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TNO report
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TNO EARLY RESEARCH PROGRAM
Annual Plan 2020

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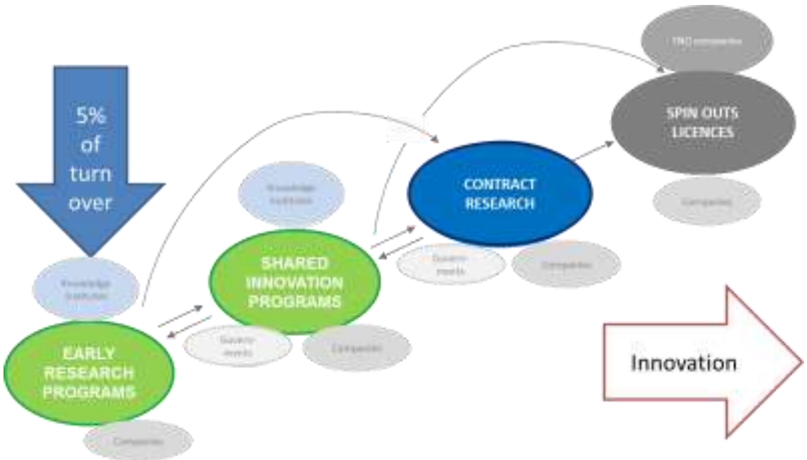
Contents

1 Introduction

The Early Research Programs (ERP's) presented here reflect TNO's vision where to put its innovative research efforts to be able to grow strong technology positions and to contribute, together with knowledge partners and stakeholders, to societal challenges and economic impact. These 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).



The main characteristics of the ERP portfolio are:

- The programs build and renew strong technology positions in the focus areas defined in the TNO Strategy Plan 2018-2021
- The programs are use-case inspired and have clear research goals: ERPs feed the innovation roadmaps of multiple TNO units with common cross-unit 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 and additional investments by stakeholders).
- The programs have substantial mass (involving on average 1,5 mln Euro ERP budget per program) and a typical running time 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 adjust and reallocate means if necessary.
- '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 five 'Seed ERP' projects 2019, the two strongest were selected for continuation as 'Full ERPs in 2020 and onwards'

Together with EZK we inform the Topsectors and Ministries of our approach of building our knowledge base, aiming at early involvement of companies and other stakeholders in public private cooperation. Each of the ERP's is described by its overall goals and its intended results in 2020.

Overview of the most prominent FULL ERP results 2020

ERP	Results 2020
Quantum Computer / Internet	Globally first quantum computer based on spin-cubit quantum processor (QantumInspire)
Energy Storage & Conversion	Design of a lab scale factory for CO2 to methane and CO (photons to chemicals) and of a demonstrator for CO2 to Formic Acid (electrons to chemicals)
3D Nanomanufacturing Instruments	Imaging demonstrator of sub 400nm features at depth > 5um with a top-actuated GHz system, applicable to alignment marker metrology for improved overlay in chip manufacturing
Large Area Ultrasound	Demonstrator of dynamic imaging for healthcare at TRL5 with an ultrasound imaging array
Self-adapting smart batteries	Cell-level sensing demo's with >20 cells in a module, for module-level and for cell-level control in batteries
Decarbonisation	Launch of multiple program lines in the Brightsite initiative
Sustainability and Reliability for PV and thin film devices	Quantitative and qualitative schemes of the failure mechanisms in (opto)electronic devices, as well as accelerated test protocols for new device types to improve device reliability, and reduce costs and environmental impact.
Body-Brain Interactions	Causal models and experimental setups by integrating psycho-social and molecular-physiological mechanisms to improve cognitive performance and disease control.
Social eXtended Reality	A user-centric, distributed XR environment and test setups to enable seamless, low-latency edge computing and holographic communication.
Personalized Health	Biomarker panel (up to 10 biomarkers) and new intervention strategies to optimize low-grade inflammatory resilience. Personal health advice system combining biological and socio-psychological knowledge to support citizens with healthy lifestyle choices.
Organ on Chip	Validated and integrated organ-on-chip (gut, liver, lung) models for pharmaceutical and nutritional applications. Novel technologies (chips, readouts and protocols) for higher throughput and easier use in practice.
Digital Twin for Structural Integrity	(Hybrid) physics-based and data-centred models and methods to support the maintenance of existing structures (bridges, networks) and to improve the design of new macro-structures.

Submicron Composites	Thermochromic solar control coatings and pigments for sustainable buildings. 3D printed parts for load and structural integrity monitoring and parts exhibiting stimuli-responsive functionality.
i-Botics	State-of-the-art demonstrator for tele-manipulation, including smart selection and processing of sensor data. Simulation models for exoskeletons to make predictions for human body impact using task profiles.
Hybrid AI	Architecture and demonstrator of autonomous platform for “smart-home” applications, including sensing, tactical maneuvers, and explanation capabilities. Demonstrator of intelligent decision support, including causal reasoning and human feedback, for a medical application.
Exposense	Two demonstrators combining particulate matter sensing and chemical identification, with a portable sensor device, for occupational and environmental applications. (Data-driven) models for personal exposure profiling (‘exposome’).
Lasersatcom (Frontiers)	Novel concepts and technologies to advance fast, secure, multipoint Optical Satellite Communication (OSC) in particular: (1) a photonics based concept for a multi-beam receiver/ transmitter, (2) A Proof-of-concept of a high reliability, high data throughput link using OSC, and (3) concept technology for a large-aperture, large FoV, low SWaPC receiver telescope.
Wise Policymaking / Policy by Simulation	A first instrument based on utility functions to assess and experience the impact of policies on wellbeing. A set of value-based reasoning methods to support policy makers in using these instruments in the real world of policy making. A knowledge base on state-of-the-art inventories with regard to policy related to long term wellbeing.

Mapping of ERP topic per TNO 2018-2021 strategic area

ERP	Nano & Quantum	Hybrid energy systems	Smart and green materials	Smart megastructures	Media synchronisation	Artificial Intelligence	Robotics	Neurotech / Medtech	Subsurface Engineering (Geology)	Valorisation of (meta) data	Inside the Human Body	Inside the Human Mind	Integr. social-system modelling and forecasting	Security (ICT)
	STRATEGIC AREAS 2018 - 2021													NEW
Quantum Comp	X													X
3D Nano	X							X						
Optic Sat Comm	X						X							X
Holst Ultrasound	X		X					X			X			
Holst Smart bat	X	X	X				X							
Holst Reliability	X	X	X											
Energy Stor & Conv		X	X											
Subm composites		X	X				X							
Structural Integrity				X										
Hybrid AI						X				X				
i-Botics							X					X		
Organ on Chip											X			
Personalized Health											X			
Exposense	X		X								X			
Wise Policy												X	X	
Decarbonisation		X	X										X	
Body brain interaction											X	X		
Social VR					X									

2 QuTech Quantum computing and quantum internet

<table>
<tr><td colspan="2">General information</td></tr>
<tr><td>Title ERP</td><td>QuTech - Quantum computing and quantum internet</td></tr>
<tr><td>Contact person TNO (DM en VPM)</td><td>Peter Werkhoven
Rogier Verberk</td></tr>
<tr><td>Contact person(s) government or topsector</td><td>Michiel Ottolander (EZ)</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">Program 2020</td></tr>
<tr><td>Summary</td><td>Program description
Where the first phase of QuTech (2014 – 2017; Proof of Principle) focused on accelerating research and making the transition towards a mission-based way of working, the current phase (2018 – 2022; Proof of Concept) is used to demonstrate progress on key technologies (critical milestones) resulting in the following QuTech deliverables in 2022:
A. an online platform giving access to a pre-prototype fault tolerant quantum computer based on three qubit technologies that currently are being considered scalable: superconducting qubits, electron spin qubits and spin qubits in NV centers.
B. a pre-prototype quantum internet consisting of a three-node internet between The Hague, Delft and a third node of which the location still needs to be determined accessible through an online portal allowing quantum communication between nodes.
Both pre-prototype deliverables (demonstrators) play a key role in bringing this new technology to society. In order to do so, an ecosystem is being created to increase our connectivity with stakeholders.

Plan 2020
Towards QuTech goal A:
- In 2018 and 2019 TNO developed the Quantum Inspire platform (www.quantum-inspire.com) hosting a quantum emulator for simulating quantum chips. The first hardware chip (based on electron spin qubits) is being integrated into the system and tested. In 2020 we will make this chip available for online access to external users, making it the world’s first prototype quantum computer based on this qubit technology. In the years thereafter we plan to connect this system to quantum chips based on different technologies, both at QuTech in Delft as well as elsewhere in Europe with European partners.
- In 2020 this platform will give access to a superconducting quantum chip developed at QuTech, growing into a first prototype of a Quantum Computing Cloud service, also giving access to other EU developed quantum hardware platforms.

Towards QuTech goal B:
- We aim to establish the first two-city Quantum Link, between Delft and The Hague. This is however a challenging goal.
- in the Quantum Internet Alliance project, a blueprint for the quantum internet will be developed. It will be based on QuTech’s NetSquid quantum internet simulator.</td></tr>
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	- This first stable version of NetSquid will be released to 3rd parties. - First breadboard prototypes of non-existing key components (a quantum memory) of the quantum internet will be developed and tested in QuTech laser labs. - The improved version of Quantum Key Distribution technology (Measurement Device Independent) will be made ready for transfer to a new QuTech start-up, by increasing its TRL to six. *Embedding* The goals of this program are aligned with those of the HTSM top sector and the NWA route 18 as well as the National Agenda Quantum Technology. Collaboration with various partners is taking place through collaborations such as in IARPA and EU flagship sponsored projects.
Short Description	Quantum Technology at TNO The first quantum revolution – understanding and applying physical laws in the microscopic realm – resulted in ground-breaking technologies such as the transistor, solid-state lighting and lasers, and GPS. Today, our ability to use previously untapped quantum effects in customized systems and materials is paving the way for a second revolution. TNO aims to exploit these effects in new systems and new concepts using our core quantum technology expertise in • quantum systems engineering; • development of quantum materials and devices; and • quantum encryption and protection. To fully profit from our unique position we are collaborating with the world leading groups at TU Delft in these efforts, and have been a full partner in the QuTech consortium since its very beginning. QuTech QuTech's mission is to build the first scalable quantum computer prototype and a secure quantum internet. *Fault Tolerant Quantum Computing* QuTech's Fault-Tolerant Quantum Computing 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. The Fault Tolerant Roadmap is aiming for an online platform giving access to a pre-prototype fault tolerant quantum computer and is developing technology in close collaboration with Intel Research. TNO's contribution to Fault Tolerant Roadmap Milestones in 2020: - The Quantum Inspire platform (www.quantum-inspire.eu) is a pre-prototype quantum computer. This platform has been launched, making both a quantum emulator available to society, as well as QuTech's quantum computing chips. In 2020, it is planned that this platform will host different kinds of quantum computing chips that have been developed at QuTech and will grow into a first proto-type of a Quantum

	Computing Cloud service, also giving access to other EU developed quantum hardware platforms. *Topological Quantum Computing* The focus of QuTech's Topological Quantum Computing roadmap is to develop, build and demonstrate the first topologically protected quantum bit based on Majorana-bound states. We will continue our efforts in combining material science, theoretical physics, and novel device design to obtain more control of the underlying constituents of the topological qubit. The objective of the Topological Roadmap is the realization of a topological qubit encoding a quantum state that is protected for at least a second. As building blocks we use pairs of Majoranas that emerge in semiconductor nanowires in contact with a superconductor. The Topological Roadmap is executed in close collaboration with Microsoft Research Station Q, located in Delft and headed by prof Leo Kouwenhoven. TNO's contribution to Topological Quantum Computing Roadmap Milestones in 2020 is providing support based on TNO's development of quantum materials and devices expertise. *Quantum internet & networked computing* The focus of QuTech's Quantum Internet and Networked Computing roadmap is to to build an optically-connected network of many (small) quantum computers. Such a network enables the exchange of quantum information 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". The Quantum Internet Roadmap is aiming for a pre-prototype quantum internet consisting of a three-node internet between The Hague, Delft and a third location accessible through an online portal allowing quantum communication between nodes, making use of a dark fiber (=unused) network from KPN. TNO's contribution to Quantum Internet Roadmap Milestones in 2020: - In 2020, the first two-city Quantum Link will be established between Delft and The Hague. - Furthermore, a blueprint for the quantum internet will be developed in the Quantum Internet Alliance project. The development of this blueprint will be based on QuTech's NetSquid quantum internet simulator. - In 2020 this first stable version of NetSquid will be released to 3rd parties. - Finally, first breadboard prototypes of non-existing key components of the quantum internet will be developed and tested in QuTech laser labs.

	- The improved version of Quantum Key Distribution technology (Measurement Device Independent) will be made ready for transfer to a new QuTech start-up, by increasing its TRL to 6.
Results 2020	QuTech collaboration In 2020, Business Development activities of QuTech will expand. The spin-out QBlox will start selling room-temperature control electronics for quantum computing based on intellectual property that has been transferred from QuTech. At least one additional spin-out company is expected to be created in 2020 from the roadmap Quantum internet & secure communication. Fault Tolerant Quantum Computing Quantum Inspire will operate a few-qubit quantum processor in 2020. It is the first platform in the world using a quantum processor based on spin qubits in silicon technology. However, the hardware design of Quantum Inspire is such that the implementation of other qubit technologies will be possible. Quantum Inspire will be the first European Quantum Computing Cloud service, giving access to different quantum hardware technologies available in the EU. Discussion with the EU projects OpenSuperQ and Aqtion about integration will start in 2020. Goal of 2020 is to bring QuTech’s transmon quantum computing chips online. On parts of the quantum computing “stack” only limited partnerships can be pursued: due the participation of Intel and Microsoft, ‘open innovation’ and pre-competitive research is no longer an option at the level of the quantum chips. For other parts of the stack (electronics, software, ...) opportunities are present for new partnerships. One of the most likely and interesting partners for technology transfer are Zurich Instruments, KeySight and QBlox. Next to partnerships with suppliers and possible producers of quantum computers, in 2020, a collaboration model (“Fieldlab”) will be investigated to interact with end-users. A new cryostat for testing quantum computer hardware will be operational in 2020. The hardware of the cryostat will have a large extent of overlap with the Quantum Inspire machine. Having a second cryostat will facilitate the development of new qubits chips that will be herein tested, while the Quantum Inspire will be kept operational for cloud computing. In addition, we will offer to commercial partners (Delft Circuits, QBlox, etc.), the possibility to benchmark their quantum hardware in this cryostat against cost. Topological Quantum Computing The collaboration between StationQ and QuTech requires a re-focus of the long term goals and the efforts needed to reach these goals, the details of which still need to be worked out. In 2020, the B2B contracts between TNO and Microsoft will be extended. TNO is providing expertise on development of quantum materials and devices. A team of about 10 TNO experts will be involved in 3 parallel projects. Quantum internet & networked computing In 2020, the first two-city Quantum Link will be established. Furthermore, the blueprint for the quantum internet will be developed in the Quantum Internet Alliance project. The development of this blueprint will be based on QuTech’s NetSquid quantum internet

	simulator. In 2020 NetSquid will be put online as an emulator for the quantum internet demonstrator, similar as QX is used as quantum computer emulator in the quantum inspire demonstrator. Partnerships will be started based on ‘open innovation’ and pre-competitive research. In principle, every party can participate. Next to partnerships with suppliers and possible providers of quantum internet, in 2020, a collaboration model will be investigated to interact with end-users. A “Randstad-network” is pursued, with Dutch partners, like KPN, ABN-AMRO, TNO-Space, etc. Moreover, in 2020 several activities will continue in the field of space ultra-secure communication with the goal of distributing quantum keys via free-space optical links. Optical links between ground and LEO (low orbit) or ground and GEO (geostationary orbit) will be studied in different projects. The implementation of the optical links with quantum key distribution protocols will be tested and validated in a representative laboratory environment (i.e., with a representative simulation of the optical losses). Use cases and application of free-space ground-to-ground links will also be evaluated in 2020.
Dynamics	<u>QuTech cooperation</u> An important recommendation of the mid-term review committee (2015-2018) was the following: Prepare for an increased focus on innovation management and business development within QuTech to match the expected maturation of quantum technology, and empower QuTech’s new Business Director to take a leading role in these activities. The QuTech business plan will be in place and executed. <u>Fault Tolerant Quantum Computing</u> One of the main obstacles currently encountered in the development of a fault tolerant quantum computer prototypes is the quality of the quantum processors. The expected progress in quality was not met in 2019. Furthermore, the collaboration agreement with Intel will be renewed. <u>Topological Quantum Computing</u> In 2020 it is foreseen that TNO and Microsoft will be working together through a framework contract aimed at developing nano-fabrication processes and devices for topological quantum computing. <u>Quantum internet & secure communication</u> In 2019 the quantum link between Delft and Den Haag will first be demonstrated (scheduled before end of 2019) using novel Measurement Device Independent Quantum Key Distribution system instead of quantum internet nodes. This field case will be available for quantum key distribution protocol testing in 2020

3 3D Nano manufacturing

General information	
Title ERP	3D Nano manufacturing
Contact person TNO (ERP)	Stefan Bäumer (PS), Rob Willekers (PMC Owner), Peter Lucas (PM)
Contact person(s) government or topsector	

Programme 2020	
Summary	*Program description* The overall goal of this ERP is the demonstration of feasibility and proof of concept for essential imaging tools required by the semiconductor industry to enable faster, smaller and more efficient semiconductor devices. To realize such devices, the semiconductor features keep shrinking (towards 2.5nm or smaller) and are becoming three dimensional. Moreover, different materials and combinations of materials will be used. Consequently, existing metrology tools are no longer adequate for process monitoring, hence the urge for new metrology tools. In addition, since the nano-devices are becoming more complex, more than one measurement modality per manufacturing process becomes necessary. To maintain throughput and to gather sufficient knowledge on the devices during their manufacturing process, multi-modal measurements have to be carried out. The required metrology tools include quantitative sub-surface microscopy/tomography (nm size features buried under up to 10um material), chemical material characterization at the nano-scale (<10nm), quantum sensing and novel optical techniques. Artificial Intelligence (AI) will be used to perform smart data processing and will eventually lead to design for and by AI. The goal of this ERP is to realize all of these imaging modes on one fast and stable platform. *Plan 2020* In 2020 the focus of the ERP will lie on first measurements and development of the chemical imaging modality. For quantum sensing a first proof of concept tool will be designed, while for the quantitative subsurface imaging modality the focus will be on very high GHz actuation and detection (10 – 50GHz): small features at larger depth. Test cases for AI data analysis and design will be put forward to integrate results from multiple modalities into a coherent characterization of the device with maximum information.
Results 2020	For 2020, this ERP focuses on developing the building blocks for the multi-modal imaging metrology tool, including: - Subsurface scanning probe microscopy (SSPM) - Material characterization at the nano-scale - Quantum sensing - Development of suitable magnetic levitation platform - Optical (soft)XR - AI-based smart data analysis and integration - A first exploration into AI-based machine design

The above mentioned objectives built on the results achieved with the ERP 3D nano-manufacturing (2015 to 2019) and are considered the first steps to realize a multi-modal metrology tool.

Subsurface scanning probe microscopy will be driven further towards real quantitative measurements and measuring structures which are buried ~10um deep. This is a relevant use case for today’s 3D NAND memories. In order to enable these measurement SSPM will be driven towards higher excitation frequencies: 10Ghz and beyond. In 2020 top actuated GHz SSPM measurements will be carried out establishing the capabilities of the technology.

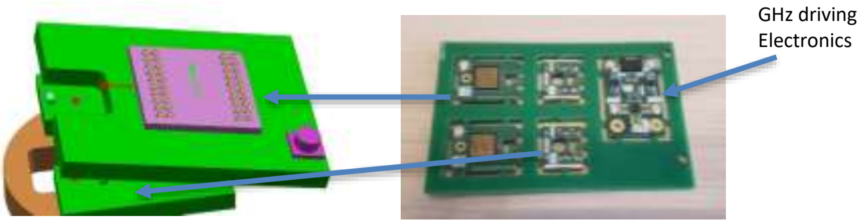
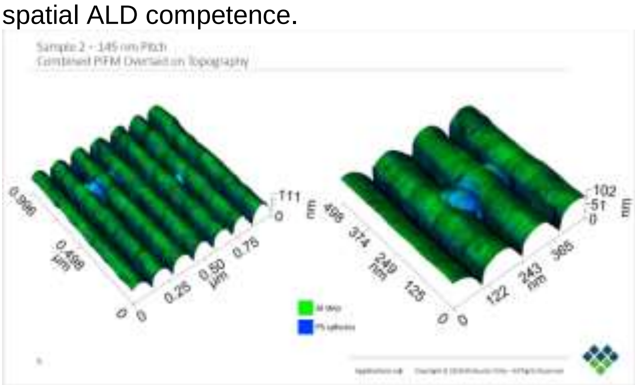


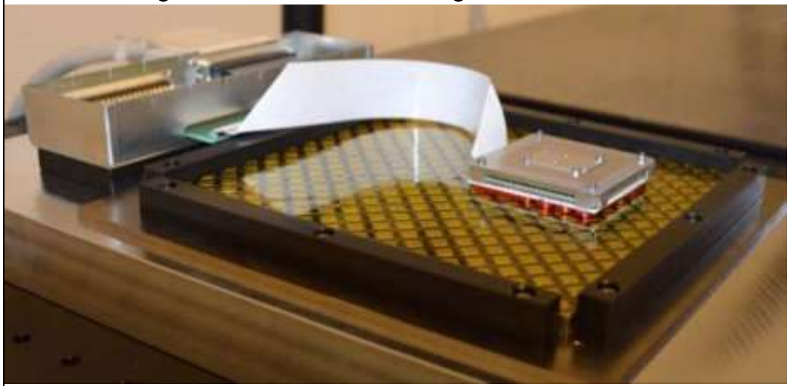
Photo-thermal-acoustic imaging, which potentially enables even higher frequencies (~100Ghz), will be carried out on relevant samples. Modelling for data interpretation will be extended to the high frequencies as well. Supporting to the ERP a proposal to the EU ECSEL call has been prepared: HiFIVE. In HiFIve subsurface metrology beyond the 5 nm node will be further developed. TNO focus will be on GHz scattering subsurface metrology.

Chemical imaging is a new field in Semicon metrology and is used for material characterization at the nano-scale. On the one hand, it is driven by contamination control: i.e., measuring organic contaminates in deep trenches of approx. 10um (industry use case) at a pitch of <20nm, but also on measuring profiles and changes of chemical composition at interface surfaces. In 2020 experiments on contaminates in trenches will be carried out, and the results will be validated with ODMs. Explorations of the limits in the lateral and chemical resolution of the method are planned as well. We will produce specific validation samples in cooperation with the TNO’s spatial ALD competence.



For this topic a proposal to the EU ECSEL call has been prepared as well: IT2. IT2 supports metrology for the 2nm node. TNO’s focus in this proposal will be to support chemical imaging at very high spatial resolution

Quantum sensing is a new research topic. The promise of this technique is that as more sensitive measurements will be possible, new features of devices will be measurable. The first use case will be to investigate magnetometry down to uT/Sqrt(Hz). Through the magnetometry conductivity can be measured. In 2020 the ERP will concentrate to setup

	an AFM system with a diamond. Goal of the setup is to perform conductivity measurements without contacting the sample enabling a full device check. TNO's AFM capabilities and the knowledge from TNO's QuTech activities will be brought together providing a head start. Today's complex devices need several different modalities to form a complete picture of the nano-electronic device and its manufacturing process. Ideally the different modality are working independent but on the same platform. That will enable measurements at the same position with the different instruments. Requirements for the metrology platform is that the platform can be positioned with sub-nm accuracy and be sub-nm stable during the measurements. Magnetic levitation has been identified as the most suited  platform for these kind of measurements. In 2020 the system architecture of the platform will be made taking into account miniaturization and parallel operation. The nm positioning of the stage will be implemented and verified. This feature is truly enabling and novel in maglev. For the maglev stage development there is some interest from industry to enter into a TKI project. The actual development of a miniaturized maglev stage could be done in such a supporting project, while the technology innovation on stability and local positioning will stay at the ERP. For AI-based systems, in 2020 we will do first simulations and experiments using lensless imaging (ptychography) as a firsts test case. We will simulate and generate data sates, and by analyzing their features, we will attempt to improve the system for AI data processing. As other optical modalities an exploration of (hard) x-ray metrology is planned. Main objective will be to investigate the opportunities for TNO in source development of an x-ray source and the algorithms needed for x-ray metrology. The eco-system of 3DNano manufacturing will be maintained with NFI / Samsung as large associates. The connection to ASML will be intensified and the joint development agreement with the TU Eindhoven will be honored by a joint PhD on a control topic: development of new tips and measurement procedures for deep 3D nano-structures and advanced control for maglev applications.
Dynamics	This ERP is the successor of the ERP 3D nano-manufacturing (2015 – 2019) and will build upon it. TNO has established significant knowledge and leverage during the last years to be a technology partner in the field of SPM, finding its culmination point in the establishing a spin-off company: Nearfield Instruments. The

	leading edge of TNO shall be kept, exploited, and innovated during the coming years. The TNO roadmap for developing these tools is fully aligned with the International Roadmap for Design and System (IRDS) roadmap, attunement with the leading industry partners and will be anchored in the PMC semiconductor metrology roadmap of TNO. Naturally the roadmap is also aligned with the roadmap of NFI through which the proof of principles can be brought to the market. Although this ERP is using the building blocks from the previous ERP, it clearly differentiates from its successor by including new research topics and by aiming for a platform for multi-modal imaging metrology. Chemical sensing for the semicon industry. Chemical composition of materials will be an essential indicator for process control and devices functionality. Quantum sensing with a diamond on a cantilever will leverage TNO's quantum technology and the AFM knowledge enabling current sensing on devices. Designing for AI, and eventually by AI, is a new direction within system engineering. TNO knows the area of AI, and in this ERP the new possibilities of designing systems differently will be researched. Lensless imaging will be the first application investigated. Having all the needed modalities available in a fast and reliable way will be realized by applying the concept of magnetic levitation. Having several mini-maglev stages working in parallel is an innovative approach. Topics of the previous years, which have matured enough for mixed funding are: - Bio-AFM. Very nice results have been achieved such as discriminating cancerous from health cells through stiffness measurements. The activities of Bio-AFM should be continued in SMO and NWA / NOW context. Proposals are being prepared to strive for the continuation - STED lithography. A prototype machine has been built and good results have been achieved: a wood-pile structure of um dimensions has been written with a new photo-initiator. This project should be continued in a TKI format. Potential partners are being approached with first use cases in the integrated photonics industry. Most of the elasticity based SSPM work will be transferred to either EU projects (HiFive proposal has been submitted) or B2B projects with NFI.

4 FutuRe Optical communication by SaTellite nEtwoRkS (FRONTIERS)

General information	
Title ERP	**FutuRe Optical commuNication by SaTellIte nEtwoRkS (FRONTIERS)**
Contact person TNO (DM en VPM)	Niek Doelman, Cristina Duque
Contact person(s) government or topsector	
Programme 2020	

Summary	*Program description* Our Digital Society requires a data communication infrastructure which is fast, secure and available everywhere. The European Commission has formulated her vision and policy actions to turn Europe into a Gigabit Society by 2025. This implies for instance a target of Gigabit/s connectivity throughout Europe. Moreover, recently (June 2019) the EU announced to build a quantum communication infrastructure (QCI) to enable ultra-secure communication. Satellites – and also aerial and naval platforms - will play a crucial role in the overall communication network. Complementary to the terrestrial network, a satellite network offers key capabilities such as high data rates, instant and global coverage and ultra-secure links over long distances. The field of Satellite Communication finds itself at the brink of a technological revolution: the transition from Radio-Frequency (RF) waves to Optical waves. The disruptive step from RF to Optical Satellite Communication offers various strong advantages, such as much higher bandwidth, very high data rates and immunity to interception. The program focuses on knowledge and technology advancements required for the future realization of the data targets. The main objective of the research program is to enable *fast, secure and multipoint communication by a network of free-space optical links between space, air, sea and ground nodes.* The central research activity aims at: *"Mastering free-space optical waves, propagating over long distances in perturbed media, carrying communication data, from quantum bits to Terabits per second".* Here the key areas are: optics, photonics, mechatronics, wave propagation through atmosphere, communication technology, network optimization and quantum cryptography. The long-term (2023) goal of the ERP research activities is to achieve a knowledge and technology basis which is at a maturity level of TRL 4 (proof of technology concept in laboratory) such that it can enter the development phase towards prototypes and products for Optical Satellite Communication in co-operation with industrial and applied research organizations. *Plan 2020* For 2020 the emphasis is on studying promising, novel concepts and technologies within this framework. Specifically: – The minimization of beam intensity fluctuations over a free-space path.

