the processing step

with the highest MP release. For this step, optimal operational protocols will be proposed that can result in less MP formation and release. These modified protocols will be tested in a demonstrator. Feedback from this demonstrator will be used to evaluate our modified protocols and could eventually result in designs for adapted recycling hardware (equipment or technologies). Finally, in 2022 we will start with the identification of possible MP removal technologies at source (e.g. nanofiltration).

WP4: *Valorization of the formation, release and mitigation knowledge.* The initial business opportunities that were defined will be explored in more detail to identify the first cofunded and B2B projects. The topic MPs in part of the "Groeifonds Duurzame Materialen" and actions will be defined to make this concrete. Academic cooperations will be initiated and concretized to strengthen the materials and processing parts of the project. Relevant calls in Horizon Europe have been identified (HORIZON-CL6-2021-CIRCBIO-01-03, HORIZON-CL6-2022-CIRCBIO-02-03) in which we plan to submit a proposal. The first version of the model that is defined in WP1 and validated in WP3 will be challenged against potential end-users. This will give us insight in the parameters and knowledge needed implement in industry and also guide us to the polymers and use cases to take up next in the program.

- **Deliverables year 2022**

- D1 Requirements and execution of first demonstrator (all WP's)
- D2 Determination of material parameters related to microplastic formation, validated for 2-3 polymers (WP 1)
- D3 Mechanical testing tool to experimentally assess MP formation for 2-3 polymers (WP1)
- D4 Show correlation between on-site sampling and in-line characterization techniques, with respect to particle size (SEM), chemical composition (CL, FTIR) and concentration (mg/m^3) (WP2)
- D5 MP emission of 2-3 polymers mapped in mechanical recycling line (WP2)
- D6 Demonstrate modified operational protocol for significant reduction of MP release during mechanical recycling (WP3)
- D7 Realize cooperation with relevant partners to strengthen individual research areas and connect ERP to broader microplastic developments (WP 4)