	– The experimental verification of technology concepts to reach ~10 Tbits/s data throughput. – Optical transmitter and receiver systems capable of accommodating quantum key distribution protocols with untrusted space nodes and beyond the repeaterless rate-distance limit. – Light-weight, low cost large aperture and field-of-view optical telescopes. – Networks of key distribution nodes. – Integrated photonic systems capable to transmit and receive multiple beams at multiple angles with moving nodes. – Optical receiver systems for photon-starved conditions with single photon detection – Network traffic optimization for highly reliable data transfer – Time-variant behavior of optical turbulence profiles
Short Description	Next to the fiber-based terrestrial network and the wireless radio-frequency (RF) links through free space, there is a clear benefit of having free-space optical communication links between ground, air, sea and space. The ERP FRONTIERS has the objective to develop knowledge and technology which Long-term target: Order Megabit per second data download from a deep space science mission, such as a planetary, asteroid or an L2 mission. Application: science 1) **Multi-point communication** Long-term target: a multi-beam optical space terminal, simultaneously receiving data from various nodes and transmitting towards multiple users. Application: defense and commercial  Figure 1 - Illustration of the 4 performance features for the ERP FRONTIERS – 1) ultra-high data throughput, 2) ultra-secure communication, 3)very long-distance link and 4) multi-point communication. Besides the performance drivers, a **Multipoint FSO Communication Network** needs to comply with specific and stringent boundary conditions, such as low Size, Weight and Power (known as SWaP), especially for satellite and aerial terminals, low cost, low latency and extremely high reliability. The Early Research Program focuses on the essential knowledge and technology gaps related to the long-term goal. The main knowledge areas of the ERP are: a) Optics and Photonics with very low aberrations for single- and multi-point communication, for high photon flux on the one end and for single photon conditions on the other end. b) Full control of the properties of optical beams, propagating over long distances through turbulent and scattering atmosphere. c) Dedicated communication (modulation, coding, network protocols) technology for constellations of satellite, aerial, sea and ground nodes. d) Quantum cryptography for ultra-secure communication.

The 2023 goal of the ERP research activities in these areas is to achieve a knowledge and technology basis with sufficient maturity (typically TRL4 – proof of technology concept in laboratory), such that it can enter the further development phase with industrial partners towards prototypes and products for the Multipoint FSO Communication Network.

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.

An important objective of this ERP is to further build the eco-system with university groups, applied research organizations and industrial partners, with the aim of establishing a knowledge development center for optical communication. The strategic 2023 objectives are, henceforth, 1) to establish a strong co-operation between university and TNO for key low TRL research in further detail, 2) joint-developments with various industrial partners; 3) successful cross-application of the developed knowledge; 4) build a strong publication and IP portfolio.

Results 2020

The research and development roadmap for the key performance features is depicted in the table below

	FEATURE	Performance Target	Target date Engineering Model TRL6	Development steps											
				2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	----	2029-2031
						TNO ROLLING HORIZON									
A	Ultra-high Throughput	10 Tbps throughput to GEO-sat 1 Tbps throughput to LEO-sat	2025		System Concept	Sub-system research and developments		Laboratory system verification	Horizontal link test		Ground station Engineering Model				10Tbit/s link prototype
B	Ultra-Secure	Network of satellite/air nodes with QKD service for Quantum encrypted communication	2025	QKD protocols quantum channel concepts		Optical Channel,Tx, Rx research	Laboratory system verification	Bulding -2-building tests			Engineering Model - quatnum channel QKD	In orbit verification	network integration with QKD modules	----	Key network service prototype
C	Very long distance	Optical communication link for deep space missions	2027		Use Case study & Reqs	Receiver system research (telescope, detector)		Experimental Verification	Laboratory System		Qualification testing		Engineering Model deep space receiver	----	Long distance link (prototype
D	Multi-point	Multi-access, multi-user Optical terminal	2025		System Concept	Sub-system research and developments + experiments		Laboratory system verification		Qualification testing	Engineering Model Multi-beam terminal			----	Multi-beam optical terminal (in-orbit)
			TRL legend		1	2	3	4	5	6	7	8	9		

In summary the most prominent results for 2020 are:

- Photonics technology concept for a multi-beam receiver/ transmitter.
- Proof-of-concept laboratory set-up for high reliability, high data throughput link.
- Technology concept for a large-aperture, large FoV, low SWaPC receiver telescope.

	In further detail, the planned results for 2020 are shown below, organized along the main performance features A to D. **A. Ultra-High Data Throughput** Here the main objective is the accurate and precise focusing of high power laser beams through turbulent, free space, conveying order Terabits per second (Tbit/s) data. The knowledge and technology development is aimed at the minimization of the losses and intensity fluctuations over the free-space communication channel, high power sources and optical systems capable of handling the high power, and network protocols to integrate the high throughput links into the terrestrial network. In 2020 the research emphasis is on: ▪ Adaptive, high order modulation schemes, specifically QAM and APSK. ▪ Scintillation reduction by Adaptive Optics and transmitter diversity. ▪ Advanced Coding dedicated to free space channel distortions and scintillation. ▪ Coherent methods for improved detection sensitivity. ▪ High power sources, collimation and beam combination ▪ Traffic optimization for constellations of ground stations and LEO satellites. The output contains reports on the above research topics and the follow-up steps to meet the high throughput target of 10 Terabit/s. Furthermore emphasis is put of re-evaluation of the worldwide state-of-the-art and comparison to the knowledge developed in the ERP at TNO. A proof-of-principle breadboard, denominated “Communication Breadboard”, is being realized to verify the various research outcomes. It is built in a smart modular way so that it can be upgraded each year to involve further critical technologies. For 2020 verification of extreme high reliability, high data throughput link technology is planned. Involved partners: TU Eindhoven, University of Leiden, University of Pisa, Industry: AirbusDS-NL, Demcon, and others. **B. Ultra-secure communication** The main objective is to arrive at an ultimately protected communication channel which is suited for the post-quantum world. Prominent research theme in the ERP is a network of Quantum Key Distribution (QKD) nodes, preferably untrusted, which can provide in the various needs for ultra-secure communication. The required free-space quantum channels need to have a low Quantum Bit Error Rate (QBER and allow for a sufficiently high secure key rate. In 2020 the particular research emphasis is on: ▪ Optical technology for enabling QKD protocols which overcome the repeaterless rate-distance limit. ▪ Technology for large aperture transmitter and receiver optical terminals. ▪ Enhanced security QKD (measurement device independent), specific resilience towards detector attacks.

	The output contains reports on the above research topics and a technology concept description for the first 2 topics. Involved partners: TU Delft, National University of Singapore, Industry/users: ABN AMRO, Eutelsat, ESA. **C. Very long distance communication** The main objective is to transfer (scientific) data over very long distances – i.e. between Earth and the Moon, or a Lagrange point, Mars or even further. Link losses are extremely high and the background photon flux can lead to a poor Signal-to-Noise ratio. This leads to the need to increase the efficiency of photon-starved links and to minimize the background noise effects. For 2020 the research will focus on the Earth-based receiver terminal with technology challenges of a large-aperture communication-class telescope, background filtering and single-photon detection. The output contains reports on the above research topics and a laboratory set-up. Involved partners: TU Delft Agencies and Industry: ESA, NASA, OHB, ADS **D. Multi-point Communication** This research topic addresses wide-field, highly accurate and simultaneous receiving, processing and transmitting of multiple optical communication beams at a space terminal. The 2019 activity has led to an opto-mechanical concept for two use cases: 1) one terminal able to communicate simultaneously with high throughput feeder links in an area covering a major part of Europe; and 2) one terminal capable to communicate simultaneously with multiple moving targets (airplanes, ships,…). For 2020 the research will address: ▪ Photonic integration of critical sub-systems, i.e. multi-beam detection system and multi-beam pointing system. ▪ Large Field-of-View telescope with limited optical aberrations The output contains reports on the above research topics and a laboratory set-up for a single, critical technology in the multi-beam optical terminal. Involved partners: TU Eindhoven, TU Delft, Industry: ADS, TESAT. Besides the above 4 work-packages, further building of the eco-system is addressed. This includes preparing a joint proposal with university groups to NWO for fundamental research and the further involvement of (Dutch) industry in the earlier phases of the R&D activities. **EXTERNAL CONNECTIONS and CO-OPERATIONS** The research activities in ERP FRONTIERS match with various roadmaps within the KIA HTSM; i.e. space, photonics, security. Several industrial partners from these Sectors are partners in the TNO program. Furthermore, it fully matches with the EU's ambition for a Gigabit Society by 2025, which

	is reflected in several H2020 programs (ICT calls) and the Quantum Communication Infrastructure (QCI). The program also connects to NWA routes, specifically 'Quantum/nanorevolutie' (with respect to security) and to 'Materialen – made in Holland' (regarding: photonics). The European Space Agency has specific programs for satellite communication, such as the Advanced Research in Telecommunications Systems (ARTES) program. This enables European and Canadian industry to explore, through research and development (R&D) activities, innovative concepts to produce leading-edge satcom products and services. The ESA ARTES-Scylight program is dedicated towards optical satellite communication. The ERP activities within secure communication connect to the ESA plans for the (Security And cryptoGrAphic (SAGA) mission. The knowledge development will be achieved in co-operation with research partners. Another objective of the ERP is to further build the eco-system with university groups, applied research organizations and industrial partners. In further detail, the strategic 2023 objectives are: – Joint fundamental research projects (NWO, EU funded) with university groups from TU Eindhoven, TU Delft, University of Leiden and potentially international on the key research themes of optics&photonics, free-space propagation, mechatronics, communication technology, and quantum cryptography. – Joint developments with various industrial partners (in ERP or follow-ups in SMO, TKi, EU, B2B) on systems and sub-systems. Currently, Dutch industrial parties already active in this field (with TNO) are: AirbusDS-NL, Demcon, Nedinsco, VDL, Hyperion ABN, and Celestia. Other Dutch industries with optics, photonics and mechatronics expertise have shown their interest. Internationally, there is already a collaboration with large system integrators, satellite operators and service providers. – Joint research and developments with institutional partners such as ESA, NICT, and DLR. – Attract external investment from funding agencies (NWO), institutional (ESA, EU) and industry. Target is to arrive at a roughly 50-50% balance between internal and external funding for the R&D activities. – Successful application of developed knowledge to at least 1 of the cross-over fields. – Build a strong publication and IP portfolio. In 2020 we will progress on the above objectives with special focus on co-operation with university partners; i.e. Dutch Optics Centre initiative to submit a proposal to NWO-TTW lead by TUDelft.
Dynamics	Starting 2019 this ERP has the full status (seed status in 2018) and has focussed on research for the 4 performance parameters mentioned in the previous section (high data throughput, ultra-secure, very long distance and multi-point communication). The first research phase consisted of concept system studies to identify the main requirements and define the key research directions. Most of the system studies have been finalized by now (mid 2019) and dedicated research on critical sub-systems is currently being pursued.

	As a result of the outcome of the first phase, the plan for 2020-2023 has been updated on the basis of new insights (see the listing below for details). The major part of the plan drawn up for 2019 remains unchanged however. The most important updates of the plan are: ▪ Reliability will be a key factor in the acceptance of optical links for future communication networks. For 2020 we have strengthened the emphasis on this aspect by performing a research study (under A.) on the joint optimization of the technologies of Adaptive Optics, Transmitter diversity, Coding and Network traffic to each an extremely high reliability ▪ In order to limit the Size, Weight and Power consumption, photonic integration turns out to be indispensable for a multi-point communication node. This will be the major part of activity D. ▪ The profound study on QKD protocols and their performance in 2019, has lead the activity to put the emphasis for the coming years on optical technology for the quantum channel which enables sufficiently high, secure key rates by QKD (with a favourable rate/distance behaviour) from untrusted nodes. ▪ The concept study on deep space communication in 2019 has directed the research focus to be put on the large-aperture ground-based receiver system from 2020 on. (activity C). ▪ Vibration isolation systems to reduce optical beam pointing errors have reached a sufficient maturity and is no longer within this ERP's scope.

5 Large-area ultrasound making medical imaging safe and affordable

General information	
Title ERP	Large-area Ultrasound: making medical imaging safe and affordable
Contact person TNO (ERP)	Jan-Laurens van der Steen
Contact person(s) government or topsector	Hans Naus (HTSM Electronics)

Programme 2020	
Summary	*Program description* Ultrasound for medical imaging and diagnostics has evolved into some of the most valuable medical diagnostic modalities. The diagnostic imaging capabilities of ultrasound have spread across many clinical applications, from obstetrics and gynecology, orthopedics and cardiology, to emergency medicine, breast cancer detection and more. The portability of ultrasound systems, speed, absence of ionizing radiation and cost-effectiveness are some of the key attributes that have given this technology an edge over other imaging modalities. An important new development is the transition from 2D towards 3D ultrasound imaging. 3D ultrasound images require a 2D transducer array that can steer an ultrasound beam in two dimensions. Such 2D transducer arrays are now made of small ceramic piezoelectric elements that all need to be addressed individually. The assembly of these 2D piezo-ceramic transducers is an extremely complicated and expensive process. This limits the usable size of medical imaging ultrasound devices. The main objective of this program is to develop a flexible, large-area ultrasound technology for high-quality medical imaging and remote monitoring. We use thin-film technologies that were previously developed at Holst Centre for application in flexible displays. Due to economies of scale these technologies promise affordable fabrication costs, and in fact present the only realistic way to realize large (≥ 10 x 10 cm) and flexible ultrasound arrays. The large size of the 2D arrays will lead to higher image quality and much larger field of view. Integrated in the form of a wearable patch, flexible ultrasound arrays enable *hands-free* imaging, thereby reducing the physical burden for sonographers and improving the comfort of the patient. *Plan 2020* In 2019 we have demonstrated first printed ultrasound transducer elements. In 2020 we will take the technology to the next level and demonstrate that our printed ultrasound transducers can be fabricated reliably over large area (>10x10cm^2). In addition, we will develop know-how on how to efficiently read out large arrays of sensors (>1,000,000 elements), which greatly exceed the size of current state-of-the-art transducer arrays (~1000 elements).
Short Description	In the future healthcare organization the traditional concept of a hospital will change. Medical care is migrating from healthcare institutions into the home environment, with a focus on early detection and prevention of medical conditions. Artificial intelligence may be used for automation of

	routine tasks, while interpretation and decision making is left to the medical expert. Key requirement for proper decision making is reliable information extracted from high-quality data. At the same time, moving medical imaging from a clinical setting into our homes translates into a need for a safe and affordable ultrasound technology. In 2023 we want to be able to provide large-area ultrasound imaging solutions for different medical domains. Applications include hands-free 3D imaging, remote monitoring and multi-modal imaging to complement and eventually replace CT and X-ray as preferred imaging modalities during interventional procedures. To get to this technological level, acoustic modeling, array design, thin-film fabrication, and readout electronics need to be developed in parallel in order to establish a complete system. The key technology components are • Scalable transducer technology for fabrication of high-resolution large-area US arrays. We target an array size of at least $10x10cm^2$, comprising >1 million elements. • Efficient readout of large ultrasound arrays. Addressing and readout of such a large number of sensors will require novel imaging strategies. Minimizing the electrical connections to the outside world will require monolithic integration of thin-film electronics. The TNO departments Holst Centre and Acoustics & Sonar combine their know-how and expertise in this project. Acoustics & Sonar has in-depth know-how on ultrasound imaging in a wide range of applications, incl. medical imaging. Holst Centre has a strong track record in thin-film electronics, originally developed for flexible displays and optical imagers.
Results 2020	In 2020, we plan to achieve the following results: *Technology development and demonstrators* • Technology roadmap for thin-film electronics integration (report, M3) A key attribute of our printed transducer technology is possible integration with thin-film electronics. Integration of active components and circuitry opens up new possibilities such as dynamically configurable arrays and local signal amplification. Furthermore, electronics integration is key to achieving an efficient readout of a large number of sensor elements. We will look into the available technologies and create a technology roadmap with timeline for thin-film electronics operating in the medical frequency range (2-20MHz). • Report on imaging strategies and optimal transmitter/receiver partitioning (report, M6) With the acoustic simulation framework that was established in 2019 we will study the optimal partitioning of transmitters and receivers across the array, in order to achieve a certain image quality (signal-to-noise ratio, SNR). We will look into large-area imaging concepts from other domains (seismic, industrial inspection) and learn to what extent they can be employed in the medical imaging domain. We expect this to be a particular IP-rich activity. • Dynamic imaging demonstrator (demonstrator, M6) In the 2019 technology demo, we perform static imaging of a phantom, as a first step to showcase the potential of the printed transducer technology. The array is read out one line at a time, using

a multiplexer connected to lab equipment (TRL3-4). In 2020, we will demonstrate real-time *dynamic* imaging. This demonstrates the potential of our technology in a clinically relevant environment (TRL5). Given the dynamic nature, simultaneous real-time readout is required. The appropriate equipment is not available in TNO. Although investing in an open ultrasound readout platform (e.g. Verasonics, TPAC, ULAOP) is preferred in the longer term, initially hardware may be sourced from academic partners in our network (TU/e – Richard Lopata, TUD – Nico de Jong).

- Realization of first large-area US transducer array (demonstrator, M12)
  The focus of technology development will be on demonstrating scalability to large area. With the process we developed in 2019 as starting point, we will work on front- and backplane integration and good device-to-device uniformity. An FMEA risk analysis will be performed to identify and prioritize critical technology steps.
  We will demonstrate an array with size that goes significantly beyond current state-of-the-art (i.e. >>1000 elements). The purpose is to trigger attention in the international ultrasound community. We need 'ambassadors' in that field of expertise, as a first step in the typical medical innovation cycle.

Proposition development and setting up collaborations

- Proposition Large-Area Ultrasound validated with (>3) external parties (M9)
  As part of our value proposition development, in 2020 we will reach out to internal and external stake holders at different levels (insurance companies, policy makers) to get a validated projection for size and timeline of the future ultrasound market.
- Strategic collaboration with at least two parties (M12)
  Our ambition for 2020 is to build our position in the medical ultrasound domain through collaboration with academic and medical partners in the ecosystem that we established in 2019 (EU/NL partnership, additional funding).

- Which parties will be involved?

We are actively looking for strategic partners in medical ultrasound domain, both in academia and industry. In 2020 we aim at engaging in a strategic collaboration with at least two parties in our ecosystem (see Figure 1).

As an example, we have established a close relationship with prof. Eugenio Cantatore (TU/e) who is an expert on mixed-signal circuit design for flexible electronics. We envision a collaboration where prof. Cantatore takes care of the design of thin-film transmit and receive circuitry, which we then realize in our TFT technology. Circuit design expertise is currently not covered by our team. Furthermore, we want to set up a collaboration with experts in the field of

	ultrasound signal processing. We are in contact with prof. Nico de Jong (TUD / ErasmusMC), prof. Chris de Korte (Radboud UMC) and prof. Massimo Mischi (TU/e), all experts in ultrasound imaging.
Dynamics	There are no major changes with respect to the original plan. In 2019 we reached out to several experts. They confirmed that large area ultrasound can open up new applications in the medical domain that ultrasound technology today cannot address. Also, we learned that our technology not only aligns well with the future organization of healthcare, but that 'hands-free' ultrasound can also positively impact the *current* clinical work flow: in today's practice, manual manipulation of the ultrasound probe leads to frequent repetitive strain type of injuries (#1 cause of illness reports among sonographers). According to experts, an ultrasound patch or belt could significantly reduce the physical burden for sonographers and improve the comfort of the patient. As a concluding remark, large area ultrasound is considered a disruptive technology. Getting to a sufficient level of maturity requires a multi-year time frame which, we learned, is a good fit with the time horizon of a typical medical innovation cycle. Meanwhile, we keep an eye on alternative ultrasound technology developments, such as Butterfly[1], Exo Imaging[2] (handheld ultrasound) and Philips CMUT Smart Body Patch[3] (EU Penta project ULIMPIA). [1] https://www.butterflynetwork.com/ [2] https://www.exo-imaging.com/ [3] http://ulimpia-project.eu/

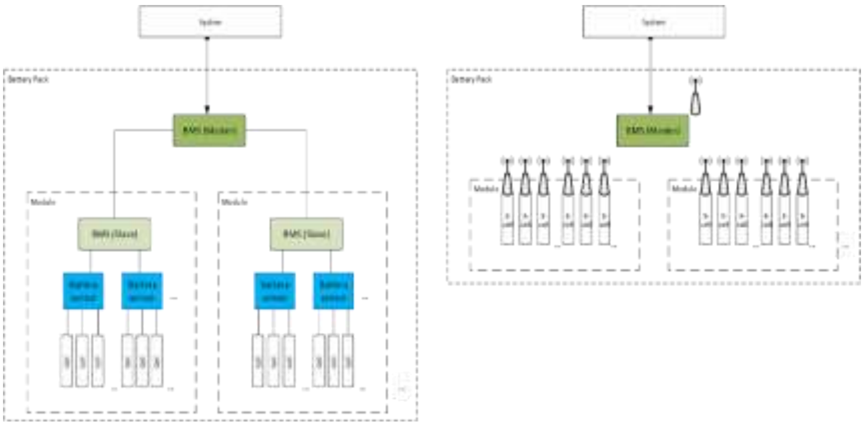
6 Self-Adapting Smart Batteries

General information	
Title ERP	Smart self-adapting batteries
Contact person TNO (ERP)	Pavel Kudlacek (PM), Eric Meulenkamp
Contact person(s) government or topsector	Richard Roemers, Marc Hendrikse

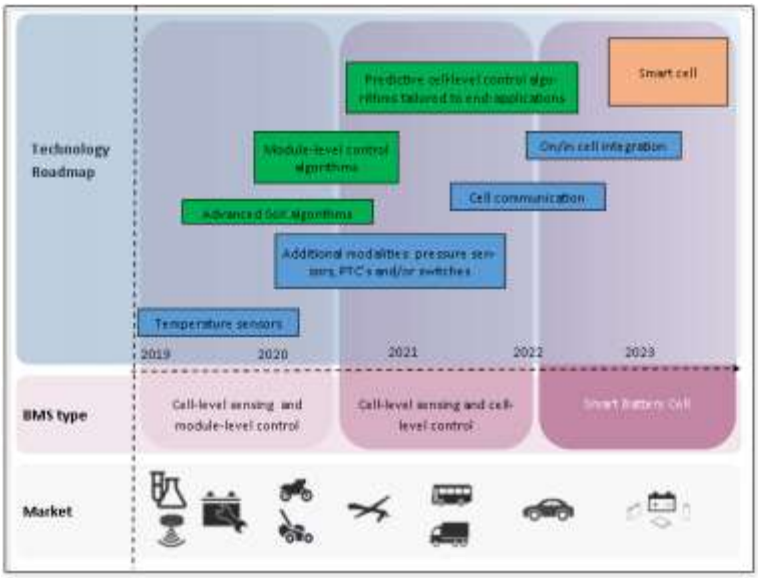
Programme 2020	
Summary	*Program description* Electric Vehicle surveys show that price, driving range and charging limitations are key factors in adoption. These are linked to current limitations of batteries: usable storage capacity & number of cycles under various operational conditions, cell safety & accelerated degradation, and total cost of usable capacity over battery life. Battery cell temperature is important for each of these as temperature monitoring and control plays a key role in domains of thermal safety, ageing and cycle-life, and control. Pressure or strain monitoring can be important too, especially for pouch cells where internal pressure build up during cycling can lead to their failure. The challenges connected to battery temperature (and pressure) monitoring and control are not limited to automotive applications but can be also found in other application domains (e.g., grid-coupled storage solutions, consumer and industrial applications). For small battery cells in consumer electronics, cell-level temperature monitoring for safety is an integral part of the system. For multi-celled battery packs, however, this is lacking, primarily due to cost and integration complexity. Consequently, due to the temperature uncertainty, cells integrated into more complex battery packs are significantly underutilized. Implementation of a cell-level battery temperature (and pressure) monitoring and corresponding control can, therefore, substantially increase battery pack safety, extend its cycle-life, better utilize capacity of individual cells in the pack and help to charge the battery faster, but safely. Practical solutions for cell-level sensing do not exist today because existing surface-mount thermistor technology is not scalable and too costly. Also, the battery system has to be designed for read-out and processing of the sensor data while balancing system cost and performance. Last but not the least, smart sensing and control algorithms and strategies to improve battery pack performance using the sensor data need to be developed and tested to prove the application value. This ERP strives to develop technologies for cell-level temperature (and pressure) sensing in battery packs and the corresponding battery management system (BMS) that turns the sensor information into benefits for battery system users and/or manufacturers. Smart batteries, which integrate the developed sensing and part of the control technologies on or in a battery cell, will simplify the BMS topology and allow more sophisticated strategies for control and management of future battery systems. *Plan 2020* In 2019 a technology for cell-level temperature sensing was developed to enhance safety and performance of existing battery packs (with coarse control). Evaluation of the benefits is ongoing. Development of cell-level

	sensing and cell-level (fine) control of battery packs is planned for 2020. Furthermore, we will investigate the value of additional modalities, such as pressure or strain sensors, and PTC's or switches, and develop the most promising one(s). Several prototypes and demonstrators will be realized for development of battery state estimation algorithms, evaluation of the technologies, and for attracting potential customers.
Short Description	The lithium ion battery (LIB) market is booming, seeing new applications day-by-day driven by the electrification of transport. Attaining the goals set in the EV30@30 Campaign for fast adoption of Electric Vehicles (EV) requires further reduction of price and enhancement of performance of batteries. Improvements of battery cell chemistries are intensively researched, but new approaches for integration of cells into a battery pack are needed too, to ensure full utilization of the cells' capacity. Common factors that hinder the utilization are insufficient monitoring and coarseness of control of battery cells in a pack. Consequently, wide operational safety margins must be applied, leading to underutilization of the cells. Temperature monitoring is of key importance as it directly relates to cell thermal safety, ageing and cycle-life. Since pressure is built up in a cell upon cycling, strain or pressure sensing can be applied for safety improvement as well. It is especially important for pouch cells. Thus, monitoring of temperature (and pressure) on cell-level is desirable and can be utilized for following benefits: (1) increase of battery pack safety, (2) extension of its cycle-life, (3) better utilization of storage capacity of individual cells in the pack, (4) faster, but safe, charging. Practical solutions do not exist today because existing surface-mount thermistor technology is not scalable and too costly. Furthermore, smart algorithms and strategies for processing, storage and use of the fine-grained sensor data for improvement of pack performance are practically non-existing and will be developed too. In summary, the following challenges must be addressed to develop commercially viable cell-level monitored and controlled battery packs: 1. how to cost-effectively monitor temperature (and pressure) on cell level, 2. how to accurately estimate the current status and future performance of the pack, (SoX – State-of-Charge, State-of-Function, State-of-Health), 3. how to control and manage the battery system so that the sensed information is turned into tangible benefits for the battery system user or manufacturer, and 4. how to implement the sensing and control technologies into a scalable battery management system. The goal of the program is to develop technologies enabling cell-level sensing of temperature (and pressure) in lithium ion battery packs and the corresponding battery management system that utilizes the sensed information for the abovementioned benefits. The envisioned solution builds on printed electronics (new temperature and pressure sensors, interconnects, switches etc.) that addresses challenge #1, which is the core competence of Holst Centre. Augmented with advanced state estimation and battery management and control algorithms, *i.e.* building on competences of TNO Powertrains, challenges #2 and #3 will be tackled. The ERP team expects that the overall complexity of future battery management systems can be reduced by development of a *smart cell*, integrating the developed sensing and part of the control technologies onto or into a battery cell. A BMS topology for smart cells

<table>
<tr><td></td><td>can be simple and can put more emphasis on a high-level software control. Firstly, it is expected to be a more cost-effective implementation of BMS and secondly, it allows more sophisticated algorithms to be used for control of the battery.


Schematic topology of battery management systems. Current solutions (left) and simplified system with smart-cells (right).

Technologies that enable the smart cell will be developed step-by-step in order to allow valorisation of already developed technologies in specific use cases as outlined in the below roadmap of the program.



The roadmap of the program</td></tr>
<tr><td>Results 2020</td><td>Plan 2020
Evaluation of benefits of the battery sensing technology developed in 2019 will continue in 2020, followed by investigation of granularity and topology for its cost-effective implementation into existing battery packs, and proposition development. Besides finalization and evaluation of the cell-level sensing prototype(s), a technology demonstrator will be made to attract potential customers.</td></tr>
</table>

	To advance beyond the current state-of-the-art battery management systems, the ERP team will start developing technologies for next generation cell-level controlled battery packs enabling loss-less balancing and better utilization of cells' capacity. A prototype for evaluation of benefits and development of next generation control algorithms will be realized. Potential benefits of additional sensor/actuator modalities, such as strain or pressure sensors, PTC's and/or switches, will be investigated. Efforts to establish visibility and strengthen national and international connections and cooperations will continue. The main objectives for 2020 are: 1. Development and evaluation of a beyond SotA Battery Management System (BMS) comprising cell-level sensing and cell-level control of >20 cells - Overall system architecture enabling loss-less balancing - Algorithm development for cell-level SoC estimation and loss-less balancing control strategies 2. Evaluation and implementation of a BMS comprising cell-level sensing and module-level control - Algorithm development for SoX estimation - Proposition development (value/cost) - Implementation on a system level into a >20 cells module 3. Evaluation of benefits of additional underlying sensor and actuator modalities - Battery swelling: strain or pressure sensors - Battery cell switching: PTC and/or switch - Packaging and integration of sensors in battery pack 4. Build prototypes and demonstrators - Prototype system with cell-level sensing and cell-level control with >20 cells in a module - Prototype system with cell-level sensing and module-level control with > 20 cells in a module - Demonstrator cell(s) with T and P sensor arrays and integrated read-out 5. Establish visibility and cooperations in the battery system domain - Business development (at least 2 shows, 3 conferences, 2 potential partners) - EU project(s) (at least 2 proposals) and academic collaboration Which parties are or will be involved This ERP is executed jointly by TNO-Holst Centre and TNO-Powertrains expertise groups. Furthermore, the ERP can help valorize the fiber optic based temperature and strain sensors developed by TNO-Optics. The ERP team is currently exploring collaboration possibilities with prof. Henk Jan Bergveld, Embedded Control in Energy Management group at TU/e, for the topic of accuracy of battery state estimation. There has been an effort to leverage the ERP proposition by participating in several EU calls around the topics of battery sensing. One out of three submitted proposals, COBRA, has been granted under the LC-BAT-05 Call. On the industrial side, the strategy is to better understand requirements, learn more about today's BMS's, better understand value chain partitioning and validate our insights, propositions and roadmap. The ERP teamed up with start-up company SPIKE Technologies B.V. to develop a module-level prototype based on SPIKE's commercial battery

	pack. Discussions are currently ongoing with Sensata, Enmech and TDK about developing sensors for battery packs, but also to better understand their requirements. Furthermore, there are active contacts with Durapower, VDL, and Cleantron who could become involved as OEMs to refine application requirements, value propositions and as possible future partners. More company contacts will be established in 2020. What is the external connection The critical importance of creating a European industry along the battery value chain has been recognized up to the highest levels in the EC, in order to retain millions of jobs linked to ICE-based vehicles. Smarter battery systems are part of the roadmaps constructed by EU industry and the R&D community. Batteries will play essential roles in the energy transition: (i) in the future intelligent energy system, creating storage to manage volatility & intermittency and optimize cost at all levels in the smart grid, and (ii) in electrification of mobility, as power source in electric vehicles. Indeed, batteries and smart battery systems have been identified as essential technologies for electrification in the ‘Meerjarige Missiegedreven Innovatie-Programma’ MMIP9. With regard to KIA’s, there are ample connections to MU1. Energie en CO_2 (energy storage, electric transport), MU6. Mobiliteit en Transport, as well as ST B. Geavanceerde Materialen and ST F. Micro- en Nano-elektronica. For the sensor materials and devices, there are also connections to the roadmap of the High-Tech Materialen Topsector (HTSM); the smart, sensor-enabled battery system fits particularly well within the HTSM electronics roadmap.
Dynamics	In 2019 the ERP team has taken a pragmatic approach and reduced desk research activities in favor of hands-on experience by building a first prototype (completed Q2-2019 instead of Q4-2019) to evaluate benefits of cell-level sensing technology. Demonstration of benefits of our solution has been identified as the key for attracting potential initial customers already in an early phase of the program (first outreach activities started in Q2-2019). The analysis of system requirements has revealed that the sensing system topology and granularity, originally planned as a development topic, are very dependent on the design of each battery pack, used cell format and application domain. To narrow down the number of implementation possibilities, the ERP team has decided to focus on development of a module-level prototype with cell-level sensing and control (ultimate system granularity – *smart cell*), which will help us investigate pros and cons in the granularity of the sensing system, the system cost and its benefits. Teaming up with battery pack manufacturer SPIKE technologies has helped us kick-start development of a module-level prototype, originally planned for 2020-21. The originally planned goal “6. First generation advanced model-based control algorithm” can be only partially achieved in 2019 as the low complexity of the cell-level prototype doesn’t allow development and testing of advanced algorithms and strategies for multi-cell battery pack control. The development of advanced model-based control algorithm(s) will continue in 2020 (as originally planned), but most of the work will be done when a module-level prototype with cell-level control hardware has been realized towards the end of 2020.

7 Energy Storage & Conversion

General information	
Title ERP	Energy Storage & Conversion
Contact person TNO (ERP)	Pascal Buskens, Nicole Meulendijks, Peter Wolfs
Contact person(s) government or topsector	
Programme 2020	
Summary	*Program description* Energy conversion and storage becomes increasingly important to realize the vital transition from fossil fuels to sustainable energy. In recent years, we made good progress in our search for new conversion and storage processes, resulting e.g. in the development and validation of plasmonic catalysts to reduce CO_2 to CH_4 using sunlight as energy source, and the development of a process and reactor concept for the reduction of CO_2 to formic acid using renewable electricity as energy source. The electrons-to-chemicals program line fits to the NWA route Energietransitie, and relates to the topsectoren Chemie, Energie and HTSM. We strongly collaborate with industry (e.g. via VoltaChem and the Brightlands Chemelot Campus and Site) and academia (e.g. Utrecht University, Leiden University, Delft University, Hasselt University and DIFFER), and will continue our developments in close collaboration with these partners and national and regional governments. Our focus will remain on the development and validation of concepts and processes at a technology readiness level of 2-4 that use electricity from renewable sources (solar, wind) or sunlight directly to convert CO_2 to C1 chemicals and fuels containing one carbon atom, i.e. CH_4, CO, HCOOH and CH_3OH. Routes to come to technically and economically viable technologies and processes will be pursued, and feasibility will be demonstrated on laboratory scale (up to TRL 4). We will focus on processes that convert CO_2 into C1 fuels and base chemicals. For fuels, the ultimate goal is to provide technologies and concepts that can be scaled up to an efficient production process at a cost of max. 800 Euro/ton. We have identified two attractive routes towards hydrocarbon based fuels. These two routes are highly interconnected. The first route (indirect) is based on generation of renewable hydrogen, and the subsequent reaction of this hydrogen with CO_2 towards hydrocarbons. The second route (direct) is based on the direct conversion of CO_2 and water towards hydrocarbons. The technologies related to these routes are based on electrochemistry (direct: electrochemical reduction of CO_2) and on photochemistry (indirect: hydrogenation of CO_2 using green hydrogen from e.g. water electrolysis). *Plan 2020* The main planned results for 2020 are as follows: • Design of a lab scale factory for CO2 to methane and CO (photons to chemicals) • Demonstrator for CO2 to Formic Acid (electrons to chemicals)

	The dissemination of the project results through research articles, patents and at network events is part of the plan. Establishing a joint research project focused on CO2 reduction is also envisioned.
Short Description	In the last decades, the massive use of fossil fuels had a big impact on the emissions of CO_2. A strong acceleration is needed to timely transform the Dutch energy landscape from the current fossil fuel based one to a CO_2 neutral renewable energy infrastructure based on the goals as set by COP21 and 22 (UNFCCC), and accorded by the EU (RED)[2] and the "Energie agenda". Conversion and storage of renewable energy are pivotal for achieving this change. In this program we focus on the use of renewable energy, i.e. renewable electricity and sunlight, CO_2 and green H_2 as a feedstock to produce C1 chemicals and fuels, which provides a great opportunity to store energy to overcome the inherent fluctuations in supply of renewable energy, and the spatial and temporal mismatch between demand and supply. It changes the actual energetic system towards a sustainable system and simultaneously implements a CO_2 neutral system. The ERP Energy Storage and Conversion consists of two main research lines: (1) Photons-to-chemicals using sunlight and (2) Electrons-to-chemicals using renewable electricity as energy source. Both research lines focus on the conversion of CO_2 to C1 chemicals and fuels. The research line <u>Photons-to-chemicals</u> is focused on the conversion of CO_2 to C1 chemicals and fuels, using sunlight as energy source for driving the reaction. The long term goals are: • To develop and validate catalysts for production of the C1 chemicals and fuels CH_4, CO and CH_3OH through sunlight-fueled hydrogenation of CO_2. • To develop suited reactors for sunlight-fueled chemical processes, and combining these with catalysts and additional components to realize a lab scale mini-factory (TRL 4-5). • To develop catalysts for production of $C_{>2}$ chemicals, e.g. ethylene or ethanol, through reductive coupling of CO_2. The research line <u>Electrons-to-chemicals</u> is focused on the process development for the conversion of CO_2 to C1 chemicals and fuels, e.g. formic acid (FA) and CO, using renewable electricity as energy source. These small molecules can be used either as a fuel or as base chemicals. The electrochemical conversion of CO_2 to FA and CO are, based on the electron consumption, the most efficient to pursue. To be able to develop a cost effective process concept, these four main requirements need to be fulfilled: 1. Current density should be above 1 KA/m^2; 2. Faradaic efficiency should be above 50%; 3. Power consumption lower than 500 kWh/kmol; 4. Electrode lifetime should be above 8000 hrs. The ERP Energy Storage and Conversion has established strong strategic partnerships with key academic (e.g. Profs. De Jongh and Weckhuysen/Utrecht University, Prof. Koper/Leiden University, Prof. Mul/Twente University, Prof. Van Bael & Buskens/Hasselt University, Prof. Goetheer/Delft University and DIFFER) and industrial players in the Netherlands (e.g. via VoltaChem and Brightlands Chemelot Campus) on energy storage in molecular bonds.

<table>
<tr><td></td><td>Following expertise and competence have been developed, and will be deepened and expanded to address the challenges in this ERP:
• Nanoparticle catalyst development and characterization, chemical conversion studies, reaction kinetics and energy conversion efficiency;
• Process and reactor concepts;
• Design and generation of photonic and electrochemical reactor concepts;
• Business case development.

The ERP Energy Storage and Conversion activities have resulted and will result in transfer of IP, knowhow and networks to related TNO VPs. The close collaboration in Voltachem, the Interreg projects LUMEN and E2C, the activities at the Brightlands Chemelot Campus and ECCM are good examples for this. Next to that, the living labs development in Rotterdam and Geleen are accelerated because of the results generated to date in this ERP.</td></tr>
<tr><td>Results 2020</td><td><u>PHOTONS-2-CHEMICALS:</u>
Photochemical conversion of CO_2 to the C1 chemicals/fuels CH_4 and CO using sunlight as energy source:
In 2019, based on the input from the companies in the business team of the Interreg project EnOp and experts from the Chemelot Campus, we started to focus on producing CO besides CH_4. This conversion is expected to be economically more favorable. For that purpose, new metal nano-catalysts are developed which will be optimized, characterized and validated. Furthermore, we will design and establish a mini factory tailored for CO_2 conversion with plasmonic catalysts and sunlight as energy source.

Deliverables 2020:
Interreg-LUMEN:
- Further development of the reactor for plasmon catalytic conversion of CO_2 to methane, including validation.
- Optimized catalyst for plasmonic photoconversion of CO_2 to methane with respect to activity/space-time-yield (STY)
- Development of a library of catalysts for the conversion of CO_2 to CO:
    o Variation of plasmonic metal
    o Variation in shape/geometry of the metal NP
    o Different carrier materials (cooperation with Sibelco)
- Initial tests on activity/selectivity for the library of catalysts described above under 3.
- First design of complete lab scale mini-factory for the conversion of CO_2 to methane and CO.
ERP:
- Development of strategies of commercially feasible photo(electro)chemical conversion of CO_2 to methanol
- Dissemination of project results:
    o >1 original research article
    o 1 review/perspective article
    o 1 LUMEN newsletter
    o >2 symposium contributions
    o 1 network event LUMEN
- IPR landscaping study possibly leading to new IP</td></tr>
</table>

	The activities on CO_2 hydrogenation will be supported by selected scientific studies performed at Utrecht University (reaction mechanism, NWO project Unravelling the Mystery of Solar Steam Nanobubbles), Hasselt University (synthesis and characterization of nanocatalysts, Interreg projects EnOp and LUMEN) and Zuyd University of Applied Sciences (development of flow reactors for plasmon catalysis, Interreg project LUMEN). Furthermore, experts from the Business Team of the Interreg project EnOp and the Chemelot Campus will be consulted with respect to technoeconomic feasibility of these processes. The 'photons-to-chemicals' concept fits to the NWA route Energietransitie, and relates to the topsectoren Chemie, Energie and HTSM. **ELECTRONS-2-CHEMICALS:** The main goal of this research line is to convert CO_2 to FA and CO using renewable electricity as energy source. To be economically feasible, the CO_2 capture, conversion, and downstream product processing need to be integrated into one reactor and process concept. When CO_2 has to be captured first from a dilute stream (e.g. flue gas, air capture) and purified, the cost of the CO_2 will be, depending on the source and scale, around 100 to 600 euro per ton. It is clear that, based on the current prices of FA and CO, it would be difficult to realize an economically attractive process. Furthermore, the process needs to fulfill following requirements: - Current density should be above 1 KA/m2; - Faradaic efficiency should be above 50%; - Power consumption lower than 500 kWh/kmol; - Electrode lifetime should be above 8000 hrs. In 2019, we demonstrated an integrated CO_2 capture/conversion methodology, the efficiency of this concept for very dilute CO_2 sources (i.e. air capture) was explored and a detailed techno-economic evaluation of the developed process concept was performed. For the first time in the world, TNO has demonstrated that a reactive capture media for CO2 can be used as an electrolyte for the reduction of the absorbed CO2 with reasonable efficiencies. This was done based on synthetic flue gas conditions. With the obtained knowhow, we are going to demonstrate that our (patented) approach can as well be used for integrated CO2 capture from **air** and direct conversion to value added products. **Deliverables 2020:** Interreg E2C (two seas): - Pilot scale pressurized bench scale unit (Electra) for CO2 to formic acid - Design of ~1 kg/hr CO2 to FA demonstrator, construction in 2021 - Optimized reactor design related to mass transfer based on flow promotors and 3D electrodes ERP: - Proof of principle integrated CO2 capture and conversion starting from air - Electrolyte optimization for integration with flue gas CO2 capture (target: 60% faradaic efficiency)

	- Development structured electrodes to improve current density to 100 mA/cm2
	- Dissemination of project results:
	    o >1 original research article
	    o 1 review/perspective article
	- 2 patent applications
	- Establishment of a shared research project focused on CO2 reduction.
	
	The work will be performed in collaboration with the groups of Mark Koper (University of Leiden), Petra de Jong (UU), Earl Goetheer (TUD) and Guido Mul (UT). Outside the Netherlands, we will collaborate with VITO and University of Antwerp. The electrons-to-chemicals fits to the NWA route Energietransitie, and relates to the topsectoren Chemie, Energie and HTSM

Dynamics	**PHOTONS-TO-CHEMICALS:** • In 2018, we first successfully demonstrated the concept of plasmon catalysis for sunlight-fueled hydrogenation of CO_2 to CH_4. • In 2019, we focused on setting up the development of plasmonic metal nano-catalysts for sunlight-fueled hydrogenation of CO_2 to CO, based on the input from industrial experts. • Furthermore, in 2019, we also started the design of a tailored reactor for plasmon catalytic conversions. This is required to establish a demonstrator that enables technoeconomic validation. This development will be continued in 2020, first designs of a mini-factory will be made together with partners. The fabrication of the mini-factory will be subcontracted as part of the Interreg LUMEN project. • In 2019, we have developed initial concepts for photochemical and photoelectrochemical water splitting for producing green hydrogen. This is selected based on business case studies for hydrogenation of CO2 that clearly illustrate that the high costs for green hydrogen from electrolysis negatively impacts the business case. The results of this study resulted in a proposal for a kiem-ERP. • In 2020 we will further expand the research with the development of strategies of commercial feasible photo(electro)chemical conversion of CO_2 to methanol. **ELECTRONS-TO-CHEMICALS:** A major lesson learned during the beginning of 2018 was that it would be feasible to thermochemically produce CO from electrochemically produced FA. A combination of two different conversion methods seem to be the most cost effective method to produce CO from CO2 flue gas. This result have changed our approach from decoupled CO2 capture and electrochemical conversion towards integration of both. In 2019, we realized a proof of concept (TRL 3) for integrated CO2 capture and conversion using an inhouse developed continuous flow reactor with an optimized three compartment GDE based cell. For the first time in the world, TNO showed that it is possible to integrate CO2 capture from flue gas with conversion with faradaic efficiencies above 40%. Two methods have been developed, based on an aqueous and a non-aqueous capture solvent. In 2020 we will continue this path and further expand the

	possibilities of the by TNO patented methodologies towards CO_2 capture from air and subsequent conversion. **<u>GENERAL:</u>** The whole field of energy conversion and storage is evidently larger than the two focus areas of this ERP. Continuous attention for new promising developments is required to prepare for alternative solutions. This ERP also includes such new technologies, e.g. heat storage. TNO started in the field of heat storage the multiyear project Dope4heat in 2017 and the multiyear project MAT4HEAT in the second half of 2018.

8 Reliability and Sustainability for PV and other (Opto-) Electric Thin-Film Devices

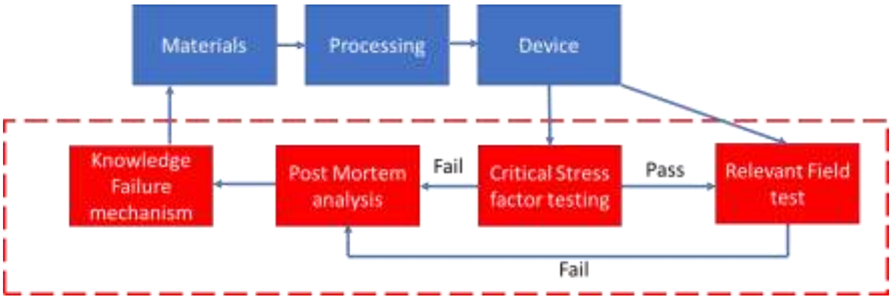
General information	
Title ERP	STAR: Sustainability And Reliability for PV and other (opto-)electric thin-film devices
Contact person TNO (ERP)	Ando Kuypers (project mgr) Mirjam Theelen (lead scientist) Wim Sinke (Roadmap Solar Energy)
Contact person(s) government or topsector	
	Participating units: ECN (Solar Energy) IND (Flexible Freeform Products) CEE (Circular economy)

Programme 2020

Summary	*Program description* 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. To improve reliability, reduce cost and reduce environmental impact, the objective of the project is to achieve more predictable and longer lifetimes of embedded optoelectronic devices in multi-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. Focus will be 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 scale of PV deployment (up to km^2) provides a unique opportunity to achieve the project objectives, as degradation on nanometer scale can be studied with statistics on km^2 scale. *Plan 2020* More specific objectives of this ERP in 2020 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 will be written concerning sustainability and circularity of integrated PV and other optoelectronic devices, connecting to the European actions on Ecolabeling.
Short Description	1.1 Long term goal: 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. 1.2 Long term goal: Sustainability

	The large scale introduction of photovoltaics and other optoelectronic devices should have a minimal environmental impact. This is important in the production process, 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. In order to address circular economy aspects and reduce the environmental footprint of (integrated) PV and other optoelectronic devices, in 2019 the first contours of a long term TNO strategy for sustainability have 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 devices.
Results 2020	2.1 Reliability of interconnections and interfaces in integrated (semi)flexible electronic devices Reliability and stability of opto-electrical devices in general is very broad and not all topics can be covered. In order to obtain optimal synergy from the collaboration between Holst Centre, Solliance, ECN part of TNO Solar Petten, and Circular Economy, the four most relevant topics were selected which are generic between the selected technology lines and enable a mutual strengthening of market positions: • Potentially flexible PV: CIGS (high TRL), Perovskites and their integration in tandems (lower TRL); use CIGS field data to identify relevant failure mechanisms and use this to guide lab testing of both CIGS and perovskite with focus on active layer. • Crystalline Si PV: focus on novel module materials (encapsulants, interconnects, front/backsheets and their impact on cell and module degradation) and degradation testing of encapsulants designed for easier dismantling of modules; customized (or dedicated) mono and bifacial module types (flatplate, 3D curved) for floating PV, BIPV and Infrastructure Integrated PV. • Stretchable and ductile interconnects for flexible (opto)electronics; devices for medical and healthcare (Holst) and flexible PV. • Study tradeoffs between minimal degradation of integrated devices and their recyclability in the context of economic and ecologic ecosystems (e.g. BIPV as valuable electronic waste component in low cost building material waste flow). **Optimized designs for integration through basic understanding of failure mechanisms as identified by post-mortem analysis of failed devices** The main goal of this project is: The following approach will be used (Figure 2). By the determination of failure mechanisms occurring in devices, relevant in situ test methods and new optimized designs for integration can be obtained: 1. Execute post-mortem analyses for failed commercial and in-house produced products in order to find the bottlenecks in failed devices. 2. Obtain a detailed insight leading to detailed description of the fundamental mechanisms

	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. 4. Verify failure mechanisms with dedicated test samples and propose improvements The focus will lie on failures as a consequence of external stressors that are related to (inter)connection technology and interfaces of active and functional layers , and their interaction with encapsulation materials. Many of these effects will be generic and will allow maximum synergy between the technology lines. Process development will be 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 2: Proposal of the scope of this project displayed as the red blocks. Many activities within TNO focus on the production of layers and devices, while their long term stability and reliability is not studied. In this project, we will take already existing products and study their intrinsic (material related) and extrinsic (device and environment related) stability and reliability.* 2.1.1 Cases The general project contains an expanding number of sub-projects focusing on specific cases with a high level of cross fertilization. They are generic stepping stones towards a general model based understanding of how failure modes develop under relevant stress combinations in (integrated) field applications, and how they can be effectively dealt with without compromising cost effectiveness and sustainability. The final goal will lay in the introduction of (semi-)flexible devices, while rigid flat plate devices can function as model and reference. The following cases will be addressed in 2020: - Materials: Stability and reliability of interfaces in (thin film) PV layers and optoelectronic stacks, Focus on activeand functional layers (CIGS, perovskites, crystalline silicon, sensor materials), transparent conductors (more stable TCO's), and novel encapsulants. - Passivation: Stability evaluation of novel passivation strategies: focus points are Poly-Si and metal oxides (MO_x) for xSi, alkali treatments of CIGS, and ALD passivation of Perovskite. - Stress factors: Thermomechanical/electrical stability of transitions (interconnections) between and within materials with different mechanical, thermal, etc. properties under combinations of practical stresses: temperature, humidity, light, mechanical load, vibrations, hail, thermal shock, exposure to solvents/vapors/salt

	water, partial shadowing, and (high voltage) potential induced degradation. - Specific devices to be tested on stability under multiple stress combinations: designs for stretchable printed electrical interconnects, CIGS and Perovskite PV on glass- and flexible substrates, glass encapsulated cSi with Poly-Si or MOx passivation with EVA-replacing encapsulants for customized or dedicated mono- and bifacial module types (flat plate, 3D curved) for floating PV, BIPV and Infrastructure Integrated PV devices and also tandem devices. 2.1.2 Required technology For these goals, the following competences are required. These competences are available at one or more of the involved research groups: - Acquiring of test samples and failure statistics, either from commercial partners and end-users after failures or from within TNO. - Competences in advanced microstructural (in-situ) characterization, chemical and physical processes, materials science and modeling. - Development of non-destructive analysis methods and preparation methods for test samples and -devices, and accelerated life time testing 2.2. Sustainability In order to set up a concrete ERP for sustainability (including recycling by design) for PV and electrical devices some key questions need to be answered first: • What are the important drivers (economic, legislation, global) and the business cases for the three platforms to work on this topic? • What are the potential long term R&D topics, opportunities and market chances for TNO to work on these topics? In 2019, we execute a first study to answer the key questions and to make an inventory of (existing) environmental assessments that could form a guideline/basis to identify technology opportunities that will create market chances for TNO in the near future. In 2020 we will write a TNO position paper describing our vision on circularity and sustainability of integrated PV in the context of Dutch and European regulations, and research actions we intend to deploy. 2.3. Connection to national and international roadmaps The research themes for this ERP contribute to the important goals set on quality and sustainability in the roadmaps as defined in the program lines of the TKI Urban energy and other Knowledge Innovation Programs (KIAs) like HTSM as well as corresponding Multi-annual Mission-driven Innovation Programs (MMIPs), that have resulted from the discussion tables (in Dutch “sector tafels”) Electricity and Built Environment. A goal of 200 GW_p of installed PV in 2050 has been set, which corresponds to a total PV area of roughly 1400 km^2. To maintain public acceptance, integration of PV in multifunctional building and construction surface areas will be a key issue.

The project also connects very well to the goals set by the European Technology Innovation platform for PV (ETIP-PV). ETIP-PV prepared a white paper on Quality and Sustainability emphasizing the importance of R&D on these topics as these are considered as crucial factors for the long term success of PV as a reliable electricity source (https://etip-pv.eu/publications/etip-pv-publications/). For flexible electronics, strong connections with the OE-a roadmap for organic and printed electronics (http://www.vdmashop.de/OE-A-Roadmap/) and the INEMI roadmap (https://www.inemi.org/inemi-roadmap) were identified.

Within this project, the possibilities to link with NWO/Interreg/Horizon2020 funded university work will continuously be explored and actively pursued with proposal submissions. Moreover, a personal Starting Grant application within the ERC Horizon 2020 research will be filed in 2019 in order to fund in-depth research on long term PV stability.

2.4 Parties involved
The TNO teams involved in this project are those of Solliance (STA), Holst Centre, MAS, ECN part of TNO Petten (SE), and TNO Circular Economy (CAS). Participating universities are TUD (1 PhD active on partial shadowing), 1 Postdoc submitted), RU (1 PhD active on circularity, 1 PhD submitted), UT (1 Postdoc active on post mortem analysis), TUE (1 Postdoc active on CIGS field performance), 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 will be involved. A selection of national and international involved company partners are/will be Hanergy, AVANCIS, Solar Tester, Eternal Sun, EigenEnergie.net, DSM, Sabic, Exasun Tempress, Solmates Levitech, Dupont, Philips, Solvay, BASF and Henkel.

2.5 Targeted project results
The table below shows the aimed project goals for 2020 and the responsible research group. Although a leader is appointed per result, naturally all groups will collaborate towards these goals. The letters “R” and “S” represent Reliability and Sustainability goals respectively.

Nr.	Title / description	Due date	Leader
R1	Partial shadowing degradation mechanisms determined in full module by coring	M2	STA
R2	PID degradation mechanism determined in full module by coring	M4	STA/UT
R3	General degradation mechanisms for partial shadowing proposed	M9	STA/TUD
R4	Progress report listing identified failure modes by post-mortem analysis of field exposed PV modules (mechanical isolation of defects and lab analysis)	M12	STA

	R5	Report on effectiveness meander structures in stretchable interconnections	M4	Holst
	R6	Progress report on mechanical stress induced degradation in stretchable printed interconnection lines	M12	Holst
	R7	Internal report describing reliable and proven degradation test method for testing modules with encapsulants designed for easier module dismantling under water or temperature treatment.	M6, M12	SE
	R8	Internal report on application specific degradation testing of customized cSi modules with innovative module materials. (selected PV modules for floating solar, BIPV, automotive, I2PV)	M6, M12	SE
	R9	Progress report listing identified failure modes and mechanisms in cSi modules using MeOx and poly-Si passivation layers	M6	SE
	R10	At least 6 conference presentations	M12	STA/SE/Holst
	R11	At least 8 submitted scientific manuscripts	M12	STA/SE
	R12	At least 2 submitted patents	M12	Holst
	R13	Definition and submission of parallel PhD project on PSC or PSC-tandem stability issues, and actively involve PhD TUD on MeOx passivation of cSi in the reliability testing of this layer	M6	STA/SE
	S1	External publication of TNO position paper on circularity/sustainability integrated PV (BIPV)	M12	CAS
Dynamics	This ERP project has now been running for less than one year. Focus has become sharper and more coherent on specific generic elements (active layer, interconnect, and encapsulant) and application dependent combinations of stress factors (integration of PV in buildings, floating devices, infrastructure and roads, agriculture and transport, optoelectronic sensors, and stretchable interconnects for PV but also for medical, healthcare, display, etc). In order to come to a more fundamental, model based understanding of relevant degradation processes, a good start has already been made with PhD and postdoc collaborations with universities (now 2 PhD’s and 2 postdocs). A number of additional positions in collaboration with universities is foreseen as further stepping stones on the ERP STAR technology roadmap. Several project proposals (with the ERC grant proposal “IMMORTAL” as one of the most prominent, with 2 PhD and 1 postdoc positions foreseen) are being prepared and submitted. A total of 7 PhD and 4 postdoc positions at the end of 2020 may be achieved.			

	During this first year, the national MMIP's and IKIA have been finalized in order to address the agreed climate goals. A massive scale deployment of PV is targeted, demanding higher degrees of integration in multifunctional surface areas, while at the same time CO_2- and general carbon footprint reductions are recognized to become more important factors in addition to just the economic factor of low cost durable energy production. Reliability and sustainability, especially of thin film devices with their inherently lower carbon footprint, are just becoming more important. Since 40 years, much R&D effort in the Netherlands, and also at TNO, has been aiming at concepts, materials and processes for the realization of national PV production, and it achieved a world class level. In the last ten years this production activity has shifted to Asia (China) and the Dutch R&D effort was primarily motivated by national high end equipment building companies, exporting production systems to Asia. Now since 3-4 years, the Dutch climate goals, SDE subsidies, and the general acceptation by the public have led to massive deployment of PV modules imported from Asia. It is generally believed that module production, and more specifically production of building and construction elements with integrated PV, will return to Europe and also to the Netherlands; this ERP enables to position TNO to support and participate in this growing economic activity. The Netherlands are at this moment in the world wide top 10 of yearly PV installations, and to maintain public acceptance, (aesthetic) integration in multifunctional surfaces is considered crucial. TNO is very well positioned to take a leading position in reliability and sustainability of smart, fit to purpose integrated PV (and other optoelectronic devices) in multi stress environments. SE in Petten is very well recognized in reliability and LCA of crystalline silicon based PV, and innovative integration concepts. STA in Eindhoven is world class in CIGS and PSC reliability research. The shift in focus of the Holst contribution to this ERP (from reliability of sensor materials towards stretchable electrical interconnects) fits very well in the ambition to excel in ease of integration for stretchable/ 3D-shaped applications. In its first year, this ERP has thus shown to enable a concerted action of several groups within TNO to take a world class position in a (also national) rapidly growing market, confirmed by recent climate plans and research agendas.

9 Submicron Composites

General information		
Title ERP		ERP Submicron Composites
Contact person TNO (ERP)		Peter Wolfs and Pascal Buskens
Contact person(s) government or topsector		Floris Lantzendörffer (EZ)
Programme 2020		
Summary	*Program description* The overall goal of this ERP is to develop and validate concepts for achieving control over structure and chemical composition of materials that enables the development of materials with tailored functionality. Furthermore we aim to progress from static monofunctional materials to active and adaptive materials. We will demonstrate the knowledge gained in use cases in the context of Brightlands Materials Center. In line with the BMC program Sustainable Buildings, we selected infrared regulating polymer foils, and coatings or materials that capture light on large surface areas and guide it to a position where it can be used e.g. in combination with photovoltaic modules. Both materials have the potential to contribute to improving the energy efficiency of buildings, which is highly relevant in view of European, national and regional ambitions regarding energy neutrality in the built environment. To achieve the required functionalities, we will design and synthesize functional nanomaterials, and disperse those in polymer matrix materials in a controlled fashion. The infrared regulating polymer foils are an illustrative example of a material with a dynamic functionality; they will be adaptive in response to temperature. In line with the BMC program Additive manufacturing (AM) , we aim to develop new materials and processes for the production of parts with high mechanical reinforcement as well as integrated thermal and dielectric functionalities, based on AM of fibre reinforced polymers. An example of an automotive part that requires resistance against high thermal as well as high mechanical loads is an inlet manifold: an air/fuel duct operating under pressure. It has a complex geometry that strongly benefits from the design freedom of AM. Traditionally, these manifolds are made from metals, but the use of polymer composites allows the production of light-weight alternatives. *Plan 2020* With regard to Sustainable Buildings, in 2020, we aim to develop: (i) thermochromic solar control coatings to increase energy savings for heating and cooling of buildings of ≥ 10% in comparison to BMC's single-layer thermochromic coating, and (ii) thermochromic solar control pigments for better fit with manufacturing infrastructures at selected pigment producers and for stabilization against oxidation, and integration in polymer matrices. With regard to Additive Manufacturing of reinforced polymers, in 2019 we showed the first feasibility of 3D printing carbon fibre reinforced	

	polymers to enable mechanical reinforcement in simple geometries. In 2020 and further, we will expand the activities to create more complex geometries with anisotropic properties, integrate multiple functionalities, and investigate the incorporation of continuous fibres in the product that further enable those properties.
Short Description	General: The overall goal of this ERP is to achieve a level of control over structure and chemical composition of materials that enables the development of materials with tailored functionality. Furthermore, we aim to progress from state of the art monofunctional materials via materials with multiple passive functionalities to active and adaptive materials. We will demonstrate the knowledge gained within the framework of this ERP in selected use cases chosen in collaboration with the Brightlands Materials Center and its partners. Sustainable Buildings: The overall goal is to develop nanocomposite glass coatings and polymer nanocomposite films for glass lamination, to improve the energy efficiency of buildings. Focus of the ERP until 2023 is on thermochromic nanocomposite coatings and foils, that can switch from heat transmission to heat blocking and vice versa at a specific temperature. Such coatings/foils outperform the current state of the art products, i.e. low-E coatings and static heat-reflective foils, by up to 30% with respect to energy savings for heating and cooling of buildings. Ergo, this significantly contributes to realizing the sustainable energy and climate targets, specifically for the built environment. Additive Manufacturing: One of the use cases is the additive manufacturing (AM) of automotive parts. Over the past years, many automotive companies have started production of prototypes and simple spare by AM, such as clamps and fixtures that are not subjected to high loads. For further implementation of AM products in the automotive market, however, products that withstand a high thermal and mechanical load are required. To date, such products produced by AM do not exist! In this ERP until 2023, we will focus on developing concepts to realize such products based on structured AM processed polymers and composites, for example including glass and carbon fibre. In addition, we aim to include multiple material functionalities such as thermal and electrical properties and sensing functionalities. The development of materials and processes is supported by multi-physics modelling. We will target products prepared by AM from glass- and carbon-filled polyamide-6, with mechanical properties and lifetime equal to injection moulded parts, pressure-resistant and leak tight. Currently, these materials are not processable by any AM technology.
Results 2020	Sustainable Buildings: In 2020, we aim to achieve the following: • **Thermochromic solar control coatings:** Design, preparation and optical characterization of a three-layer thermochromic interference filter with one or more of the coating layers comprising thermochromic monoclinic vanadium dioxide. With this development, we aim at an increase in energy savings for heating and cooling of buildings of ≥ 10% in comparison to BMC's single-layer thermochromic coating, to be demonstrated via energy performance modeling. • **Thermochromic solar control pigments I:**

	Bottom up synthesis of thermochromic monoclinic vanadium dioxide particles with a particle size ≤ 5 μm, starting from vanadium complexes/ molecular precursors (thermochromic behaviour demonstrated via DSC, particle size via SEM/TEM and crystallinity via XRD). • **Thermochromic solar control pigments II:** Surface functionalization of top-down produced (bead milling) thermochromic vanadium dioxide nanoparticles (size ≤100 nm) for stabilization against oxidation, and integration in polymer matrices. Additive Manufacturing: In 2020, we aim to achieve the following: • **3D printed parts for high mechanical load and structural integrity monitoring:** Material and process development will be focused on using continuous carbon fiber for mechanical reinforcement, and optimizing process conditions to achieve a stiffness of 50 GPa and a strength of 500 MPa. Concept and manufacturing of 3D printed sensors embedded in filament deposition modeling. After the first proof of principle, sensing within continuous filament printing needs a boost to make a leap forward towards applications in structural integrity monitoring or heat management. The current issue lies largely within the selectivity of the active sensing element and also its responsiveness. We aim at determining the right material combination (filament plus fiber) as well as configuration for the manufacturing of strain and pressure sensors. • **Incorporate stimuli-responsive functionality during printing:** Demonstrate the use of liquid crystalline resins for the manufacturing of an active sensor within a 3D printed part. The functionality enabling the sensor is due to the alignment within the liquid crystal and its response after it is subjected to a given stimulus. This work will be a further implementation of the results of PhD projects performed at TU/e in the domain of photocurable liquid crystalline resins.
Dynamics	Activities, deliverables and milestones 2019, Sustainable Buildings: • **Synthesis route monoclinic VO_2 nanoparticles with a size below 100 nm and decreased switching temperature from 68ºC to 30ºC.** We have developed a top-down route using bead milling of VO2 powders to nanopar-ticles with a size ≤ 100 nm in 2019. Furthermore, we have demonstrated that integration of dopants to lower the switching temperature from 68ºC to 30ºC is feasible. For stabilization against oxidation, and integration in polymer matrices, surface modification of the pigment nanoparticles is required, which will be pursued in 2020. Furthermore, we will develop a bottom up synthesis of thermochromic monoclinic vanadium dioxide particles for better fit with manufacturing infrastructures at selected pigment producers. • **Lab scale preparation of nanocomposite PVB and other polymer foils comprising doped VO_2 nanoparticles.** We have prepared an example of a thermochromic nanocomposite PVB film comprising doped VO_2 nanoparticles. However, for stabilization against oxidation, and optimum integration in polymer matrices, surface modification of the pigment nanoparticles is required, which will be pursued in 2020.

	• **Development of lamination procedure, and optical characterization of nanocomposite polymer foils integrated between to glass sheets.** Multiple lamination procedures for glass-glass and glass-solar panel have been successfully established. • **Development of hollow/porous VO_2 nanoparticles to lower the refractive index in the visible (2019-2022, PhD at Hasselt University).** This work is part of an ongoing PhD project at Hasselt University. • **First nanoporous VO_2 coatings on glass realized**. This has been realized, and the concept has been patented in 2019. In 2020, we will design, prepare and optically characterize a three-layer thermochromic interference filter with one or more of the coating layers comprising thermo-chromic monoclinic vanadium dioxide. We aim to increase energy savings for heating and cooling of buildings by ≥ 10% in comparison to BMC's single-layer thermochromic coating, to be demonstrated via energy performance modeling. Activities, deliverables and milestones 2019, <u>Additive Manufacturing</u>: • **Validation of the process-structure-property relations and models to predict product performance and product lifetime, as developed in the period 2017-2018, in collaboration with Eindhoven University of Technology (TU/e).** The work carried out by the PhDs is soon to be completed. One dissertation has already been submitted (along with promotion) and the remaining five are expected in the coming months. One patent application has been filed based on the results. Additionally a computer app has been developed for the structure-property prediction of printed parts produced using DLP. This app makes usage of the most relevant results of the modeling of photocurable materials carried out within this ERP. • **Show the first feasibility of 3D printing carbon fibre reinforced polymers to enable mechanical reinforcement in simple geometries.** We have optimized the processing conditions to improve the mechanical performance, and have produced several test products based on continuous carbon fiber FDM. A patent application regarding this is in preparation. Also, we have explored the feasibility of using the integrated carbon fibers as strain or temperature sensing elements. This will be explored in more detail in 2020. **Experimental proof-of-concept for creating specific, anisotropic thermal or dielectric functionality by alignment of reinforced polymer composites.** This activity is supported by modeling work done in the period 2017-2018 in collaboration with the TU/e Polymer Technology group. New composite materials were synthesized based largely on the modeling predictions investigated at the TUe. The formation of alignment and anisotropy within the newly created materials has been demonstrated. Experiments are done to compare the added functionality provided by the alignment in comparison with the base materials.

10 Decarbonisation

General information	
Title ERP	Decarbonisation
Contact person TNO (ERP)	Dick Koster, Nicole Meulendijks
Contact person(s) government or topsector	
Programme 2020	
Summary	*Program description* The causal link between the exponentially increased CO_2 emissions in the last 100 years and the accelerated global warming since then has meanwhile been convincingly demonstrated for most scientists and policy makers. In June 2019 the Netherlands government has formulated its ambition to reduce greenhouse gas emissions at a national level by 49% by 2030 and by 90% by 2050 compared to 1990. Given the geographical location and associated good supply and export possibilities, there is an above-average high concentration of large-scale chemical industry in the Netherlands. With the associated use of energy and fossil raw materials for the production of fuels, chemicals, plastics and artificial fertilizer, the chemical sector in the Netherlands, compared to most other countries, makes a high contribution to the total national emissions of CO_2 and other greenhouse gases such as N_2O. In Limburg, the share of the chemical industry, located at the Chemelot site near Geleen, in the total energy consumption and the emission of greenhouse gases is even greater. Compared to other chemical sites, the activities of the various companies operating at Chemelot are highly integrated. Companies make use of joint infrastructure wherever possible, which is centrally maintained and further developed by Sitech Services BV. The location Chemelot and its companies therefore provide an environment and partner base with a special potential, compared to other chemical sites in the Netherlands and Western Europe, to realize "Climate Proof Chemistry" in a field lab on industrial scale. At Chemelot in the past 10 years - with a 20% growth in production - a substantial reduction in emissions has already been achieved and that further reduction to meet 2030 reduction targets is considered possible on the basis of existing technology options. However it is also clear, that these innovations will be insufficient to achieve the climate targets of 2050, and that, in particular for the most CO_2-emission-determining (natural gas) combustion processes, far-reaching and new technological options will have to be explored, developed and applied. In order to achieve the "climate-proof" status of the Chemelot site and provide an international leading example on the basis of which access to additional national and international funding sources will be possible in the appropriate frameworks, a new shared research center, "Brightsite", was established at the premises of the Brightlands Chemelot Campus in June 2019. On a national scale, the Brightsite initiative can be linked to incentive programs which are made available by the Dutch government to achieve the objectives of the climate agreement. By this initiative the application of climate-proof Chemistry on industrial scale can become a reality by 2050. TNO has played a leading role in formation of Brightsite and has the ambition to continue this in the development and execution phase.

	To achieve the outlined goals, the ERP Decarbonisation program has been set up to provide for the development of new breakthrough technologies and knowledge which can be scaled up and demonstrated in collaboration with Brightsite partner Sitech and site users at Chemelot and similar industrial plants. To involve and provide a suitably educated research and workforce, Brightsite partner University Maastricht coordinated the collaboration with existing academic partners and aims develop a new circular engineering education program. *Plan 2020* In 2020 the ERP plans to launch multiple program lines in the Brightsite initiative such as reduction of emissions by electrification, securing integral process safety and societal acceptance, and transition scenarios. TNO will primarily take position from a market perspective and challenge research hypotheses based on facts and realistic expectations obtained from feasibility and desk studies. Dissemination of project results in form of publications, presentations and patents is a part of the plan.
Short Description	*Give a short description; what is the long-term goal of the ERP in 2023. What knowledge / technology is needed to get there (max. 1 A4).* In the first phase of the program, in 2019, the focus and scope of the Brightsite and associated ERP Decarbonisation have been defined. Several feasibility studies were conducted to identify the most promising research topics in view of their possible impact on emission goals, time to application and expected investments as well as safety, social acceptance and system integration considerations. After the first prioritization in close consult with stakeholders, partners and industry the further in-depth plan was developed. The following Brightsite program lines have been defined: **1. REDUCTION OF EMISSIONS BY ELECTRIFICATION** 1a. Electric high temperature heating 1b. Plasma activated cracking & decarbonisation of methane 1c. Molten metal decarbonisation of methane 1d. Sourcing, transportation and storage of electricity **2. REDUCTION OF EMISSIONS BY REDUCTION OF NAFTA AND GAS USAGE** 2a. Gasification of plastic, domestic waste and biomass 2b. Pyrolysis of plastics 2c. Dissolution/depolymerisation of plastics **3. IN-/POST-PROCESS EMISSION REDUCTION** 3a. CO_2-Capture/Storage/ Use (CCS/CCU) 3b. Reduction of N_2O-emission 3c. Use of residual heath **4. SECURING INTEGRAL PROCESS SAFETY AND SOCIETAL ACCEPTANCE** 4a. Safety Leadership 4b. Governance & processes 4c. Asset design & operations **5. TRANSITION SCENARIOS AND SYSTEM INTEGRATION TOWARDS 2030-2050**

	5a. Modeling of the Chemelot site and its connections to the outside world 5b. Outlooks for developments external to the Chemelot site 5c. Stakeholder engagement **6. EDUCATION AND HUMAN CAPITAL** 6a. Bachelor of Science Circular Engineering 6b. Master of Science Sustainable Manufacturing Where appropriate R&D activities in program lines 1-5 can start in an academic environment and be completed at demonstration level in a realistic industrial environment. TNO will focus on the intermediate investigation and transition of new and emerging technologies and strategies and use the ERP and additional funding to lead and participate in feasibility studies to be carried out by Brightsite multi-partner teams. These teams will investigate new developments and application perspective of existing and new technology and implementation options in view of their possible contribution to meet the 2030-2050 emission goals and in relation to the associated investments and possible political and societal considerations. For this roadmaps with parallel and interrelated pathways have been drawn up in 2019 for each program, illustrating how and when emission reduction steps may be possible based upon technology developments and scientific questions to be addressed on one side and market drivers, business opportunities and societal developments on the other side. The market and technical scope of Brightsite closely interacts with roadmaps of the units Industry, Circular Economy and Environment and ECN part of TNO. Brightsite will focus on a number of transition programs that are energy, circularity & alternative feedstock, system integration and process safety related.
Results 2020	*Give a short description of the intended results and deliverables for 2020. Which parties are or will be involved. What is the external connection with government or topsector agendas (KIAs) or with NWA routes. Be concrete! (**max. 1-4 A4** (dependent on the budget of the ERP)).* In 2020 the following research topics will be continued and addressed in Brightsite ERP Decarbonisaton- research lines. **1. REDUCTION OF EMISSIONS BY ELECTRIFICATION** • Feasibility studies on durable high temperature electric heating to qualify as preferred partner for the execution of the trilateral multi-decade “cracker of the future” program with Sabic and similar German/ Belgian stakeholders. • Extended business case exploration and technical experiments on plasma and molten metal based hydrogen production by decarbonization of natural gas oriented at definition of demonstrator scale unit operations. • Study on possible electrification technologies and implementation scenarios in relation to practical, financial and societal (im)possibilities and considerations for Chemelot as well as for external energy supply infrastructure needs, plans and options.

	2. REDUCTION OF EMISSIONS BY REDUCTION OF NAFTA AND GAS USAGE • Definition of demonstration scale pyrolysis and gasification unit operations based on present and future feedstocks and value chains at Chemelot. • Identification of potential options to include recycling of plastics by solvo-chemical methods with existing and planned Chemelot activities based on obtained overview of emerging technologies for dissolution and depolymerization processes. • Feasibility assessment of dissolution and depolymerization of selected waste plastics at laboratory scale including reactor design considerations. • Screening of technologies to valorize biomass streams relevant for Chemelot based as alternative feedstock. **3. IN-/POST-PROCESS EMISSION REDUCTION** • Evaluation and redefinition of CO2 storage and use options with industrial relevance at Chemelot in view of Climate Agreement regulations, focusing heat & mass balance studies for conversion routes of CO_2-rich residual gases to ethylene and/or other (high value) chemicals. • Translation of inventory of residual heat harvesting and use options to technology development and implementation possibilities. **4. SECURING INTEGRAL PROCESS SAFETY AND SOCIETAL ACCEPTANCE** • Investigation an implementation of working hypothesis resulting from consultation of Safety Task Force Members and evaluation of Learning From Incident strategy at Chemelot executed in 2019. • Investigation and implementation of new ‘Safe by Design principles on process level’ and development of basic principles for ‘Early Warning systems’. • Investigation and implementation of data-driven Early Warning technology by combining detection systems ("smart sensing networks in Industry”) **5. TRANSITION SCENARIOS AND SYSTEM INTEGRATION TOWARDS 2030-2050** • Modeling of the Chemelot site and its connections to the outside world combining building blocks available at Sitech and TNO, that allows to check the consistency of material and energy flows, calculate OPEX and CAPEX, as well as the environmental and economic effects. • Analysis of future developments and possible energy pathways outside the Chemelot site based on and by combining available scenario studies to reach the Paris goals. • Identification and engagement of (possible currently unknown) stakeholders relevant for the full scope of the Brightsite program, based on behavioral sciences supported identification and creation of win-win situations. **6. EDUCATION AND HUMAN CAPITAL** • Providing input for and co-development of research groups within the faculty of sciences and engineering and associated education curriculum at Maastricht University to ensure appropriately trained

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human capital to investigate, develop and apply new climate proof chemical technologies.

GENERAL:

Dissemination of project results:
<ol type="a">
>1 original research article
1 review/perspective article
>2 symposium contributions
1 network event Brightsite

IPR landscaping study possibly leading to new IP

Relevant external connections:

Societal Challenges: Energy, COz, Circular Economy
NWA routes: Energy Transition, Circular Economy, Resource Efficiency
Topsectors: Chemistry, Energy, HTSM
National Safety programs: Duuzame Veiligheid 2030 (I&W), Safety Delta Nederland

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<td>Dynamics</td>
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Give a description of the developments in relation to the plan drawn up for 2019 and indicate what the consequences are (max. 1 A4).

In comparison to the 2019 plan, the outline and focus of the 2020 TNO-activities have become much further defined and clear, as defined in the broader Brightsite collaboration agreement formalized on 25th of June 2019. The challenge for TNO is now to keep its activities positioned in between the practical short term oriented reality of the daily business of companies at Chemelot and the long term, green field/blue sky approach of the present and future academic Brightsite partners.
TNO will primarily take position from a market perspective, but will challenge (dis)believes based on facts and realistic expectations obtained from feasibility and desk studies. Based on the unique ability of TNO to combine technological, business and societal considerations the scope of possibly applicable options to be investigated will be widened or narrowed. As a result of this the mindset of industrial partners will be opened and academic options will be aligned, thus creating resonance along the knowledge chain of partner positions, which is required to achieve the required transition towards climate-proof chemistry at industrial scale in a safe and publicly accepted way and time frame.
Breakthrough technology results from other (inter)national initiatives, business developments and political-societal changes can be expected to change the emission reduction landscape in which Brightsite operates. In the partnership TNO is in the position to assess the impact and guide possible changes in the outline and focus of the Brightsite program when and where appropriate.
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11 Structural Integrity

<table>
<tr><td colspan="2">General information</td></tr>
<tr><td>Title ERP</td><td>ERP Digital Twin Structural Integrity</td></tr>
<tr><td>Contact person TNO (ERP)</td><td>Henk Miedema</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">Programme 2020-2023</td></tr>
<tr><td>Summary</td><td>Program description
Our society is depending on the availability of complex macro-structures. Important critical infrastructure is indispensable, e.g. for the supply of energy, in transportation, communication, defense and in protection against water flooding. Utilizing these infrastructures requires both stationary macro-structures (e.g. bridge, offshore wind structure, pipeline) and mobile macro-structures (e.g. vehicles, trains). Massive investments in these macro-structures have been made to reach the current level of economic and social development. Due the aging of this massive amount of structures, there is a need for a new generation of methods and techniques for the management of these assets and the (re)design of structures.

Premature and unpredictable failure of structures, with undesirable and unacceptable consequences can be disastrous for industry and society. Our present ability to forecast a structure's integrity in the design phase, and assess and forecast it when built and in operation, is limited because our means of determining factors influencing reliability and our understanding of the process of degradation and failure of structures is still limited. With this state-of-the art, given the large number of structures to assess and structures to (re)design, costs are sharply increasing, and proper levels of safety are under threat of becoming unaffordable. For example, without new technology a significant part of our aged infrastructure will have to be replaced because of insufficient means to assess that it is still reliable.

This early research program develops Digital Twin (DT) technology for Structural Integrity supporting design, management and maintenance of macro-structures. We develop technology for creating :
<u>DT for existing structure – single object/component</u> to assess the safety of existing macro-structures, increase their availability and limit the (increase in) cost to society. It will be endowed with intelligence and will be easy to interact with. It will improve the condition assessment and forecast of the future state. We focus on two use cases: steel bridge, bolted connection in offshore wind substructure.
<u>DT for existing structure – a road network</u> – that provides information on vehicle loads on road structures, which updates its information from distributed data sources and can be used to explore future loads. This will enable a more accurate assessment of the safety of structures such as bridges in the network and their expected lifetime.
<u>DT for design of structure</u>, which will assist in investigating the potential of new materials and geometrical alternatives. This will focus on the development of parts of a composite blast-resistant vehicle.</td></tr>
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	Plan 2020 Deliverables in 2020 will include the system designs of DTs and the following components: machine learning approach in DTs for existing structure; AI support in DT for design; layout of data management facilities in DTs; computational time reduction approach in DTs; physics models in the DTs; sensing capabilities (fiber optic and acoustic) in DTs existing structure; demonstrators of above mentioned DTs.
Short Description	For existing structures we will develop and demonstrate a methodology for creating and utilizing a digital twin (DT) for a single object/component as well as for an ensemble (network) of 'objects'. The ultimate goal will be to incorporate the single object DTs as elements in a network DT. Our focus is on the single object/component. The goals for 2023 will be a) a toolbox for creating DTs for existing objects and components in civil infrastructure and offshore structures; b) a DT for the loads on a road network, which can be adapted to other road networks. For the design of structures our ultimate goal is a generically applicable Digital Twin for Design (DT4D) methodology. It should be "interactive" and "evidence based". The latter implies that the implemented models are verified and validated by experiments. The digital twin consists of a system of modules, to describe the structure at multiple scales of detail. ***DT Existing structures*** The safety of a structure (or component) is assessed by making a model of the structure that requires input with respect to, for example, the traffic load, geometry of the construction, boundary conditions, material properties, and deterioration or damage, if any. Depending on the required accuracy, the model can be more or less sophisticated, ranging from relatively simple quick scan, parameterized models to stochastic, nonlinear finite element models with detailed 3D mesh. The input is acquired from design information, databases, ad hoc measurements and guidelines with default values. Together, model and input form sensors and other information sources are the core for a DT of the object. We define a structural integrity DT for an object/component to be such a core that is a) enhanced with machine learning to realize an intelligent core for system/damage identification that reduces input uncertainty and modelling uncertainty and b) embedded in an environment that facilitates interaction with users, among them non-specialist decision makers. We define a DT of the road network with its structures (bridges, viaducts, tunnels) to be a virtual system that updates its information from distributed data sources and can interactively be used to explore future loads. It will enable a more accurate assessment of the safety of structures in the network and their expected lifetime. ***DT Design of structures*** Essential in the development of the DT4D is how to bridge the various scales (from micro material scale to the scale of the entire structure) without losing essential information of the lower scale and on the other hand also providing the correct input and boundary conditions provided by the larger scales. The consistent interaction is challenging especially in the high dynamic conditions of impact and blast response. Knowledge on numerical (multiscale) and AI techniques have to be gained and tailored to realise the consistent interaction between the scales in the DT4D. Within the benchmark of the design of a composite blast-resistant vehicle cabin a second objective is defined, namely to reveal the physics and exploit the potentials of composites under high amplitude impulsive loading by means of experiments and computational modelling. The two objectives, DT4D development and composite materials physics use for

	design purposes, clearly interact. The development of the digital twin will assist in the determination of the best combination of computational and experimental efforts at multiple scales, whereas the deeper understanding of the potential and behaviour of composites for this application will validate the design twin and provide for its learning potential. Since the ERP program is executed at the same time that TNO is developing the composite vehicle protection with a series of international partners within EDA, the majority of the testing required for DT4D development, can be obtained from the EDA project. In this sense, ERP and EDA projects will be tremendous multipliers and ERP efforts will focus on the development of the DT4D.
Results 2020	***DIGITAL TWIN – existing structures: object/component system identification*** We distinguish three approaches that differ in how much they rely on a physical model versus measurement data from the object. We will concentrate on the first two and explore the third. • <u>Physics-model centred approach</u>: using machine learning to improve the safety assessment by the physics-based model by improving the estimation of the input parameter values. This approach appears to be appropriate when the model used can be assumed to be valid both for the assessment of the safety risk as well as for prediction of the responses measured when loads are applied to the structure. This approach will require: 1) identification of input parameters having the largest contribution to the uncertainty in the reliability calculation, 2) identification of the responses that can be measured and monitored that are sufficiently sensitive to the variation in these input parameters in the range concerned, 3) strategy for selecting the number and locations for sensors that measure these responses, 4) learning algorithm that optimizes the input parameter values on the basis of the measured responses. • <u>Hybrid approach</u>: the physics-based model is complemented with a machine learning model that reduces the discrepancy with the response prediction as much as possible. This approach appears to be appropriate when the model used for the assessment of the safety risk cannot be assumed to be sufficiently complete for either the assessment of the safety of the structure or the prediction of response measured when loads are applied, or both. In that case a neural network model can be optimized so that it produces a component that can be added to the physics-based mode prediction. For example, a neural network could be used that takes FEM output with additional input parameters as input and predicts structural responses. A more sophisticated approach would allow for a deeper intertwining between the FEM and machine-learning models. • <u>Data centred approach</u>: using machine learning for developing a machine learning model. This approach appears to be appropriate when no accurate physics-based model is feasible (e.g. too complex, too computationally demanding, our understanding is limited i.e. no strong theories). Instead of a physics model of the structure, this approach is data-driven but searches for an optimal fit that respects the physical laws. This approach needs relatively accurate and abundant data but is agnostic with respect to many features of the structure such as boundary conditions and

	geometry. This approach is the most experimental of the three mentioned here. Program lines for realizing an DT object/component system identification toolbox are described below. We will take **two use cases** from practice on which elaboration in the program lines will be focused, as an exercise and for demonstration of the capabilities of a DT. In 2020 we will use for the two use cases available datasets and other information, in 2021 we will develop field sites for these use cases. The following preliminary description of the use cases will be further discussed and elaborated in 2019. a. Bolted ring flange connections in an offshore substructure of a wind turbine. These connections have been widely applied in monopiles but their performance in existing structures is uncertain and the typical bolt design solutions face the limits of application in practice. Design and installation need to be improved, thereby enabling safer ring flanges for deeper foundations and larger turbines with increased capacity. In particular the structural behavior of the ring flange connection (i.e. combination of pre-loaded bolt, flanges and welded connection to monopile) need to be better understood and input parameters for including / mitigating tolerances from the installation and environmental conditions validated. We will develop a digital twin of bolted connections for assessment of safety and remaining service life. b. Steel bridge (Galecopperbrug, Brienenoordbrug, or IJsselbrug). We have datasets for these bridges that are particularly of interest for our physical-model centred and hybrid approach because the measured response was not quantitatively equal to the model prediction. As preliminary steps we finalize our analyses of data from concrete bridge 705. The results will provide a starting point for the developments with respect to the steel bridge. For validation and demonstration of a structural model that is enriched with sensor data, the models and algorithms developed for bridge 705 will be combined with the dataset produced by sensors on this bridge for a full probabilistic safety evaluation. Subsequently, these algorithms will be applied and further developed for the steel bridge for which (strain) measurement data are available, in order to make the algorithms more robust and applicable to structures in general. Also, the algorithms will be applied in combination with simple (e.g. 2D) structural models, that will be updated using different realistic (i.e. without violating mechanical principles and known properties) damage and modelling error scenarios in order to fit the measurement data. These different scenarios will be weighted according to their likelihoods and the remaining model uncertainty quantified, both to be used in determining the reliability. Strategies will be explored on how to use such hybrid models that were calibrated with daily measurements in the linear elastic range for the assessment in ultimate limit state with typical non-linear behavior. Program line 1) *System design*, *applied AI and enabling ICT technologies* System design System requirements documents will be made for use cases as well as a functional specification of the required system and its sub-units. The practical boundary condition for application of the system in its context will be taken into account, such as the time and budget required for usage of the system, the easiness of installation, outdoor environment

	of the hardware, response time, multi-user accessibility, etc. Sub-units of the system to be described are, among others, the sensor sub-system, models, data platform, user interface. Visualization of DT is considered to be essential for improving the communication of multidisciplinary experts engaged in a system approach to managing an asset, as well as facilitating decision makers and communication over the chain from modeler, inspection team to contractor. Selecting and specifying the integration of an available visualization module is part of this work. Applied AI- machine learning We will evaluate which type of approach (model-centred, hybrid, data-centred) is most appropriate for different needs. This starts with mapping the needs and challenges involved our use cases. A significant part of the work will be an orientation on the various techniques that are available for each of the different approaches, including their exploration using available datasets and studying their theoretical foundation. Also Bayesian updating will be considered. Data management A data platform is an important sub-unit in a DT. The sensor system sub-unit will produce huge amounts of data that need to be pre-processed and stored and must be accessible for the model, the learning sub-units, and the user interface sub-unit. We have made an inventory of available platforms and are exploring the use of the Pi-system for handling the data from our optical fiber measurements at bridge 705. By the end of 2020 we will have sufficient experience with a selected platform so that it can be incorporated in the DT and we will have identified what data management facilities such as anomaly detection, handling missing data etc will be needed. Computational speed Operation of digital twin is computationally demanding and hence time consuming. To achieve sufficient interactivity and short response time, substantial reduction of computation time is required. This reduction challenge can be tackled from two fronts: hardware and algorithmic. The algorithmic approach, focusing on increasing convergence rate in reliability analysis will be finalized resulting in an approach that significantly reduces computational time for the reliability analysis and for the model updating will be integrated in the DT system concept. Furthermore, we will explore the usefulness and utilization of advanced FEM calculation procedures based on reduced basis function finite element modeling, and start the other approach and implement cloud computing for increasing calculation speed for our models. Program line 2) *Modelling and inspection & monitoring* Dedicated model development Here we will address the developments needed for incorporating models in digital twins for the use cases. Acoustic sensing We have focused on characterization of concrete material, more specifically measuring the local Young's modulus using the Direct Velocity Mapping (DVM) technology. The narrow-band inspection system is upgraded to a wide band inspection system, for mapping the thickness dependent Young's modulus. Further development of the non-contact wide band inspection technology for other concrete parameters, will depend on the exploration in 2019 of their expected added value. Acoustic technology will be used to quantify stresses in bolts of monopile substructures for offshore wind, with a potential follow-up on identifying crack activity by AE. We will address the developments needed for incorporating acoustic sensing in a DT with a view to the use cases. Fibre optic sensing We further developed a multi-parameter single mode Fibre Optic (FO) monitoring system to measure temperature, strain and vibrations, spatially distributed along the fiber using Optical Time-Domain Reflectometry (OTDR). The next development of our patented Distributed

	Acoustic Sensing (DAS) principle to monitor vibration (and acoustics) will focus on 1) reduction of the spatial resolution (shorter sensor gauge lengths), 2) semi-real time analysis and processing of large raw data files in the data platform as to enable integration in a digital twin and 3) proper installation concepts and procedures. We will also address the development needed for incorporating FO sensing in a DT with a view to the use cases. Program line 3) *Validation and demonstration* Scale model of a bridge TNO and Bundesanstalt für Materialforschung und -prüfung (BAM) have designed and are building a DT demonstrator. It represents a real bridge, downscaled in size to 'transportable' dimensions, that can be subjected to loading conditions, weakening and repair. The core of it is a sensor system monitoring loads and structural response, FE models programmed in Python, and a module to visualize the DT on a screen. Because the current model is not yet sufficiently realistic it will be further improved to match requirements formulated. Future field sites We will choose two field sites for our DT technology in 2021, one of them being a monopile with bolted connection. Options for the other are a steel bridges that do not pass the quick scan that is being carried out by RWS or a concrete bridge with unknown behavior of connections between horizontal girders. ***DIGITAL TWIN – existing structures: Network Vehicle Load*** Data traffic loads are important for the safety assessment of structures in the road network and for forecasts potentials issues and estimate service life of the structures as well as of the road surface. At present the information on loads is scattered, not sufficiently reliable, and not equally valid for all the situations to which they are applied. A digital twin of the road network that updates its information from distributed data sources and can be used to explore future loads will enable a more accurate assessment of the safety of structures in the network and their expected lifetime. Vehicle load maps We will work towards a tool that geographically visualizes the load characteristics for infrastructure road networks, which utilizes combined data-sources about the actual measured traffic characteristics, with predictive traffic scenario and statistical models to enables prediction of future scenarios. Focus in 2020 is on increasing the number of data sources, extending the functionality of the tool, and the software implementation. A first version of the traffic scenario generation and analysis will be developed. In addition, a framework for the site-specific assessment of loads for the reliability assessment of individual objects will be elaborated. Steel bridge as a Weight-in-Motion sensor In the Netherlands a limited number of Weight In Motion (WIM) systems have been installed on specific locations in the highway by Rijkswaterstaat. Their performance and reliability is not satisfactory at the moment. We are developing as an alternative a system that can be put on a steel bridge and loads. Currently, a proof of concept is available that shows that trucks, axle weights and axle distances can be detected. What is still lacking to realize impact in practice is robustness, generalization to other measurement set-ups and connectivity to other technology (e.g. load map and structural assessment tools). Improvements considered for next year are: robustness, generalization for other sensor layouts, combination with other data sources like video footage and traffic loops and 'plug-and-play' connections to other relevant tools like structural assessment tools for

	bridges and vehicle load maps. ***DIGITAL TWIN – design of structures*** The envisaged DT for the lightweight, blast resistant composite vehicle cabin addresses 4 scale levels: Integral scale (I), focusing on the entire vehicle or vehicle cabin; Macro-scale (II), focusing on structural cabin components (such as the floor structure); Meso-scale (III), where the focus lies on simple design elements, such as (curved) panels; Micro-scale (IV), characterized by the microstructure inside the composite materials, focusing on properties such as lay-up, fibre and resin type, etc. Bridging the scales consistently with the right information exchange is challenging. The dominant effect of the composite material design is on the levels IV up to II, while the geometrical freedom gained by the application of composites dominates the levels II and I. In 2020 we focus on the levels III and IV. Numerical models have been developed for these levels, a " bridging" model is under development and a reference set of blast experiments on panels with different lay-up design have been performed, revealing a "best design". Like for the "Digital Twin - existing structures" here we also distinguish between a "Physical-model centred approach" and "Hybrid approach". Because of the limited data base, a "Data-centred approach" is not relevant for the design twin. In 2019, AI techniques were explored and a strategy was defined to identify the most dominant design variables in a "hybrid approach". This step will be followed by a "physical-model centred approach" to evaluate the developed physics based bridging model and to identify how to speed up the simulation of the detailed FE models (algorithmic approach) enabling the application of machine learning and neural network techniques. This research planned for 2020 should result in a new "AI-best design". Direct comparison with the "classical best design" will be a demonstrator of the added value of AI supported design. The deliverables for 2020 will be: • Extended numerical models at level IV and III of the fiber splitting phenomena (failure mode due to extreme dynamic loading) • Digital Twin for Design (DT4D) covering micro/material level (IV) up to structural element level (III); • Application of numerical models and execution of experiments to scale up from material to structural element level; • Exploration and evaluation of applicability AI techniques for design. • Integration and evaluation of AI in design at and between levels IV and III. • Implementation of AI techniques at level IV and III to assist in the validation of numerical models with respect to the performed experiments. • Demonstrator of AI supported design of impact resistant full composite laminate. • Application, evaluation and validation of TNO material and structural design tools in EDA & MoD R&D composite light weight military vehicle projects. This ERP is linked to RWS' Innovatieagenda, herijking januari 2017 and Vervangingsopgave Infrastructuur. It is connected to agenda's and programs of ProRail, provinces and municipalities, Topsector Energy and Topsector Water, to the national MOD SKIA (Strategische Kennis en Innovatie Agenda) and DIS (Defensie Industrie Strategie) and to the EDA

	capability development plan. Furthermore it fits in material roadmap of Topsector HTSM and the NWA “Materials- Made in Holland”.The ERP cooperates with the related TNO roadmaps and these roadmaps will add additional funding to activities described here. A connection will be made with the research in ERP/VP AI with respect to common key challenges: hybrid AI, explainability and robustness. There is close and extensive cooperation with TUD, and academic cooperation on AI in structural health and design with especially UvA/IAS and UT will be extended. Our common program with Bundesanstalt für Materialforschung und -prüfung (BAM) on topics of this ERP will be continued.
Dynamics	The scope of the development of DT technology for existing structures has widened from civil infrastructure to also include offshore wind substructures, by incorporation as a first step the development of a component DT for bolted connections in monopiles. The program for 2019 consisted of a number of exploratory program lines that should give the basis for a focused program in the years thereafter. The present program builds on much of the work that been done in 2019, but is rearranged considerably and directed towards the realization of three types of digital twins: DT for existing structure – single object/component; DT for existing structures- network; DT for design of structures. For each type the development is further focus on one or two use cases. We will initiate cooperation with asset owners on DTs for existing structures, in a first step focusing on data platforms and on future field sites. We will also start the cooperation with asset road network owners on the DT for loads on the road network. The international collaboration with industry for the development of a composite vehicle will be further developed. TNO has the possibility and is in the position to take a leading role in these new developments with respect to DTs for macro-structures. The work described here is not only supported by ERP funds but also by VPs in the roadmaps Maritime & Offshore, Buildings & Infrastructure, Protection, Munitions & Weapons. Moreover, there is no sharp boundary between the core of advanced work carried out in this ERP and projects for which external funding has been acquired on the basis our ERP and which have also a strong focus on research & development. An example of the latter is the work that Krauss-Maffei Wegmann GmbH has commissioned to TNO for development of a component (door) of a composite vehicle based on our new material developed in the ERP.

12 Social XR

General information	
Title ERP	Social eXtended Reality (SXR)
Contact person TNO (ERP)	Omar Niamut, Maria Boen-Leo
Contact person(s) government or topsector	Mariëlle Beers-Homan (EZ)
Programme 2020	
Summary	*Program description* Digital transformation enables people to share knowledge and experiences. Gartner foresees a blending of the digital and physical worlds to create an immersive world, through innovations in immersive experiences and empowered edge devices. Conversational platforms change the way in which people interact with or through the digital world, whereas AR/MR/VR change the way in which people perceive the digital and the real world. Holographic communication is a future form of mediated social communication that enables collaboration and shared experiences. It provides a strong contribution to societal challenges, such as enabling virtual meetings to reduce commutes and lower our economic and ecological footprint, providing expertise at a distance, enabling remote education and training, and support inclusion of citizens with accessibility barriers. The technology is applicable in multiple domains. 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. In 2019, the topic of Social eXtended Reality (XR, the superset of AR/MR/VR) was explored as a seed ERP and in 2020 and onwards it will be continued as a full ERP. In it we will realize the first-time engineering of a shared and networked XR environment, where participants get the feeling of being in the presence of, and interacting with, other persons at a remote location. To reach Internet-level scale, cross-layer and joint orchestration of multimodal media, computation capabilities and network functionality is essential in a holographic communication platform. Research focus lies on immersive experiences through volumetric video and tactile data, and empowered edges for distributed computation and transmission. Our main scientific partners are major knowledge centers, including all national technical universities and CWI. We collaborate with Dutch incumbent KPN, TNO spin-off Tiledmedia and explore collaboration with Philips. We become members of the H2020 CSA XR4ALL and the EuroVR Association, and a preferred contributor to the most relevant European XR industry event VR Days Europe. We collaborate with ERP i-Botics and are poised to contribute to the XPRIZE Avatar proposal. While competitors focus mainly on hardware, location-based experiences and lifelike avatars for the entertainment and gaming

	industry, TNO contributes to a scalable, open and inherently mobile communication platform, with respect for European privacy regulations and with contributions to societal challenges at its focus. *Plan 2020* Expected results for 2020 include i) proof-of-principles for orchestrated and distributed capture, coding, streaming and rendering of volumetric video and tactile data; ii) measures and guidelines for the quality and synchronization of mediated social communication experiences; iii) proof-of-principles for automated and orchestrated deployment of processing modules on cloud and edge infrastructures, and for network assistance and monitoring services; iv) test setups for experimentation with different mobile networking scenarios and application modules; and v) a set of mockup demonstrators, based on the showcases derived from specific interests from several TNO units, and a report on their evaluation.
Short Description	Communication is more than an exchange of words. Digital transformation enables people to share knowledge and experiences. Gartner[1] has identified the strategic technology trends with substantial disruptive potential that is beginning to break out of an emerging state into broader impact and use. The combinatorial effect of multiple trends to produces new opportunities and drives new disruption towards an **intelligent digital mesh**, where AI is present in virtually every existing technology, where connections between expanding sets of people, businesses, devices, content and services are exploited, and where the digital and physical worlds blend to create an immersive world. Here, conversational platforms change the way in which people interact with or through the digital world, whereas Virtual reality (VR), augmented reality (AR) and mixed reality (MR) change the way in which people perceive the digital and the real world. This combined shift in perception and interaction models leads to future **immersive experiences**. These experiences are captured and consumed via endpoint devices (e.g. cameras and head-mounted displays) which are increasingly equipped with sensing, storage and computational capabilities. Edge computing describes a computing topology in which content collection, processing and delivery are placed closer to these endpoints. Cloud computing and edge computing evolve as complementary models with cloud-native applications being  Top 10 Strategic Technology Trends for 2019 through 2028 (source: Gartner)

[1] https://www.gartner.com/smarterwithgartner/gartner-top-10-strategic-technology-trends-for-2019/

	orchestrated over and executed in distributed servers and on **empowered edge** devices. 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), 5G and Tactile Internet. 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. In the **ERP social XR** we aim to realize the first-time engineering of a shared and networked XR environment, where participants get the feeling of being in the presence of, and interacting with, other persons at a remote location. Such a system has clear potential for TNO roadmaps and societal stakeholders. It provides a strong contribution to societal challenges, such as enabling virtual meetings to reduce commutes and lower our economic and ecological footprint, providing expertise at a distance, enabling remote education and training, and support inclusion of citizens with accessibility barriers. Within the ERP the technological focus lies on (media and network) **orchestration**, from capture to rendering, and from transmission layer to quality of experience. 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. In the ERP we therefore focus our research on: • Orchestration of user-centric distributed and networked systems for capturing, coding, streaming and rendering of multimodal media, specifically of volumetric video (e.g. light fields, point clouds, meshes and multi-viewpoint images, and tactile data, especially related to social interaction (e.g. eye contact, facial expression, gestures, body posture and proximity, prosody, social touch, and collaborative haptics), and the assessment of the perceived quality of the **immersive experience and social interaction**; • Automation and orchestration of user-centric mobile computing and processing with joint optimization of communication and processing in hybrid cloud / **empowered edge**. While we treat these topics in parallel in 2020, we foresee integration of empowered edge devices into immersive experiences for holographic communication in 2021 and beyond.
Results 2020	**Results and deliverables for 2020** Immersive experiences:

	We investigate **multi-camera configurations** that capture color and depth information from the participants in a social XR experience. Such capture systems are typically construed by arranging depth sensors in an inward-facing configuration. They require automated calibration and synchronization of resulting captured data, such that point cloud data can be generated and rendered at runtime, aligned on a 3D geometrical plane. By improving the current technology in terms of calibration and synchronization, we will establish true volumetric video capture. With respect to **coding and streaming**, we study both (hybrids of) video based as well as 3D geometry orientated coding methods and associated container formats, to select the most efficient and robust volumetric video and tactile data representations for transmission over mobile networks, under latency and bandwidth constraints. In particular, we investigate suitable protocols for real-time and efficient **delivery of tactile data**. For rendering of volumetric video, we aim to develop new shaders that can cope both with multiple incoming color-plus-depth data streams, and with the mapping of 3D hand positions in relation to the position of the user. To provide an immersive experience comparable to face-to-face communication, our envisioned system should reliably convey information about both the shared environment (VE) and about all relevant **social cues**. Important issues are (1) the **synchronicity** between the different sensory signals that is required to achieve a coherent multisensory experience and (2) the **bandwidth** required to optimally convey relevant social cues (e.g., gaze direction, eye contact, prosody, facial expression, non-verbal sounds, gestures, body posture, orientation and proximity, social touch, collaborative haptics, pupil size, eye blinks, etc.). The coding of volumetric video and tactile data should be sufficiently efficient, and typical internet networking effects such as time delays, jitter, or packet loss should be minimized to maintain the levels of system transparency and stability that are required to provide an **immersive and synchronous multisensory communication experience**.  Rendered environment for our Social XR *Deliverables:* i) a proof-of-principle of the orchestrated automated calibration and synchronization of a networked multi-camera configuration; ii) a proof-of-principle of an efficient hybrid video and point cloud data coding and streaming format ; iii) a first design of tactile data streaming format; iv) a demonstration of improved mapping of 3D hand positions relative to the user; v) a demonstration of improved eye contact; vi) a minimal set of measures that maximally describes the quality of the mediated social communication experienced at different affective (sensory, perceptual, and decision making) processing levels; vii) initial guidelines on the synchronization (in-)tolerance of visual, auditory, and haptic social cues, and viii) a report on how to deal with typical internet networking effects and on how to determine a good benchmark regarding these challenges.

Empowered edge:

Edge computing aims to localize and decrease network traffic and to reduce networking delays by ensuring that information processing, content collection and delivery are performed near the endpoints. Such **delay reduction** is vital for many innovative, highly demanding real-time applications such as Social XR. At the same time, a deployment of a large number of edge (mini-)clouds can incur significant costs to service providers and network operators. They need to perform cost/benefit analyses (i.e., weigh the delay reduction against the expenditures related to installation and maintenance) in the design phase and continuous assessments of services health and placement in runtime, to avoid instantiating new services at already overloaded edge nodes. Therefore, edge computing and its **integration into mobile networking** infrastructures is an important research area.

Empowered edge computing enables seamless, low-latency interactions at the digital-physical boundaries.

To be able to leverage the full potential of edge computing, (1) instantiation of edge and cloud resources has to be **orchestrated** and the resources have to be timely available to the Social-XR clients; (2) network connections between the clients and the edge nodes, and between the edge nodes and a central cloud, have to be **configured** and established; and (3) the Social-XR clients and infrastructure have to be configured for optimal use of the available **computing and transmission resources**; (4) continuous **monitoring** of the Social-XR service needs to be in place and the mechanism for the correcting actions (e.g., re-allocation or resizing of the components) need to be available. We will study these aspects, starting with the **localization and deployment** of edge computing resources along with the associated benefits and the costs. Important factors for the performance of the Social-XR service are the capabilities of the edge node (e.g., CPU, RAM, and GPU availability) and the network performance (e.g., throughput, latency, and jitter). As such, we will enable **GPU acceleration** in our computing infrastructure and we will develop an **orchestrator service** based on TNO Research Cloud/Hi5 platform that automatically and dynamically deploys, re-deploys, scales in and out the modules of the Social-XR service at various places in the network (i.e., on both edge devices and centralized servers, depending on the configured policies and telemetry), making the Social-XR services available as application functions in the mobile network. With respect to optimally using the edge infrastructure and network resources, we will study which **key performance indicators** have to be extracted from the edge computing infrastructure and 5G mobile network, in order to serve as input parameters for a dynamic orchestration and configuration platform. In addition, we will study how the Social-XR service and the infrastructure/network can interact and exchange information, such that the delivery of the media streams can be enhanced. We will look into the possibilities of exposing an API from a Network Assistance Service towards the Social-XR service and client, such that an **information exchange** can be facilitated. We will study how both application and infrastructure/network can adapt to each other.

As part of this application and infrastructure/network integration, it is important to understand the network connectivity to the edge, including the characteristics of 5G radio access networks (RANs). We will study how RAN performance translates to the application layer performance, such that the application can properly adapt to the situation and the network can provide QoS when this is needed. Based on existing work and network simulation techniques, we will investigate the vulnerability of mmWave channels for blocking and its effects on throughput, throughput variations, latency, jitter, and packet loss. We will use these results to build a test setup that allows for experimentation with the Social-XR application under different networking conditions. The test setup will make use of a network emulator developed by TNO. Finally, the information about various parameters of the (emulated) RAN will also serve as input data to the metering system, which in turn makes the performance parameters available to the Social-XR application.

Deliverables: i) a proof-of-principle of the automated and orchestrated deployment of Social-XR processing modules on the cloud and edge infrastructures; ii) a report and conference publication with guidelines for the placement of edge computing resources; iii) a report and conference publication on the performance of 5G radio access networks in different simulation scenarios that captures the characteristics of mmWave radio channels and provides solutions at link/network layer to deal with the intermittent nature of these channels, in the context of Social XR applications; the conference publication focuses on the link/network layer solutions; iv) a test setup that allows for experimentation with different 5G mobile networking scenarios; v) a proof-of-principle of the network and infrastructure monitoring service; and vi) a proof-of-principle of the network assistance service for Social-XR that may be used for adapting the application, network, and infrastructure.

Showcases:
Several TNO Units (specifically; DSS, HL, ICT, TT) are interested in holographic communication and its constituent technologies. With such a system, national security personnel (e.g. police officers) can ask for remote assistance and discuss with expert colleagues about crime scenes on location; distributed teams of soldiers can jointly train for critical missions; companies can let personnel meet and discuss remotely, and public services offering Mobility-as-a-Service concepts can add an new modalities to their portfolio. In 2020, we develop a set of mock-up demonstrators, to showcase the potential of our knowledge and technology in the context of Unit roadmaps. The evaluation of these mock-ups will lead to new insights for our further development of our social XR platform.

Showcases for units DSS, ICT and T&T.

	Deliverables: i) report on requirements for a set of showcases, based on specific interests from several TNO units; ii) a set of mockup demonstrators, based on the showcases derived from specific interests from several TNO units; and iii) a report on the evaluation of this set of mockup demonstrators. **Strategic collaborations and connections** Our main scientific partners will be major knowledge centers on the topics of i) mobile networking and softwarized networking infrastructures; ii) multimedia computing; and iii) multimedia systems quality of experience. We are in the process of strengthening and/or exploring connections to **Delft** University of Technology (Lab on Internet Science), **Eindhoven** University of Technology (Center for Wireless Technology) and **Ghent** University (Internet Technology and Data Science Lab) for topic i) and Computer Graphics and Visualization and Multimedia Computing groups for topic ii)); **Utrecht** University (Multimedia group for topics ii) and iii); and University of **Twente** for all three topics. Members of our Steering Board (Paul Havinga, Hans van den Berg and Jan van Erp) have part-time affiliations at University of Twente, and we explore a part-time affiliation for lead scientist Omar Niamut at Delft University of Technology. We intend to allocate up to 10% of the programme budget for academic collaborations involving PhDs. In addition, we strengthen our partnership with **CWI** (Distributed and Interactive Systems) for all three topics. We continue our strategic industry collaborations with Dutch incumbent **KPN**, primarily through the long-term research program where we create and standardize IP on volumetric video coding, XR streaming and VR communication; our spin-off company **Tiledmedia**, who are currently bringing our earlier R&D results on bandwidth-efficient 360 video streaming to market. We expect to collaborate with **Philips** R&D on 3DoF+ and 6DoF AR/VR video standardization in MPEG. We further participate in the most relevant international standardization bodies, on coded representation of immersive media (**MPEG**-I, in particular Phase 2) and future mobile communication services (**3GPP** Study Item on Extended Reality over 5G). We will become members of the H2020 Coordination and Support Action **XR4ALL** and the **EuroVR** Association, and increase our efforts in international academic communities related to top-tier ACM and IEEE conferences, in particular ACM Multimedia Systems, EUCNC, IEEE AIVR and IEEE VR, and the most relevant XR industry events such as **VR Days Europe**. We have strong internal and external connections with roadmaps, programmes and R&D agendas. In 2019, we have established specific links with the following Unit roadmaps, VPs and associated PMCs: - Operations & Human Factors (e.g. Mission Simulation) in Unit DSS; - National Safety (e.g. remote assistance by police) in Unit DSS; - Immersive Human Communications and Customized Digital Infrastructures from PMC cluster Fast and Open Infrastructures, as part of ICT roadmap in Unit ICT; - Smart and Sustainable Mobility roadmaps of Unit T&T (e.g. not to travel); - VP Radar en Sensorsystemen (P104, e.g. processing close to sensor) in Unit DSS; - VP ICT (P706, e.g. media and network orchestration) in Unit ICT.

	ERP Social XR further interacts and collaborates with **ERP i-Botics**, and the output of ERP Social XR is absorbed in VP ICT and VPs in Unit DSS. ERP Social XR is poised to contribute to the **XPRIZE Avatar** proposal, specifically on social interaction, latency reduction and bandwidth usage optimization. Social XR is also closely linked to **MoD research** programs, such as “Human Factors in Immersive Technology” (NL: ‘Immersie op Maat’). These projects mutually benefit from transfer of knowledge and R&D equipment. The program is linked to the goals of the **topsector HTSM**, roadmap ICT. Specially, as part of the new Kennis- en Innovatie Agenda Sleuteltechnologieën 2020-2023, the Meerjarenprogramma on **Beyond 5G** Future Networks and Services includes holographic communication as one of the primary application challenges. The link to the various activities is also shown by an increasing portfolio of social XR related projects, for instance the EU H2020 project VR-Together.
Dynamics	In the KIEM ERP 2019 we started to address three problems with current technologies for remote communication, i.e. i) that existing avatar-based telepresence solutions do not provide the feeling of being present in a mediated environment; ii) that, despite the importance of social touch in co-located interpersonal communication, it is currently underexposed in modern communication technologies; and iii) that creating high-quality and immersive shared XR experiences between remote participants puts a significant demand on a mobile communication infrastructure. We also identified five underlying challenges, i.e. a) developing photorealistic and volumetric human representation in a format that can be easily captured, compressed and transported to AR/VR devices; b) realizing shared and networked tactile interaction; c) orchestration of softwarized network infrastructures; d) dealing with the intermittent nature of ultra-high frequency wireless mobile connections; and e) enabling convincing shared and social XR experiences. We have validated these problems and challenges with worldwide academic and industry developments presented at e.g. IEEE VR 2019, and have refined our vision to focus TNO contributions on investigating the impact of social XR on future communication networks, and strengthening our knowledge and technology base from 5G, social VR, and haptic interactions into an integrated platform for sharing AR/VR experiences across different locations and through sensory modalities beyond sound and vision. In 2019, our approach was to making our vision (more) visible by developing an integrated Proof of Concept of a shared and networked XR experience. As such, our efforts were on development and integration, leveraging previous R&D results from parallel activities and projects. This approach has been fruitful, as our integration efforts raised specific research challenges that allowed us to define the outline for a complete and comprehensive multi-year ERP program. In addition, we received the Best Demo Award at the prestigious ACM Multimedia Systems Conference[2] for our showcase of “Multi-Sensor Capture and Network Processing for Virtual Reality Conferencing”, where we introduced a multi-view, multi-sensor capture end-to-end system,

[2] http://www.mmsys2019.org/

running on top of a cloud-native social VR platform; and our paper to the IBC conference[3] on “Everyday Photo-Realistic Social VR: Communicate and Collaborate with an Enhanced Co-Presence and Immersion” was selected for “Best of IBC” as one of this year’s top 10 best papers out of over 500 submissions. Our work on social VR and 5G was covered by NOS Jeugdjournaal[4] and in NRC[5].

Award-winning demonstration of our social XR PoC at the ACM MMSys 2019 conference.

Conference attendees point out that “8 point cloud streams and renderings in real-time is amazing” and that they “felt so immersed in the operational VR conferencing setup” they saw for the first time. In particular, they pointed out that “these 3D renderings are much more immersive than the earlier demo with video-planes”. From our research and development in 2019, we learned that key research issues lie in i) the spatial alignment and synchronization (i.e. joint spatio-temporal orchestration) of volumetric video and tactile hand data, ii) (edge) cloud-native GPU-based acceleration of application functions such as volumetric video (de)coding and iii) improving Quality of Experience through cross-layer optimization of application and network resource usage. We also learned that aiming to perform full user evaluations in a technical PoC system can rapidly lead to project delays; we therefore decouple system developments from user evaluations in 2020, and plan to develop showcases and run user evaluations based on mockup demonstrators. In the outside world, we primarily see i) a stronger interest in shared and social XR services and technologies (e.g. in MPEG and 3GPP standardization roadmaps; Facebook, Magic Leap and Microsoft all invest in remote telepresence); ii) new developments in mobile VR and tactile hardware for gaming and entertainment and iii) a renewed interest in AR and underlying volumetric media formats. We accommodate for these changes by presenting our ideas in international standardization with a keen understanding of communication networks, promoting an open platform to foster collaboration and prevent the walled-garden options from global players, focusing on universal tactile streaming and data protocols, and accelerating research into AR and volumetric video.

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[3] https://show.ibc.org/conference-programme-2019/tech-talk-forging-the-next-generation-of-360-entertainment

[4] https://jeugdjournaal.nl/artikel/2281707-veel-sneller-gamen-op-je-mobiel-5g-komt-eraan.html

[5] https://www.nrc.nl/nieuws/2019/08/01/vergaderen-in-de-onwerkelijkheid-a3968880

13 Hybrid AI

General information	
Title ERP	Hybrid Artificial Intelligence
Contact person TNO (ERP)	Serena Oggero, Albert Huizing
Contact person(s) government or top sector	

Programme 2020

Summary

Program description

In recent years, significant progress has been achieved with Artificial Intelligence (AI) in conducting specialized tasks such as image recognition, natural language processing, and games. However, the current generation of AI has still significant shortcomings with respect to general-purpose tasks, safe operations in an unpredictable world, interaction with humans, and adherence to laws, regulations and ethics. The long-term objective for 2023 of the ERP Hybrid Artificial Intelligence is to develop AI capabilities that enable safe, ethical and effective operations of autonomous systems in an open world, privacy-aware, fair, and transparent decision making, and effective collaboration and co-learning in human-machine teams. This objective will be achieved by developing, integrating and demonstrating the required AI capabilities in two generic use cases that represent future AI applications in domains such as Health, Mobility, FinTech, Energy, Justice, Security, and Defense:

- *Application "Time-critical autonomous decision making in an open world"*: Involves the development and integration of AI capabilities for an autonomous system under meaningful human control incorporating context awareness and detection of novelties, self-assessment, self-management, and explainability.
- *Application "Effective, fair, transparent decision making in continuously learning human-machine teams*": Comprises the development and integration of AI methods for accurate and unbiased decisions, personalized explanations and justification of decisions, and continuous co-learning in human-machine teams.

The development and integration of AI capabilities in both generic use cases will be guided by the needs for AI and lessons-learned in specific use cases from demand-driven TNO AI projects for autonomous driving, surveillance, detection of fraud, and case law. New ideas for AI capabilities will be provided by scientific exploration in the area of ethical goal functions for meaningful human control, legal protection by design, efficient deep learning, hybrid intelligence, and methods for causal discovery and inference. This fundamental research will be conducted in close collaboration with academic partners in The Netherlands and Europe (UvA, VU Amsterdam, TU Delft, LIACS Leiden, UU, VU Brussels) through research collaboration agreements, NWO research programs, and EU projects. Collaboration in the field of AI will be stimulated by participating in national and international networks such as the NL AI coalition and CLAIRE, respectively.

Plan 2020

- *Application "Time-critical autonomous decision making in an open world"*: A demonstrator in a lab environment of an AI-enabled autonomous system that can recognize novel entities and attributes, assess its own competencies, adapt its own

	configuration and behavior to optimize performance with respect to the goal of the task, and explain its decisions to the human supervisor. • *Application "Effective, fair, transparent decision making in continuously learning human-machine teams*": A demonstrator in a lab environment of an AI-enabled decision support system that makes effective, fair and justified decisions and learns from human feedback. The 2020 research results will be disseminated via publications at international AI-related conferences and in journals.
Short Description	The current generation of AI has still significant shortcomings with respect to the execution of general-purpose tasks, safe operations in an unpredictable world, interaction with humans, and adherence to laws, regulations and ethics. The long-term objective of the ERP Hybrid Artificial Intelligence is to develop the next generation of AI that: • enables safe, ethical and effective operations of autonomous systems in an open world; • supports privacy-aware, fair, and transparent decision making; • advances collaboration and co-learning in human-machine teams. To achieve this objective, the next generation of AI will need to have the following capabilities: • Controllable AI Goal-oriented behavior under meaning human control, self-assessment of own competencies, self-management of own configuration; • Explainable AI Meaningful and adaptive explanations to humans and continuous learning from their responses; • Responsible AI Learning to draw accurate inferences from (distributed) data while still adhering to the principle of fairness, transparency, and privacy preservation; • Hybrid AI Understanding of the context and novel situations by integration of domain-specific knowledge, symbolic reasoning, and machine learning to obtain better (causal) models for demanding problems. The required AI capabilities will be developed, integrated and demonstrated in two generic use cases that represent future AI applications in domains such as Health, Mobility, FinTech, Energy, Justice, Security, and Defense: • Time-critical autonomous decision making in an open world (Controllable AI, Explainable AI, Hybrid AI) • Effective, fair, transparent decision making in continuously learning human-machine teams (Responsible AI, Explainable AI, Hybrid AI) A successful integration of the required AI capabilities and associated methods and techniques needs a multidisciplinary approach and, in addition to domain expertise, also expertise from the fields of systems engineering, human factors, law, ethics and behavioral science. As a multidisciplinary applied scientific research organization TNO is uniquely positioned for this integration challenge. TNO has expertise and a knowledge position on topics relevant for the controllable, explainable and responsible AI capabilities; TNO has knowledge on expert-driven models in

	specific domains such as defense, mobility, health, and TNO has experts on advanced machine algorithms and symbolic reasoning, and finally, TNO has a strong experience on approaching applied problems from a multidisciplinary and system integrator perspective.
Results 2020	The following table illustrates the structure of the ERP Hybrid AI in 2020. The rows correspond to work packages; the link with the AI capabilities (ERP Hybrid AI research lines in 2019) is indicated in the final 4 columns. The main collaborations and co-funding from external organizations (multipliers) that are currently known are indicated through logos; more partners will be pursued during the program.

Work Package	Co-funding	Collaboration	Controllable	Explainable	Responsible	Hybrid
WP1: Time-critical autonomous decision making in an open world	Fraunhofer IOSB	TU Delft GRAKN.AI				
WP2: Effective, fair, transparent decision making in continuously learning human-machine teams		liacs TU Delft				
WP3: Scientific exploration	NWO	VUB Vrije Universiteit Brussel Universiteit Utrecht Universiteit van Amsterdam TU Delft				
WP4 (Inter)national collaboration	Preparatory Action on Defence Research ECSEL JU Horizon 2020	NEN CLAIRE NL AI Coalitie				

In 2020 there will be two work packages explicitly focusing on the integration and demonstration of the required AI capabilities in two generic use cases that are relevant for various application domains

	• Time-critical autonomous decision making in an open world (Controllable AI, Explainable AI, Hybrid AI) • Effective, fair, transparent decision making in continuously learning human-machine teams (Responsible AI, Explainable AI, Hybrid AI) A third work package focuses on more fundamental research questions that are relevant for the required AI capabilities. This scientific exploration is mainly conducted in collaboration with academic partners through co-supervised PhD researchers and co-funding NWO and EU projects. A fourth work package is aimed at supporting national AI strategies, e.g. NL Strategisch ActiePlan AI (SAPAI), (inter)national collaboration in the field of AI, e.g. CLAIRE, NL AI coalition, AI standardization activities, e.g. NEN, and support of TNO AI strategy (Appl.AI). **- WP1 Time-critical autonomous decision making in an open world** The objective of this work package is to develop, integrate and demonstrate AI capabilities for an autonomous system under meaningful human control incorporating context awareness and detection of novelties, self-assessment and self-management, and explainability. The result in 2020 is a proof-of-concept and demonstration in a lab environment of an AI-enabled autonomous system that can recognize novel entities and attributes, assess its own competencies in a new situation, manage its own configuration to optimize performance with respect to the goal of the task, and communicate and explain decisions to the human supervisor. *[Competence assessment of the whole system]* We will use the method developed in 2019 for competence assessment (a part of self-awareness) which expresses the performance of the individual data-driven components of an AI as function of their input quality and output quality, to study a performance function of the entire AI system; this function will combine the numerical information related to the quality measures, with the conceptual information specifying the context (configuration) that a component of the AI is currently in. *[From self-awareness to self-management of the AI components]* We will develop a proof-of-concept based on the ideas developed in 2019 on how to manage the settings of an individual component (self-management), using machine learning in combination with knowledge on the functionality of the component. We will also research fundamental solutions on how to discover and manage the system's configuration given the task that was given to the system. The above activities will be conducted in close collaboration with the TNO project RVO Autonomous systems, TU Delft, the company GRAKN.AI, and in cooperation with Fraunhofer IOSB, through an ICON project of 1 M€, matching 330 k€ per year for 3 years to the ERP Hybrid AI. *[Tactical decision making with ethical policy]* We will implement and demonstrate the planning of a series of tactical maneuvers for an autonomous vehicle based on a balance between a goal-oriented task-policy and an ad-hoc developed ethical policy. The task-policy will be provided by the EU ECSEL project PRYSTINE. The ethical policy will be firstly formally described to indicate which type of tactical actions (and state of the world) are desirable from an ethical point of view. Secondly, we will develop a computer model of concepts and relations to

	characterize the situation (context), plan hypothetical actions and analyze the impact on its ethical aspects. This activity will make use of the research, vehicle and experiments planned in the ECSEL PRYSTINE project for 2020, and will also cooperate with the ERP Wise Policy Making for finding a formal policy-model that is machine readable [Tactical decision making with an ethical policy] *[Explainability of competence and decision making]* We will develop methods to provide human observers with meaningful and timely explanations of the performance of the autonomous vehicle and of the tactical decisions. The explanations will make use of the results of the three previous activities, as well as methods studies by the Explainable AI project in 2019. The activities will be harmonized with V1723 (“Zelfstandige taakuitvoering door onbemande systemen”). (1) Adaptation of the, rule- or example-based, contrastive explanation to the human and context, (2) its contribution to the understanding of causality, and (3) the validation of its effects will be core research objectives. *[Hybrid architecture]* We will realize an integrated architecture and algorithm combining machine learning components with a knowledge representation of the “internal self” (AI components and their configurations) and the external context (environment, based on a description of the context where the demonstrator will take place).The capability to detect unknown objects, learning the characteristics of these objects and add them to the knowledge base will be implemented and demonstrated. *[Demonstrator: intelligent system for a “smart-home” application]* We will demonstrate the results in an experiment with an autonomous platform (for sensing and tactical maneuvers) and a Nao or Pepper robot (for communication of the explanations to human observers). The demonstrator will be inspired by a smart-home application, where the intelligent system can be imagined as the helper of an elderly person, in charge of e.g., monitoring the environment for unexpected object or people fallen on the ground. - WP2 Effective, fair, transparent decision making in continuously learning human-machine teams The objective of this work package is to develop and integrate of AI methods for accurate and unbiased decisions, personalized explanations and justification of decisions, and continuous co-learning in human-machine teams. The result in 2020 is a proof-of-concept and demonstration in a lab environment of an AI-enabled decision support system that makes effective, fair and justified decisions, learns securely from sensitive distributed data, and provides personalized based on human feedback. *[Experimental method for obtaining XAI requirements]* When generating an explanation, it is crucial to know what type of explanation is required for the user and how the explanation can best be conveyed. We will develop an experimental method that will provide the generic requirements, patterns and ontology for adaptive XAI. The method will be inspired by the medical use case but be generally applicable to decision support systems.

	[Personalized explanations] In 2019, we have developed a method to model the user's decision process to explain novel and mismatching elements between system and human. We have also developed an explanation memory module to focus explanations on novelty and circumvent repetition. In 2020 we will combine these two models into one personalized XAI system, which will also be validated on usefulness for the user during the demonstration. *[Validation of different methods for explainability]* In 2019, we have developed a user study to validate a generally applicable XAI method on usefulness for the human collaborator. In 2020, we will develop a tool suite to validate different types of XAI methods developed within WP1 and WP2. Similar to WP1, WP2 will conduct a validation experiment to advance our understanding of causality and validate the Personalized Explanation design pattern. *[Fair predictions]* In 2019 we developed several general methods to balance the utility of a database for predictions with ethical and legal conditions in a quantitative way. In 2020 onwards, we will study specific scenario's for sharpening and validation. Depending on the prediction task, certain patient information may or may not be exploited for prediction models because of privacy laws. Alternatively, information like gender, age and ethnicity can give valuable background information to improve diagnostics and treatment in the medical domain. However, in medical datasets such information is often used to select and create patient groups. Studying the influence of these parameters on medical conditions is therefore extremely demanding. *[Secure learning]* In 2019 the focus for the secure learning was on collaboratively and confidentially learning linear AI models, which is needed for privacy laws and company confidentiality in domains like FinTech, Medical, AgriFood, Energy, Safety & Security. In machine learning with a single data base the state-of-the-art models are complex non-linear models such as kernelized support vector machines, random forests, and gradient boosting. We plan to work on these non-linear models where secure Multi Party Computation technology will be need to be combined with Federated (local) Learning to obtain feasible solutions for state-of-the-art machine learning. *[Hybrid architecture and model for human feedback]* We will realize an integrated architecture and algorithm combining the machine learning components developed in other activities with - knowledge representations of the "internal self" (AI components, their configurations, e.g., origin and type of labelling of dataset), to be able to provide a quality measure of the predictions adapted to different contexts (configurations, datasets available) - knowledge representation of the application domain (possibly medical causal models), to link data-driven correlations to causal modelling; - and knowledge representations of the human feedback, to be able to incorporate additional domain knowledge from human collaborators feedback provided during the operational use of the system. This architecture will build upon the functional architecture realized by the Explainable AI project in 2019, integrating components from the functional architecture realized by the Controllable AI project.

	[Demonstrator: intelligent decision support for a medical application] We will demonstrate the results in an experiment with a decision support platform (for information extraction from different datasets) and a Nao or Pepper robot (for communication of the explanations to human observers). The demonstrator will be inspired by a medical application, where the intelligent system can be imagined as the helper of a patient or a doctor, in charge of e.g., providing personalized advices on health conducts or diagnoses. - - WP3 Scientific exploration The objective of this work package is to scientifically explore concepts, methods and techniques that are needed to achieve the long-term goal of AI that can conduct general-purpose tasks in complex dynamic environments in cooperation with humans, subject to ethical and legal constraints. The work package will mostly deliver research papers and more fundamental knowledge. The activities are mostly conducted by PhD researchers and/or in matched EU and NWO research projects. To ensure knowledge exchange and collaboration between the several PhD researchers active in the ERP, we will support joint PhD meetings around a core ERP theme or AI capability and relevant Hybrid AI methods. *[Legal protection by design]* At the end of 2019 we will have a first idea of the challenges and potential solutions for legal protection by design of autonomous intelligent systems. In 2020 we will extend these results so to create a kind of contract-language by which the system would understand what kind of decision it can make autonomously (or not) in what situations. This so to accommodate a future solution on legal accountability as a system that did something unlawful either has violated the contract, which can then be verified, or has an invalid contract, when the contract was not violated yet something unlawful occurred. This activity will be conducted by a PhD researcher co-supervised by Prof. Mireille Hildebrandt (VU Brussels). *[Efficient learning]* We conduct two research projects. One researches algorithms to combine language and vision in multi-model deep neural networks; the other researches algorithms to model long-term temporal behaviour of tracks in videos. For both research goals, we will also study whether methods for Explainability developed in other projects of the ERP can be applied to the solutions for efficient deep learning. This activity will be conducted by 2 PhD researchers within the NWO Perspectief program on Efficient Deep Learning, a project of 24.5 FTEs (2 FTEs co-supervised by TNO which contributes 1/4th of the FTEs costs), matching 300 k€ over 4 years to the ERP Hybrid AI. One will be co-supervised by Prof. Cees Snoek (UvA) and the other by Jan van Gemert (TU Delft). TNO will also have the chair of the Advisory Board of the program (Klamer Schutte), allowing for a stronger strategic position in the consortium. *[Ethical goal function]* In 2020 we will continue our research on how an intelligent system can achieve goals defined by humans operating within ethical constraints, modelled through an ethical utility function. This activity will be conducted

	by a PhD researcher co-supervised by Prof. Peter Werkhoven (TNO/University of Utrecht). *[Enlarging trust in DL-based systems for image analysis]* This activity will be conducted in the context of the EU PADR-EMERGING Explorer project, a project of 600 k€, matching 430 k€ to the ERP contribution over 3 years. TNO DSS is leader of a consortium with FOI, SAFRAN, Oktal-SE, COSMONiO, ONERA, Fraunhofer IOSB. The overall objective of the EXPLORER project is to develop technology to make the ground-breaking results using Deep learning for image analysis in civil applications applicable in the military domain, where the number of training examples is limited, trust in the system is needed and adaptability to the today's conflict is key. The contribution of TNO for which ERP matching is provided focusses on the goals of performance assessment and trust. We will address the challenge of increasing trust in the system, by development of operational readiness scores and reliability assessment methods (self-assessment of the AI components). We will also research methods to explain the decisions of the system to the user, possibly adapting results from the Explainable AI project in 2019. [*Potential PhD projects*] Potential additional PhD projects that could be funded from this work package include: - on responsible and explainable AI, within the NWO call "HAPPY"; - on hybrid AI systems supervised by Prof. Frank van Harmelen (VU Amsterdam); we aim at a structural collaboration with the NWO Zwaartekracht Programma Hybrid Intelligence (https://www.hybrid-intelligence-centre.nl/) where Frank van Harmelen is one of the principal investigators and Mark Neerincx is one of the visiting researchers. **- WP4 (Inter)national collaboration** The objective of this work package is to support national AI strategies, (inter)national collaboration in the field of AI, AI standardization activities, and support of TNO AI strategy. The main activities are listed below. *[NL AI Coalition]* The primary objective of NL AIC is to realize a joint approach in the area of AI through a single national knowledge and innovation network. This will stimulate effective cooperation between the different research centers and prevent fragmented AI initiatives. The ERP Hybrid AI will fund activities to support the NL AIC. *[CLAIRE]* CLAIRE (Confederation of Laboratories for AI Research in Europe) is an initiative by the European AI community that seeks to strengthen European excellence in AI research and innovation. The ERP Hybrid AI will fund activities to support CLAIRE. *[NEN]* The ERP Hybrid AI funds participation in the NEN standards committee on AI that is concerned with determining the national standards for Artificial Intelligence. The standards committee participates in international standardization work, which takes place at ISO/IEC JTC/SC 42 Artificial Intelligence and follows European developments in this area. The aim of

	the participation in the NEN AI standards committee is to transfer the ERP Hybrid AI results on ethical and responsible AI into engineering standards.
Dynamics	The integration of the research efforts in 2019 across different research lines appeared quite challenging. The project Hybrid AI Systems was tasked to find common generic use cases to start drawing integrating (functional) architecture and subsequently to integrate the results, but this objective appeared more challenging than expected. The current projects inform each other thanks to (some small) overlap in team members and informative meetings, but the actual collaboration and integration of results has yet insufficiently taken place. For this reason, the main development in 2020 will be the restructuring of the program with a different work approach. We want to stress that in 2019 we have been struggling with two aspects concerning capacity management: - availability of talented junior and medior AI researcher, able to dedicate at least 1, possibly 2 days per week on research for our ERP. Despite having stressed this requirement in multiple settings with our internal stakeholders, the operational dynamics of some research departments involved have had priority on our requests, resulting in some cases in too large teams with too little room per colleague to work on a topic; - availability of experienced project leaders, able not only to steer the process on deliverables and objectives, but -importantly- to coordinate a research effort also at a content-level, with integration of efforts at least at the conceptual level; next year, WP1 and WP2 will pose even higher demands to the PLs, who will need to coordinate the integration also at the development level. The mentioned points are strong requirements for the success of the 2020 plan.

14 i-Botics

General information	
Title ERP	ERP i-Botics
Contact person TNO (ERP)	Jan van Erp, Nanja Smets
Contact person(s) government or topsector	
Programme 2020	
Summary	*Program* description Our society increasingly makes use of robots, at the workplace and at home. The robots at work or industrial robots can function with a high degree of autonomy, particularly when the task variability is low and the task environment is well controlled. But when performing operations in ever changing situations with unpredictable task constraints and task demands, a high degree of cognitive, perceptual, and motor skill intelligence and flexibility is required at a level not feasible with autonomous robots in the near future. That is where hybrid/ interactive solutions are needed where robots and people collaborate. i-Botics (interactive roBotics) focuses on optimal human-robot collaboration to conduct different tasks in the most challenging, unpredictable, and dynamic situations. These integrated robotic systems transport human senses, skills and cognition to a remote environment in real time and enable us to see, hear, touch and interact with physical environments and other people through a robotic avatar. TNO together with several public and private partners is competing in the ANA Avatar XPRIZE competition (avatar.xprize.org). This prestigious four-year global competition shares i-Botic's vision and will lead to the development of an Avatar System that transports a human's sense, actions, and presence to a remote location in real time, leading to a more connected world. The participation in this competition is a strong basis to apply the knowledge and technology developed in ERP i-Botics in relevant use cases. *Plan 2020* We are targeting the following results for i-Botics in 2020: 1) improved 2019 state-of-the-art demonstrator, with data on the effects of intuitive control, embodiment, while limited sensor data is available; Methods for smart information selection and task virtualization. 2) simulation models for exoskeletons that predict human body impact using task profiles, sensing and control algorithms for back and arm exoskeletons. The developed knowledge and technology aims to support mechanical workers in heavy, mobile and 'difficult to automate' situations and people with impaired motor functioning at home or work.
Short Description	Our goal for 2022 is to have the scientific knowledge required for designing integrated interactive robotic systems: **(1)** Telepresence systems that remotely enable us to see, hear, touch and interact with physical environments, breaking the barrier of distance. We focus on a bimanual, human-controlled robotic system for inspection, repair, and maintenance tasks.

(2) Wearable robots and flexible robotic suit systems for mechanical support.

According to SPARC[6], the interaction between robots and people will grow over time. Industrial robots can function with a high degree of autonomy when the task variability is low and the task environment is well controlled. However, high degrees of generic or universal autonomy are (technically) impossible to achieve in the near term and may even be undesirable in some situations. Examples include tele-inspection, tele-maintenance and tele-problem solving, and tasks where high variability requires human manual and decision making skills and thus a human-robot interface that enables full employment of these human capabilities. This goal dictates the essential robot capabilities and desired knowledge/technology targets, listed below following the definitions of SPARC:

Configurability	Tailor-made, plug and play configuration of robot and human-robot interface
Adaptability	Real time adaptation to human-state, task, and remote environment
Interaction	**Intuitive**, non-obtrusive and compliant **interaction** using **remote environment virtualization**
Manipulation	Synchronous motion and **haptic feedback** through an **wearable robot** for bimanual control
Perception & Cognition	**Telepresence** perception and feedback though (robot)**body ownership**
Operational and social embedding	Efficient, accepted, safe and healthy system

This ERP will focus on the following technology targets[7]:

(1) intuitive interaction using remote environment virtualization
(2) bimanual control with haptic feedback through a wearable robot / exosuit or advanced force feedback devices
(3) telepresence through (robot)body ownership
(4) Wearable robots / exosuits for mechanical support

Intuitive interaction using remote environment virtualization
Approach: create a full, multisensory virtual representation of the remote environment which makes interaction independent of communication channel capacity and quality and enables adding virtual elements to assist the human operator. Important aspects include: sensing and reasoning about the remote environment, integrating different sources of information, and building a multisensory virtualisation (vision, audition, touch).

Bimanual control with haptic feedback through a wearable robot / exosuit or advanced haptic feedback devices
Approach: use exosuit technology or comparable technology to track the operators intentions and actual motions to control the two arms and end

[6] The SPARC roadmap (The partnership for robotics in Europe): http://sparc-robotics.eu/
[7] Please note that partners in the Joint Innovation Centre i-Botics focus on other targets.

	effectors (i.e. hands or grippers) of the robot and display haptic and tactile information about the remote environment provided through robotic sensors and/or the virtual control layer (see under virtualization). Important aspects include: sense motor intention and actual movement, scale forces and kinematics from robotic system to operator, substitute essential haptic and tactile cues depending on human interface device, and reduce the strain and increase the comfort of exosuits. *Telepresence through (robot)body ownership* Approach: provide cues to evoke ownership of the robotic device so the operator can behave and perform as if being present at the remote location without 'thinking'. Important aspects include: boundary conditions of (the illusion of) (robot)body ownership, vulnerability for mismatches between the (form, size, capabilities of the) robot and the operator, and effects of ownership on performance and workload. *Wearable robots / exosuits for mechanical support* Current exoskeletons need improvement in usability, effectivity and comfort. New research and innovation efforts aim for soft exoskeletons or suits rather than rigid structures. For mechanical support applications these systems should also be adequately tuned. For example, they should adequately scale forces imposed on the suit by the user, to forces that the exosuit applies on the to be manipulated object.
Results 2020	*Intended results and deliverables* 1. A state-of-the-art demonstrator developed in 2019 for tele-manipulation will be improved next year. More experiments with respect to intuitive control and embodiment and its effects. Also it is important to know how to deal with limited sensor data availability when tele-operating. Smarter information selection, processing and sensors are part of the focus together with using virtualization for this task. 2. Simulation models for exoskeletons, this will make it possible to make prediction for human body impact using task profiles. Next to sensing and control for back and arm exoskeletons. *Parties (to be) involved and links to roadmaps and knowledge agendas* By request of the Dutch government (through the Ministries Ministry of Infrastructure and Water Management, Economic Affairs and Climate Policy, Justice and Security and Defense) TNO is competing in the ANA Avatar XPRIZE competition (avatar.xprize.org). This prestigious four-year global competition focused on the development of an Avatar System that will transport a human's sense, actions, and presence to a remote location in real time, leading to a more connected world. The participation in this competition is a strong basis to apply the knowledge and technology developed in ERP i-Botics in relevant use cases. TNO has formed the i-Botics Avatar XPRIZE team, consisting of leading institutes and high-tech solution providers: University of Twente, ETH Zürich, Halodi Robotics, Haption and Sensiks. With this team TNO / i-Botics aims to develop a universal cockpit and two robotic twin avatars to win the XPRIZE Avatar competition. By using a universal, modular and generic approach i-Botics strives to have major impact on the full field of remote controlled robotics.

	The i-Botics avatar concept is based on a Universal Cockpit from which an operator can control a variety of avatars. The Universal Cockpit will be able to provide the operator with a full immersive experience on multiple modalities (senses) by combining several breakthrough, emerging and novel technologies in one integrated system. The modalities available to the user will be visual perception of the environment, haptic force feedback, motion feedback, tactile feedback, (bi-directional) audio, temperature sensation, smell sensation and even superhuman senses. The multitude of modalities available to the operator is what will make this control cockpit universal, not focusing on one specific problem, but applicable in a vast amount of use-cases. The solutions developed by the i-Botics Avatar XPRIZE team will be widely applicable and form the backbone for numerous follow-up projects and valorization. A market exploration has been performed by XDELFT and by TNO in order to identify relevant and high potential applications of the i-Botics Avatar solutions in multiple domains such as: National Security, Defense, Healthcare and Inspection and Maintenance. There is a close connection to multiple Topsectors, Missions and "Vraaggestuurde Programma's". The program is linked to the goals of the topsectors HTSM, Logistics and Life Science and Health. iBotics and Avatar XPRIZE have external connection with the KIA 'Veiligheid' 2020-2023 and its mission 'Samen sneller innoveren voor een adaptieve krijgsmacht'. In this mission the spectrum ranges from remote/ tele-operation/ man-machine interfacing to fully autonomous AI systems. i-Botics is also closely linked to MoD research programs (doelfinanciering) V1719 on 'Behavorial Impact of Humans – Nonhuman-Intelligent-Collaborators Teaming and V1717 project on telemanipulation for Countering IED and EOD applications. This ERP is closely connected to the Joint Innovation Centre i-Botics. Besides the founding knowledge partners TNO and University of Twente, public and private parties are actively involved including Boskalis, Shell, Rijkswaterstaat, and ProRail or expressed their interest in one of the use cases such as Bosch, Moog, Teledyne, SAAB, Thales, various Law Enforcement Agencies, Demcon, IHC, A-Hak, and KLM. i-Botics collaborates with other national platforms, including Holland Robotics, SPRINT Robotics, RoboValley, LEO Robotics, Space53; RoboHouse. NWA connections are evident with the Energy Transition, Smart Industry, Logistics, water / Blue Route, and health care routes. International collaboration and coordination of activities are in place with SPARC Robotics. i-Botics is also part of the Digital Innovation Hubs medical robotics and Inspection and Maintenance Robots (RIMA).
Dynamics	i-Botics started in 2018 as a full ERP project and is running for 1 ½ years now. The workplan for 2019 incorporates the latest i-Botics Technological Roadmap. XPrize Avatar is mentioned in the 2019 plans and we foresee no major changes in that relation to the targets or the planning.

15 Organ on a Chip

General information	
Title ERP	Organ on a chip
Contact person TNO (ERP)	Evita van de Steeg, Ivana Bobeldijk
Contact person(s) government or topsector	
Programme 2020	
Summary	*Program description* Over the past few years, the development of alternative, more physiologically relevant human cell based *in vitro* models has evolved. These so called organ function-on-a-chip models are designed to better mimic tissue function and architecture than conventional single cell based models. With these models, it will be possible to study relevant biological mechanisms and disease mechanisms. Moreover, organ function on-a-chip models provide a promising approach to solve translational issues that are evident in not only the pharmaceutical industry, but also the nutritional, chemical, environmental and cosmetic industries. The ultimate goal of organ-on-a-chip models is mimicking human (patho)physiology of specific organs within an *in vitro* system which has simple readouts. Science and in particular drug development can greatly benefit from human functional organs-on-a-chip technologies, both in terms of reliability of results and in costs. The challenge is to bring the models to a next level, with proven added value for science and industry: organ-on-a-chip for human diseases, long term exposure, patient-derived stem cells, providing an unique opportunity to discover personalized human drug targets, related to the underlying genetic background of the patient and to test and select the specifically designed medicines. The main goal of this ERP is to contribute to the development of stratified and/or personalized interventions by developing the concept of population on-a-chip. By 2023 we will develop a (stem-cell based) in vitro pre-clinical toolbox with integrated readouts, enabling the introduction of population variability earlier in drug development. This will enable development of precision medicine, support selection of drug candidates effective for specific group of patients and improve the design of clinical trial by pre-selecting patient groups already in a preclinical phase. Moreover, this will significantly reduce animal testing in preclinical development. *Plan 2020* Deliverables for 2020 will be several validation and implementation tests of specific elements of the established organ on-a-chip models (gut and liver) conducted both for pharmaceutical and nutritional applications. Integration of on-line read-out technologies of these models will continue. In addition, we will work on the connection and combination of the individual models, gut and liver, supported by mathematical modelling to translate the in-vitro results into results in humans.
Short Description	The objective of the ERP ‘Organ on chip program’ in 2019-2022 is to improve the development of better predictive, more physiological (personalized) human stem-cell based *in vitro* models that will enable

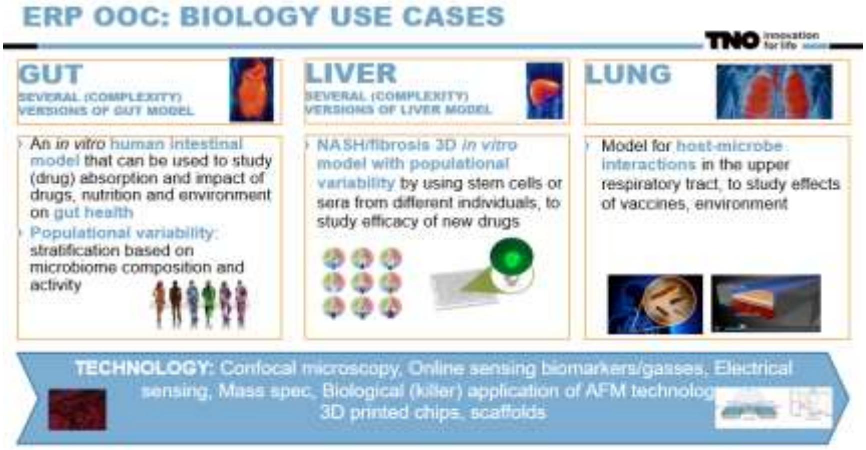
'population on-a-chip' development. We distinguish so called "**organ function on-a-chip models**", which are complex, multicellular (stem cell based) microfluidic models representing functionalities of a specific organ, and the concept "**population on-a-chip**", in which these organ on-a-chip models are expended to study interindividual and populational variation by application of stem cells from various individuals and combination of healthy donor cells with individual sera or microbiota. With these models we will help pharmaceutical industry to lower the attrition rates in drug development, thus lowering the development costs and time to market as well as help both pharmaceutical and food industry to develop stratified and in the end personalised interventions for treatment of different metabolic and immune health dysfunctions.
Our program focuses on tissues and disease areas in which TNO has extensive knowledge, experience, and market position ("right to play"), and develops validated applications relevant for pharmaceutical and nutrition industry.

We focus mainly on liver and gut as organs as well as host-microbe interactions in lung. In addition to these biology use cases, a third line of the ERP focuses on the development of state-of-art organ on-a-chip hardware and readout technologies, for applications within the focus use cases, but also applicable for other organs and disease areas, in collaboration with external collaborators or via licensing.

Goals for 2022/23

Technology that is and will be developed will be embedded in Roadmap Biomedical Health by 2021. The combined achievements will be :

- Partnership with at least 2 top 10 pharmaceutical companies for application of the developed better predictive preclinical models (organ function on-a-chip models) for drug efficacy or toxicity screening in order to select the right drug candidates and reduce attrition rates
- Together with at least 1 pharmaceutical company TNO has demonstrated the reduction of testing therapeutic interventions in animals by application of better predictive in vitro models
- Together with at least 1 industrial partner TNO has demonstrated the added value of the concept of population on-a-chip technology for early screening of (populational variability in) drug efficacy and/or kinetics
- TNO Organ-on-a-chip technology is used to test the (negative) effect of environment and/or lifestyle on human health
- TNO has developed an organ-on-a-chip based technology platform enabling drug development for tomorrow's medicines



1. Gut

Within the use case gut function on a chip we aim to develop and implement advanced in vitro human intestinal models that can be used to study drug absorption and the impact of drugs, nutrition and environment on gut health. In 2020 we will have a first version of population on a chip (and the corresponding clinical responses like drug absorption, metabolism and efficacy) based on microbiome composition and activity and the interaction with gut epithelium and by 2021 we will be applying it in B2B projects and large research projects. By 2022/23 we will have combined gut with other organs, such as liver and kidney for new applications.

2. Liver

Within the use case liver function on a chip we focus on addressing patient variability already in preclinical efficacy screening using advanced cell models. The approach will be by using stem cells from more individuals (mimicking the population variability in the clinical trial phase) or by using serum from individuals/patients and primary hepatic cells. By thorough characterization of the disease pathways using the signatures and knowledge on disease mechanisms developed in Roadmap Biomedical Health, we will be able to define patient subgroups and select the right drug for the right patient using our models, by 2021. By 2023, we will be applying the liver model in combination with gut and kidney, for new applications.

3. Lung

For lung, we do not develop a TNO model on a chip, we collaborate with LUMC and use their lung-on-a-chip model. We add our expertise of the microbiome of the upper respiratory tract and together co-develop a model for lung host-microbiome interactions. TNO is developing specific protocols for DNA isolation from very small samples that are needed for these specific applications. The applications of the model will be for example in vaccine development, where human pre-clinical models are essential.

4. Technology

The technology line focuses on the development of state of the art organ on-a-chip hardware which can easily be used in industrial applications (cell culture scaffolds, tissue slices), and which will enable the organ on-a-chip and population on-a-chip applications. We focus on both read-out technology / online detection of biomarkers needed to support and further develop the selected use cases gut and liver, and on smart hardware which enables organ (on chip)-organ (on chip) interactions and the integration of human tissues in OoC. The detection technology is also

<table>
<tr><td></td><td>applicable in other (disease) areas as well as measurements of environmental exposure (link to ERP Exposense and Roadmaps CEE), and we develop advanced readouts with AFM. By 2021 we will have the technology needed to support the GUT and Liver applications, by 2023, we will have increased throughput by including robotics and mathematical modeling.</td></tr>
<tr><td>Results 2020</td><td>Summary of main deliverables of the Organ on a chip Early Research program is shown in the figure below and outlined in the following text.

1: Gut function-on-a-chip in 2020
Within the “gut-function-on-a-chip” program we will combine biological and technical expertise and develop a predictive humanized *in vitro* model of the gut to study the impact of drugs, nutrition and environment on gut health. The developed model will mimic important gut characteristics, such as structure, microbiota and absorptive and secretory functions. The model will be developed by applying intestinal stem cells (isolated from human intestinal crypts) and/or human ex vivo intestinal tissue segments (InTESTine) inside novel microfluidic chips to mimic luminal and blood flow.
The developed model will be applicable for combination with microbiota derived from healthy or diseased (e.g. IBD, obese, diabetic) people in order to study (personalized) interactions between intestinal microbiota, gut epithelium and immune system in health and disease. We aim to be able to stratify patients (and their clinical responses like drug absorption, metabolism and efficacy) based on microbiome composition and activity and the interaction with gut epithelium and immune system.

Deliverables 2020:
✓ Validation report of gut model based on human intestinal organoids on-a-chip,
✓ Gut-on-a-chip with aerobic and anaerobic compartments
✓ Gut-on-a-chip coupled with mass spectrometry
✓ Coupling gut-microbiome-liver on a chip

2: Liver function-on-a-chip in 2020
The “liver-disease-on-a-chip” will be a predictive *in vitro* disease (i.e. non-alcoholic steatohepatitis; NASH) mimicking model using co-culture of human pluripotent stem cell-derived hepatocytes or primary hepatocytes</td></tr>
</table>

	and stellate cells on an *in vitro* 3D cell culture platform that will have its application in testing the effect of compounds on the disease prevention, development and / or disease resolution. The combination of disease, materials, stem cells, system biology and read-outs is challenging and will be a base for broader applications towards preclinical stratification strategies ("population on a chip") and a personalized health approach. In 2020 we will make next steps towards population on a chip by adding human serum as the personalized aspect to the model and transfer the 3D-triple-cell co-culture liver model we developed onto a chip design with microfluidics. *Deliverables 2020:* ✓ Demonstrator that co-culture models using sera from different individuals show variation in response on disease induction ✓ Validated model liver on a chip by using positive and negative controls, eg. drugs that stimulate or reduce the formation of the biological processes of interest (steatosis and fibrosis)Liver model based on stem-cell derived hepatocytes ✓ Feasibility study to demonstrate gut-liver axis in NAFLD-NASH pathophysiology **3: Readouts, microfluidics main activities in 2020** We develop standardized organ on-a-chip hardware and scaffolds for easy, accepted and general use within industry, with the focus on the population on-a-chip applications. We will develop integrated and novel readouts for (semi) continuous monitoring of the experiments. We will do this together with, or based on our experience with, current chip or microfluidic equipment providers, close collaboration with end-users and academic partners. *Deliverables 2020:* ✓ Microfluidic chip with general 'click-in system' for tissue, general scaffolds, with integrated liver and gut ✓ New chip (4-in-1) for higher throughput and easier use ✓ Integrated TEER and oxygen sensors in the chip ✓ Higher throughput microfluidic pumping system ✓ First version of mathematical model to translate results from chip to human ✓ Refined method for analysis of physical-mechanical properties of cells with AFM and translation to cell stress ✓ Protocols for mass spectrometry analyses as (on-line) readout for gut and or liver on a chip ✓ Refined protocols for microbiome analysis from lung-on-a chip models ✓ Demonstrator of host-microbiome interaction in lung **Dissemination, communication and transfer to Roadmaps** In 2020, we will focus on the following knowledge transfer and dissemination activities (outcomes) of the ERP results: ✓ Plan on technology embedding in Roadmaps, IP strategy ✓ Program management, internal and external communication, reporting ✓ PR material: presentations, website update, animations, graphics, LinkedIn posts and discussions ✓ Grant submission coordination ✓ Hosting of at least one hDMT meeting

Internal and external collaboration

This program will only be successful if we are in collaboration with the experts from other Units.

In many cases collaboration has already been realized, through collaboration within the projects in 2017-18. This ERP also has links to Early Research Program Personalized Food and seed ERP's Bio Nano and ExpoSense.

External collaborations, planned and current are summarized in the figure below.

External connections

This program is linked to the knowledge agenda of the top sector LSH. It aligns well with two roadmaps and two gamechangers:

Roadmap 4 Regenerative medicine: Developing curative therapies for diseases caused by tissue damage and ensuing organ dysfunction, through repair or renewed growth of the original tissue, or its replacement by a synthetic or natural substitute.

Roadmap 5 Pharmacotherapy: Discovery, development and deployment of new, safe and cost-effective personalized medications in order to cure or prevent progression of a disorder or disease.

<table>
<tr><td></td><td>NWA route Personalized Medicine: ..'Each individual should, if desired, be provided with reliable information on his or her own health status, in order to make informed choices of as effective and affordable interventions as possible….'.
NWA route Regenerative medicine: a game-changer moving to broad areas of application. Regenerative medicine offers opportunities to repair damaged tissue and organs without resorting to transplantation, to test drugs without using laboratory animals, and to customize drugs to a specific patient.
Game-changer 'Exposome' Quality of the environment:. To develop prevention measures for the health effects of pollution and environment, we need to know more about combined exposures and the revolutionary concept of the 'exposome' integrates all these environmental factors.
Economic Affairs goal "Nederland wereldleider in proefdiervrije innovatie in 2025"
The applications of the models developed within our program will contribute to the missions defined by LSH: Mission I (Lowering the effects of unhealthy environment and unhealthy lifestyle on human health) and Mission III (25% increase in the participation in the society of people with chronic diseases). Our models will be used to test health effects of environmental and lifestyle exposures, help with efficient drug development, contribute to knowledge of disease mechanisms and help to develop personalized interventions.

Apart from being linked to the Knowledge Agendas of top sector LSH this program also links to hDMT (a strategic PPS, national initiative in the area of organ on chips technologies, TNO became partner in 2016), IVTIP (In vitro testing industrial platform), and has good connections with policy makers at ZonMW and Maag Lever Darm stichting.</td></tr>
<tr><td>Dynamics</td><td>Over the last 3 years, the ERP Organ function on-a-chip evolved from a seed ERP (2015) into a full ERP (in 2017).

The program started with three use cases: gut-, liver- and lung-function on a chip, and for all three subprograms important technical developments as well as ecosystems development were achieved in 2015-2018, see figure below.
In 2017, development of a lung model was discontinued, after a negative business case evaluation early 2017. The ERP is now focused on medical and food applications, for gut and liver. We are not building a lung on a chip model, we are setting up a collaboration with LUMC and</td></tr>
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	Emulate, the leader in lung models, to which we will contribute with our expertise on host-microbiome interactions. We aim to become a collaborator in the European test site of Emulate @ LUMC. The lung function on a chip will open new extra opportunities in collaboration with the ERP ExpoSense. In 2019 we focused on the development of a 3D 3cell co-culture liver model based on primary liver cells, rather than continuation of the work with stem cells. This was due to maturity issues of the cells (identified by the provider, but a problems with these types of cells worldwide). Many academic groups are working on this at the moment and we hope to start development of the stem cell model in 2020. By hiring an additional postdoc, we were able to make significant progress in cell imaging and developing a suitable chip system for liver. For technology, in 2017 we started the development of several readout and imaging technologies that will be implemented in the two use cases, and we decided to further develop our own chip, rather than co-develop with Micronit. This was because the Micronit system does not offer sufficient stability and sufficient possibilities to scale up. In 2019 and 2020 we will explore possibilities of collaboration with Fluigent Biosystems in collaboration. We started a collaboration with M4I in Maastricht and will be co-developing on-line readout technologies for our applications, mass spectrometry detection amongst others. In 2020 we will continue the validation of the developed chip models and gradual transfer of the Organ on a chip development and validation activities into Roadmaps. For this, in 2019 we already had two small B2B projects where we applied the first versions of the models, in 2020 and 2021 we aim to generate sufficient opportunities through participation in consortia for grant requests (NWA call, EU projects, ZonMW, TKI and others, some of them already submitted, or will be, in 2019).

16 Personalized Health

General information	
Title ERP	Personalised Health
Contact person TNO (ERP)	Marjan van Erk
Contact person(s) government or topsector	
Programme 2020	
Summary	*Program Description* Currently, our society stimulates citizens to live an unhealthy life resulting in chronic (preventable) lifestyle-related diseases and our healthcare system is equipped to “take care” of health problems and diseases. Especially for lifestyle related diseases, evidence is mounting that lifestyle changes have a profound effect on disease progression and even disease cure is possible. Changing lifestyle is difficult; personalization, i.e. tailoring to an individual’s needs and preferences, is an important factor for achieving sustainable healthy lifestyle habits. In the ERP Personalized Health we develop biology and research methodology innovations for personalized health optimization. The innovations in this ERP are pivotal in the envisioned disruptive change that will result in a higher quality of life and lower healthcare costs. The innovations from this ERP PH program will land in future PPS projects that will implement personalized health innovations in real-life. With regard to biology innovation we focus on one of the major driving mechanisms for lifestyle-related disease: inflammation, and specifically, on the value of challenge tests to identify instability in this mechanism. We consider the roles of different tissues and the mycobiome using model systems. Moreover, we research how we can reprogram inflammation or optimize inflammatory resilience. With regard to research methodology innovation: In order to bring together all knowledge and data and connect this to the needs of citizens, personalized health advice models are developed. These models will be based on data (Bayesian) as well as knowledge (system dynamics). This is intertwined with activities and innovations in ERP Applied AI. We will build a prototype community to investigate its value in empowering citizens and patients in their lifestyle changes. Within this community, behavioral change innovations are combined with innovations in data collection and volunteer study methodology. *Plan 2020* In 2020 we will prepare for the further integration in a proof-of-concept study (in 2021) of the various parts that are being developed in this ERP. Deliverables in 2020 will include the further development of markers and new personalized intervention strategies to optimize low-grade inflammatory resilience. The Personal Health Advice System will incorporate the knowledge on chronic low-grade inflammation and socio-psychology collected in 2019/2018. In addition, a prototype health market data place will be tested.
Short Description	ERP Personalized Health develops biology and research methodology innovations for personalized health optimization.

	Lifestyle related diseases are to a large part preventable, reversible and curable. The important overarching processes that underlie these diseases are disturbed metabolism, low-grade inflammation and oxidative stress. The previous ERP (PF) focused on metabolism and resulted in a systems and personalization approach towards metabolic processes. This established TNO as world leading with our personalized intervention strategy, as was illustrated by the fact that Habit/Campbell selected TNO as a strategic science partner for their product development. ERP Personalized Health focuses on low-grade chronic inflammation, another fundamental process in the development of chronic lifestyle related diseases. This ERP will consider the role of the mycobiome (symbiotic fungi) as one of the keystones in this process; this is another innovation in which TNO is a front player. The biology innovation in this ERP is targeted towards elucidation of curbing low-grade chronic inflammation by lifestyle modulation. We are building the biological basis for prevention, reversal and cure for diseases with a chronic inflammatory component (WP1 of the ERP PH). The PhenFlex challenge test technology (as developed by TNO) is included in this innovation and further adjusted to inflammation. Human studies have shown that the PhenFlex challenge test allows for detection of disturbed inflammatory resilience via quantification of dynamical inflammatory response profiles. Moreover, these studies have shown that a disturbed mycobiome may also be an important factor in low-grade chronic inflammation. By 2022, we will have developed new personalized intervention strategies to measure, train and thereby optimize inflammatory resilience. In combination with earlier developed personalized metabolic interventions the aim will be to prevent, reverse and cure lifestyle related diseases. Within this ERP, the combination of metabolic knowledge with innovative knowledge and application of inflammation will take the personalized systemic approach of health optimization to a next level. To achieve personalized health optimization, research methodology innovation is essential. In this ERP, we focus on development of state-of-the-art technology and connect these innovations to the Personal Health Advice System (PHAS), which is focused on lifestyle related health. By 2022 we aim to develop a set of concepts and building blocks for a world-leading personal health advice system (PHAS) for all aspects of lifestyle related health and diseases (WP2a of ERP PH). New compared to the previous ERP PF, that mainly used knowledge-based advices, is 1) the innovative way to combine biological, behavioral and socio-psychological diagnostics and interventions in one system and 2) the new modeling techniques. The new models can be applied on the individual level, as well as within communities. They are self-learning and hybrid; i.e. partially knowledge-driven and partially data-driven. The system uses “content” (knowledge, rules, models developed in WP1 and WP2b) in an architecture to collect and manage user data. The PHAS system services as a generic backbone for multiple digital techniques that provides diagnosis, advice and support and monitors behavioral change to improve and maintain a healthy lifestyle, both directly to patients/citizens and to healthcare professionals. A key factor for success of personalized health optimization is for patients and citizens to be in control over personal health(care) data. Within this ERP, we build the fundaments in order to initiate, facilitate, and to test “personal health data valorisation” in a prototype research and health community that empowers citizens to achieve a sustainable lifestyle change. Key here is citizens empowerment through ‘personal health data

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<td>valorization’ via community driven health data marketplaces, which will be in place by 2022 (WP2). Simultaneously, we will include the system around the citizen by setting-up the building blocks for systems-based behavioral change tooling. Our initial use case is type 2 diabetes (T2D) patients and their communities. By 2022, this will have resulted in a systems toolbox for sustainable behavioral change exploiting bio-socio-psycho-environmental aspects (WP2b of ERP PH).

Thus, we target an important underlying cause of disease (inflammation), we build self-learning computational advice models, and provide that directly to persons using digital techniques who in return provide new input data for personalization and improvement of these models.</td>
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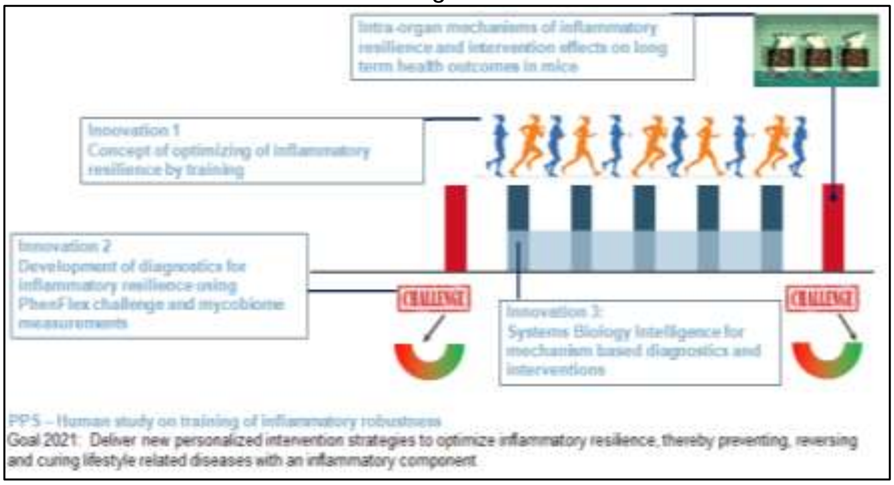
<td>Results 2020</td>
<td>WP1 – Biology innovation: towards inflammatory mechanism and robustness
WP1 will obtain knowledge about new personalized intervention strategies to optimize low-grade inflammatory resilience. The figure below represents the knowledge and innovation areas that WP1 aims to develop for the coming period within ERP Personalized Health.
Following the ERP, a new public private partnership (PPS) will implement the technology and knowledge developed in WP1 in a human volunteer study. This study will focus on training of inflammatory resilience as a strategy or treatment to improve low-grade inflammation. Before starting up a PPS the following technologies need to be developed: 1) Diagnostics for inflammatory health based on mechanism based biomarkers. 2) Proof of concept in in vivo mouse models that inflammatory resilience can be trained and that low grade chronic inflammation can be reversed. 3) a human study design developed to train inflammatory resilience with defined interventions in order to reverse low grade inflammation.


In 2019, WP1 activities focused on the following innovations:
Innovation 1: Concept of training of inflammatory resilience.
A review paper has been published named ‘Current and Future Nutritional strategies to modulate inflammatory dynamics in metabolic disorders’ in frontiers of nutrition introducing the concept of training of inflammation.
Innovation 2: Development of new sophisticated diagnostic methods to quantify inflammatory resilience.
A selection of TNO’s portfolio of miniaturized assays for inflammation was applied in human samples of young, old, lean, obese and type 2 diabetics</td>
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(5040 analyses performed!). Also mycobiome measurements have been performed in different metabolic disorders.
Innovation 3: Systems Biology Intelligence (SBI) pipeline for mechanism based diagnostics has been developed and automated
Innovation 4: Mechanistic unraveling of reversal of organ-inflammation through lifestyle interventions in mice. We gained new knowledge on the mechanistic rationale for the observed effects: why liver inflammation was very strongly reduced by both healthy diet and exercise and why adipose tissue inflammation was partly reduced by either healthy diet or exercise without an additive effect.

In 2021, we will conduct a proof-of-concept study to test integration of the various parts, technologies and knowledge that has been developed during this ERP.
In 2020, the focus within WP1 biological innovation will be on the further development of markers and new personalized intervention strategies to optimize low-grade inflammatory resilience. The biomarkers that already have been identified during this ERP, will be tested in suitable (already conducted) human intervention studies. Bioinformatics tools will be used to identify nutritional analogous of compounds that have been selected using in the mycobiotic iScreen methodology. We will write publications on results from 2019 and preparation will take place (protocol, recruitment) for the proof of concept study that will be conducted in 2021.

In 2020, these are the intended results and deliverables for WP1:

- Publication on Proof of concept of reversal of organ inflammation through life-style interventions in mice (based on results of 2018/2019)
- Innovative biomarker panel (1-10 biomarkers) to be applied on samples from a conducted intervention study (e.g. intermittent fasting study led by Hanno Pijl) or suitable (cohort) study, aiming to test the concept of training of inflammation.
- Publication on Systems Biology Intelligence (SBI) pipeline for biomarker discovery in a peer-reviewed journal.
- Identification of compounds for modulating inflammation by applying the Mycobiome screening technique and the SBI platform.
- Identification of novel nutritional analogues by applying TargetTri tools using the compounds from the Mycobiome and SBI platform as input for new intervention strategies.
- Draft protocol for the PoC study integrating WP1 and WP2 knowledge and technology (to be conducted in 2021).

WP2 – Research methodology innovation:
Our society allows and even stimulates its citizens to live an unhealthy life and has created a healthcare system that is ready to “take care” of the resulting diseases. In WP2 we develop building blocks for innovations in research methodology in order to disrupt the present system. Realizing a system change, requires personalized strategies promoting behavioral maintenance of individuals (focus in 2018), as well as a focus on (health) communities (virtual GROZzerdam [Kennis-en-innovatie-agenda 2020-2023]) as a whole (2019). The central concept in both foci is empowerment through personal health data valorization, which enables individuals and community to take control over their own lives and communities. Also in

	WP2, we will explore and exploit community driven health data marketplaces, which are key for personal health data valorization. WP2 has 3 focus areas: Personal Health Advice system (2a), health communities and sustainable behavior change (2b) and health data valorization – fair trade of personal health data (2c). WP2a. Personal Health Advice system WP2a will develop a set of concepts and building blocks for a world-leading personal health advice system (PHAS) to support citizens in maintenance of lifestyle related health and prevent/cure diseases. This PHAS combines biological, behavioral and socio-psychological diagnostics and interventions in one system. In 2020 we will incorporate in PHAS the knowledge on chronic low-grade inflammation and sociopsychology collected in 2018/2019. In addition, we further develop related ontologies, ontology-based reasoning and will consider different modeling techniques for a world-leading PHAS in collaboration with the ERP applied Artificial Intelligence (ERP aAI). In the first two years we have built upon earlier research on T2D, using the data, models and knowledge to deliver a technical demonstrator, using the TNO Diamonds platform and a smartphone app (iOS and Android). This demonstrator has been implemented and further improved in the PPS 'T2D Health Data Community' that started in July 2018. The core of PHAS is composed of a time-based predictive model for personalized health trajectories related to T2D and predicted required interventions to prevent these trajectories. In 2020 this system will be further tailored towards the knowledge derived from WP1 around inflammation markers and interventions for inflammation resilience in preparation for a proof-of-concept (PoC) study in 2021. For this we will further develop ontologies and incorporate ontology-based structured reasoning for knowledge on nutrition and behavior in PHAS. In 2020 this will also be applied for the behavioral models that have been defined in the distillation and matching model (see WP2b below). ERP aAI will develop the fundamental mechanisms of ontology modeling while this ERP develops the biological knowledge to fill these ontologies and models. In 2019, a pilot to use smartphone collected data in training of our system, federated learning capabilities was developed. In 2020 federated learning capabilities will be developed further in close collaboration with the ERP aAI to be able to train models on personal app data without challenging privacy. In 2020, WP2a will extend the work from 2018-2019 with the following intended results and deliverables: • Ontological representation of inflammatory knowledge and expected data for PoC study • Development of Hybrid (knowledge - data driven) predictive models for supporting PoC study • Test feasibility of deduction of possible personal interventions from the models • Prepare the model to become self-learning, i.e. update the model based on data from the PoC and real-world data WP2b. Health communities and sustainable behavior change In 2020 WP2b will extend the work of 2018-2019 on effective behavior change techniques (BCTs) aimed to promote personalized, sustainable

lifestyle interventions. In 2018-2019 we have identified core behavior change techniques and developed a distillation and matching model (D&M model) for the systematic design of tailored interventions. The D&M model advices on key strategies based on identified behavioral and socio-psychological barriers. The D&M can be a key driver for the PHAS. In 2020 we will extent the work in two ways:

First, we aim to test and finalize the D&M model (2.0) based on input gathered from experimental users, and by inclusion of implicit behavior change strategies (strategies specifically targeting behavior automaticity).

Second, we aim to determine the most optimal intervention for a single participant.

Although the advice system is tailored to the personal situation, most of the behavioral intervention content is based on between-group comparison data. The problem here is that even when, on average, a BCT may be effective, taking into account differences within a group, some people may have no or even negative effects in response to the same intervention. In order to be able to provide fully personalized interventions requires within-person designs, which can be used to understand the behavioral trajectories of a person, as well as the effectiveness of a particular BCT for that person. Thus, we require another type of design, where the focus is not on the size of the sample, but on the amount of observations per individuals (and where the comparison is the individual; so called N-of-1 trials).

This WP2b will start individual-level experiments, in which a selected group of people will receive individually tailored lifestyle advice, based on biological, behavior and psychological intervention methods in time. To understand both predictors of behavioral maintenance (weight loss, physical activity) for a particular person and the effect of a particular intervention we need intra-individual level data. Therefore a small set of people (N = 10) will be followed intensively. For this subset, a selection of interventions will be derived from the D&M model in combination with various measurements – collected through EMA (Ecological Momentary Assessment; applied in TNO's HowAmI -App), activity tracker, connected scales, food intake technology.

Intended deliverables for WP2b in 2020:

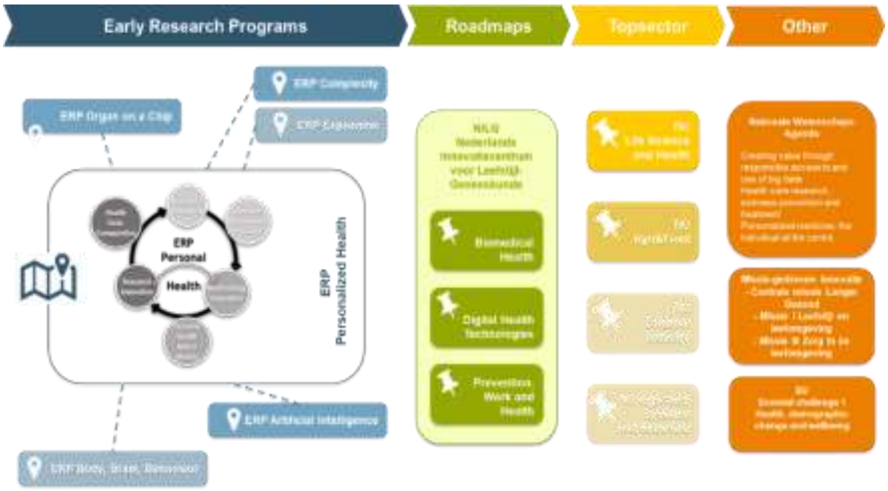
- Publication on technology acceptance of the individual advice system for DM2 patients (based on the work of 2019)
- Updated DM model 2.0, that will be made available as interactive eTool.
- Proof of concept of N-of-1 trial for personalised behavior interventions

WP2c. health data valorization – fair trade of personal health data (2c)

The focus of WP2c is on personal health data valorization. The future of personal health data valorization will be via community driven health data marketplaces (https://www.futureofpatientdata.org/). In 2019 we addressed the important questions in which way citizens and patients can be convinced to make use of such health data marketplaces and identify ethical, economic and social obstacles. In addition, a community framework was established that can be used for community organization and building. In 2020 the knowledge obtained from these activities will be applied in a prototype health market data place that will be set up in close collaboration with digi.me, a partner that is able to create an infrastructure where patients are able to store personal health data in a secure way. The community framework, the consent knowledge and sharing knowledge from WP2c in 2019 will be used to build this health data community with the aim to valorize health data. The use case for this health data marketplace could be testing of the prognostic models that are developed during in WP2a. Again the knowledge derived from this pilot will be used for defining the PoC study that will be conducted together with WP1 in 2021.

Intended deliverables for WP2c in 2020:

- A scientific paper about the legal/ethical aspects of a (community driven) health data marketplace
- A Proof of Concept health data marketplace around a small (10-20) number of patients.



External connections
ERP PH interacts and collaborates with ERP Applied AI, ERP ExpoSense, ERP Organ-on-a-chip and ERP Body Brain interaction. Output of ERP PH is absorbed in VP Biomedical Health (including new PMC Prevention 2.0), Digital Health Technologies and Prevention Work and Health. Furthermore, this ERP is linked to the Netherlands Innovation Center for Lifestyle Medicine (NILG – www.nilg.eu, founded by TNO and LUMC).

ERP Personalized Health connects very well with several routes of the NWA:
025: Creating value through responsible access to and use of big data
006: Health care research, sickness prevention and treatment
017: Personalised medicine: the individual at the centre

The research focus of ERP PH contributes to the central mission 'Langer gezond' and also to the dedicated missions 'Leefstijl en leefomgeving: In 2040 is de ziektelast als gevolg van een ongezonde leefstijl en ongezonde leefomgeving met 30% afgenomen' (mission I) and 'Zorg in de leefomgeving: In 2030 wordt zorg 50% meer (of vaker) in de eigen leefomgeving (in plaats van in zorg instellingen) georganiseerd, samen met het netwerk rond mensen' (mission II). Also the research aligns with the activities in the KIA 'Gezondheid en zorg' 2020-2023 of Topsector LSH.

The digitalisation co-created in the ERP program and the biological knowledge helps in the further development of the Dutch 'sleutel-technologieën' (as defined by the government): digital and life-science

	technologies. These developments are streamlined with the work in DTL (Dutch Techcentre for the Life sciences), FNH-RI and HealthRI.
Dynamics	In 2019, we have changed the organisation of the ERP into 2 work packages (instead of 3 in 2018). This has worked well, has provided focus and has stimulated interaction and alignment of the different activities related to research and methodology innovation. We will continue this organisation in the coming years and are working towards an integration of outcomes in a proof-of-concept study in 2021. From Sept 2019 onwards the scientific lead of this ERP will be in hands of Dr. Suzan Wopereis and Dr. Andre Boorsma, with a core team of principle (Ben van Ommen and Robert Kleemann) and senior scientists as advisors and leaders of the main activities in the work packages.

17 Body-Brain Interaction

General information	
Title ERP	Body Brain Interactions
Contact person TNO (ERP)	Dr. Jasper Kieboom (PM) Dr. Robert Kleemann (Pr. Sc.) /Dr. Jan van Erp (Pr. Sc.)
Contact person(s) government or topsector	
Programme 2020	
Summary	*Program Description* In 2019, the topic 'Body Brain Interactions' had the status of seed-ERP. Studies were performed demonstrating the potency to become a full-ERP and a global leader in body-brain innovation technologies. The topic will be continued as a full ERP as of 2020. The long-term goal (2023) is to understand the interactions between body and brain and ultimately to improve human cognitive and physical performance and strengthen human health. To achieve this, we combine social and molecular disciplines, integrate psycho-social sciences and molecular-physiological mechanisms and develop the required analytical tools and experimental testing platforms (human and preclinical). The ERP will develop in-depth understanding of body-brain mechanisms on both the psychosocial level and biochemical-molecular level (see figure). We will define the most critical psycho-social determinants and molecular mechanisms (causal factors) that can be targeted with psycho-social or molecular nutritional/pharmacological) approaches to optimize mental and physical fitness. To do so, we will establish i) the required novel analytical and measurement tools & technologies for body-brain interactions as well as tools needed to develop new treatments to optimize cognitive performance and prevent disease. The applicability is broad. Modulation of body-brain interactions based on underlying mechanisms 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 TNO roadmaps Operations and Human Factors, Biomedical Health, Child Health, Digital Health Technologies, and Work, Prevention & Health. *Plan 2020* Plans and deliverables in 2020 will include establishment of i) an integrated mechanistic framework of psycho-social and molecular-physiological mechanisms of cognitive performance and cognitive control; ii) a human test system to assess effects and interactions of multiple stressors (mental, physical and metabolic) on cognitive performance; iii) a preclinical experimental model that allows study of gut-brain and liver-brain axis interactions during obesity; iv) sophisticated analytical and measurement tools for human and preclinical platforms; v) international standard methodology for multiscale gut/brain axis interaction datasets using AI/machine learning; vi) participation in the first human clinical trial performing a comprehensive organ biopsy profiling and a battery of cognitive tests plus neuroimaging.

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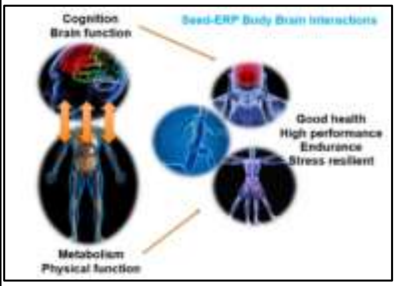
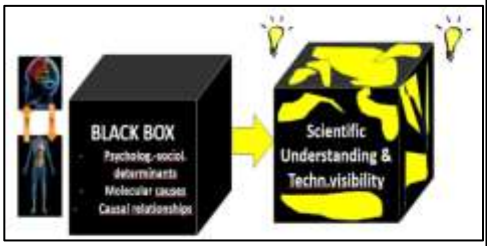
<tr><td>Short Description</td><td>
There is a growing interest to better understanding the complex interactions between our body and our brain/mind because this powerful connection can be exploited to optimize cognitive and physical performance, improve fitness and prevent exhaustion. Effective targeting these interactions can reduce the burden of chronic stress, attenuate neurodegenerative diseases and prevent a broad spectrum of obesity-associated metabolic diseases.





The ambition to optimize mental and physical fitness is timely and meets the needs of citizens in all modern societies, e.g.: 1) a lifelong high level of cognitive performance and physical fitness; 2) rapid mental and physical recovery from stressful situation; 3) optimal protection against mental and physiological stressor causing metabolic diseases/obesity; 4) strategies to counteract cognitive decline/dementia.

Obviously, recent demographic and socio-economic changes propel these needs and urge the development of first tools and interventions to stimulate protective body-brain interactions and to intervene in those that are detrimental. Importantly, these interactions encompass socio-psychological mechanisms as well as molecular-physiological mechanisms and exact understanding of both types of mechanisms is lacking (Black Box), which is why there are still no effective treatments of conditions such as mental overload, cognitive decline, Alzheimer, Parkinson etc. but also no effective interventions to increase cognitive performance and recovery from stress. Furthermore, it is also unclear how socio-psychological and molecular-physiological mechanisms influence each other.

This ERP aims at understanding the causal determinants of both psycho-social and molecular-physiological mechanisms and at defining causal relationships to enlighten parts of the Black Box, allowing first effective optimizations and treatments. Inherent to advancing into a new field, research on Body-Brain-Interactions requires development of mechanistic framework integrating psycho-social and molecular-physiological knowledge, development of predictive preclinical and human test platforms to evaluate new intervention concepts (prevention and treatment), development of dedicated analytical and big-data science technologies for sensitive measurements, multiscale data integration and analysis as well as modelling tools for biological (□□□and psychosocial (□) mechanisms.

To get there, the following steps must be taken (knowledge and technology development):

1. Identification of critical determinants and factors (psycho-social & molecular)
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2. Psycho-social & molecular-physiological framework to model the identified mechanisms and causal relations (incl predictive algorithms)
3. Technologies required to develop new preventive or therapeutic treatments: predictive test systems (human platforms and preclinical models)
4. Advanced sensitive analytics & measurements (molecular and psycho-social)
5. Data Science for complex dynamical multiscale datasets (artificial intelligence, machine learning, big data integration tools, statistical tools)

The added value of the ERP for future stakeholders and ecosystems is thus, among others, a) mechanism-based understanding of the interactions; b) broad application potential (at government, pharma industry, nutrition industry, army/police, eHealth and tech-companies); c) unique TNO position regarding integrated tools and technologies that combine □- and □□expertise to efficiently improve body-brain mechanisms.
In 2020 we will focus on two grand challenges involving body-brain interactions with clear□□- and □□components that share interrelated mechanisms and interest from multiple stakeholders:

1) OPTIMAL COGNITIVE PERFORMANCE UNDER MULTIPLE STRESSORS
2) ATTENUATION OF COGNITIVE DECLINE DURING OBESITY
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<td>Results 2020</td>
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As full ERP, Body-Brain Interactions will concentrate on the topics ‘Optimizing Cognitive Performance’ and ‘Cognitive decline in Obesity’. These topics are critical for modern societies and have connections regarding underlying stressors (both physical, mental and metabolic). The ERP is aligned with KIAs relevant for Defense/Human Factors (left column of graph below) as well as Healthy Living (right column). The work of the ERP is divided in 2 work packages described below.

This ERP has also a strategic fit with the NWA routes ‘NeurolabNL’ (theme health), ‘Jeugd in Ontwikkeling’, ‘Veerkrachtige samenlevingen’ and ‘Sport en Bewegen’. The ERP is also connected to the NeuroTechNL and i3B
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foundation as well as human performance initiatives at defense (e.g. US Army Research Lab) and shares the ambition to develop strategies for optimizing mental and physical fitness, cognitive health and attenuating disease burden, particularly related to obesity and dementia (see Nationaal Preventieakkoord & KIAs and LSH).

WP1. OPTIMAL COGNITIVE PERFORMANCE UNDER MULTIPLE STRESSORS

Background: People in modern societies are constantly challenged. This includes mental (cognitive and emotional) as well as physical stress. In all phases of life stressful situations are unavoidable which demand effective coping strategies. Key to optimal performance and effective coping is an adequate response to physical and/or mental load, as well as, the ability to optimally recover afterwards. Imbalance will result in detrimental forms of overload: physical and/or mental exhaustion. The interactions between mental and physical fitness is poorly understood and the (interacting) effects of multiple stressors has been hardly studied.

Physical and mental overload have common symptoms including tiredness, irritability, sleep disturbances, cardiovascular changes, performance impairments, and neuro-hormonal changes. The ERP will gain understanding *how* mental overload leads to physical symptoms and *how* physical overload may lead to poorer cognitive performance, together giving rise to better targeted interventions.

Focus of work: The WP concentrates on the central questions ‘What are the main psycho-social and molecular-physiological determinants that determine cognitive performance in situation of combined physical and physiological (over)load?’ ‘How can we effectively cope with such multi-stressor situations, and how could the recovery process be improved (e.g. more rapid recovery from stressor, more effective long-lasting recovery)? This includes that we will set out to identify strategies that can be taken beforehand (prevention) as well as after the situation has occurred. Specific aspects of the interrelatedness between the body and brain could thus be used as intervention targets. There is for instance increasing evidence that physical training could not only improve physical performance, but also may boost cognitive performance but the mechanisms remain enigmatic. Consistent with this view, cognitive interventions (e.g. cognitive behavioral therapy) have shown to not only to exert beneficial effects on mental health but also physical health which is in support of the presumed cross-talk.

Approach: In 2020 as full-ERP we will seek for mechanisms (□ and □-type) that are responsible for this cross-talk and experimentally test new hypotheses for interventions to attenuate the detrimental effects of overload and improve cognitive performance. The research is innovative because multi-stressors effects are typically not studied, let stand combinations of metabolic stressors (e.g. fasting, exhaustion) with physical stressors (e.g. white noise, high temperature). It will lead to a more thorough understanding of how body-brain mechanisms play a role in cognitive performance, and recovery from mental/physical stress. It will also provide new strategies for mechanism-based interventions that may effectively boost performance and diminish detrimental effects of overload.

1) In a first step, we will finalize an already initiated investigation (via literature and data analysis) how social/physical external stressors

	such as task complexity, heat, sleep deprivation, time pressure and internal stressors such as craving, fear, and anxiety influence the individually perceived overload (mental and physical), performance, and which factors determine recovery. This will lead to the identification of key determinants of body-brain interactions that can be modulated experimentally and novel interventions and a scientific publication. 2) Based on the mechanistic psycho-social and molecular-physiological interaction framework obtained from 1) and work package 2, we will investigate experimentally which determinants are most critical for an optimal cognitive performance when volunteers are exposed to multiple stressors (both mental/ physical and metabolic/physiological). This may provide new insights for interventions that can modulate cognitive performance among which: o Metabolic interventions o Physical activity interventions o Cognitive interventions 3) In parallel, we will define new use cases relevant for the full ERP phase. These cases could involve Defense & Safety employees; students/young workers; health care professionals, and patients. These groups are physically and/or cognitively exposed to unavoidable stress conditions involving multiple stressors (mental, physical and physiological), and overtraining, mental & physical overload, addiction and burnout are prevalent amongst these groups. <u>Expected output in 2020:</u> - Finalization of a literature review of psycho-social mechanisms relevant for cognitive performance and obesity (publication) - Definition of optimal stressors (physical/mental and metabolic/physiological) that can be combined experimentally and to which volunteers can be exposed during performance of cognitive tasks. - Definition of optimal readouts (cognitive tests, measurements of metabolic overload, perceived stress, hormonal stress etc.) and physical performance indicators - Design and performance of an experiment with these multiple stressors optimally powered for interaction effects (about n=30-40). - Contribution to a PPS, NWA grant, or a grant proposal involving stakeholders for application of the developed technology (in 2021). **WP2. ATTENUATION OF COGNITIVE DECLINE DURING OBESITY** <u>Background:</u> Overweight/obesity is characterized by a disturbed metabolism and affects, depending on the country, between 30-50% of the adult population worldwide. The incidence of obesity among children is worrisome and has reached epidemic proportions giving rise to impaired cognitive functioning. Overweight/obesity is characterized by metabolic disturbance of several organs (e.g. white adipose tissue and the gut) has been associated with cognitive decline. The underlying mechanisms and the molecular players are largely unknown. The interaction seems bidirectional because chronic mental stress and behavioral habits can disrupt metabolic processes in organs. Knowledge how to intercept in this

vicious circle and experimental test systems to develop interventions are urgently needed.

Focus of work: In 2020, we will concentrate on the psycho-social interactions relevant for targeting obesity and, with regards to experimental studies, on innovative molecular interactions between organs that are important for metabolic control (liver) and inflammation in obesity (white adipose tissue) and the brain. The liver and the white adipose tissue are chosen because they are thought to release molecular signals affecting the brain. The WP will generate knowledge on the exact nature of these molecular interactions on and develop new experimental model conditions allowing the study of liver-brain and adipose-brain interactions. In parallel, we will develop unique analytical technologies to identify and measure the interacting molecules. On the psycho-social level, we will define which measurements and analyses are necessary to optimally measure psycho-social mechanisms and quantify changes in behavior, or motivational and behavioral traits that drive the aforementioned vicious cycle.

Approach: On psycho-social level, we will identify key determinants that are relevant for targeting obesity based on literature and integrate these mechanisms in the psycho-social and molecular-physiological framework described in WP1. On the experimental model platform level, we will perform an experiment in which we target inflammatory factors identified in 2019 (seed-ERP phase) released by liver (complement factors) in collaboration with an academic partner of our ERP ecosystem (LUMC Clinical Genetics lab). In a separate experiment, using sophisticated fMRI techniques at our ERP partner Radboudmc (Anatomy and Pathology) & Donders Institute, we plan to examine the role of inflamed adipose tissue on brain and organs using microsurgery to dissect the disease tissue. We will develop the molecular biology tools and sensitive mass spectrometry-based analytics to analyze organs and the brain, in particular methodology to quantify structural changes of the brain and inflammation of specific brain areas (e.g. hippocampus). In the experimental studies, feces samples and intestinal samples will be collected.

We will continue our collaboration with Rijnstate Hospitals and Radboudmc regarding the worldwide first human trial (BARICO; n=150) investigating the effect of weight-loss in obesity on brain structure and function as well as cognitive performance. The trial includes a battery of cognition tests and neuroprofiling analyses including fMRI and, importantly, the collection of tissues including liver, adipose tissue, intestine/gut, intestinal mucosa, feces as well as plasma and serum for biomarker analyses. Analysis of microbiota composition will allow correlation analysis will health state of organs using ERP data science and statistical tools developed in 2019 and identify microorganisms correlating with cognitive performance as well as organ pathology in obesity. A PhD student is planned to perform analyses in this clinical trial as well as preclinical studies and fMRI analysis at the ERP partner organizations.

Together, the WP2 studies will lead to identification of novel biochemical factors that are produced by dysfunctional organs and that interconnect body and brain. The preclinical platform will be developed into a comprehensive test system allowing to assess interventions on body-brain health.

	<u>Expected deliverables in 2020:</u> - Definition of key determinants and main stressors relevant for obesity and their integration in the framework of overarching psycho-social and molecular-physiological mechanisms (publication). - Based on this framework, design of a human experiment in which multiple psycho-social and physical stressors are targeted simultaneously in a group relevant for obesity prevention (e.g. young adults). - Finalization of experimental model for gut-brain studies (publication) - Finalization of standardized methodology for complex microbiota analyses for nutrition and pharmaceutical applications (publication) - Experimental preclinical test system for liver-brain interactions in obesity and demonstrator (targeting a complement factor in collaboration with LUMC; poster) - First characterization of WAT-brain interactions in obesity in collaboration with Radboudmc and development of appropriate test system (poster) - Comprehensive analysis of microbiota (feces & mucosa) and plasma biomarkers in BARICO cohort and correlation with brain readouts (structure, function) as well as cognition tests (poster) in obesity. ERP scientists have established collaborations with the following ERP partners: - Radboud UMC and Donders Institute Nijmegen (NL): powerful fMRI technology (unique); e.g. development of non-invasive brain tool box for comprehensive test systems (humans and mice); pathology and anatomy of brain; child health & stressors, developmental psychology of children. - Wageningen University: effects of food on cognitive and emotional health; metabolic functioning of adipose tissue and inflammation. - Leiden University Medical Center: Clinical Genetics; role of inflammation in neurodegenerative disorders; pathophysiology of brain; neurobiology. Internally, this program is aligned with several TNO roadmaps and research initiatives, among which the Roadmaps ‘Operations & Human Factors: Effective, efficient, and flexible armed forces’ (Defensie en Veiligheid); and ‘BioMedical Health’ (Gezond Leven) and ‘Digital Health Technologies’ (Gezond Leven) as well as ‘Prevention, Work and Health’ (Gezond Leven).
Dynamics	The ERP is a true cross-over of social sciences and molecular sciences and bridges the Units Defense and Healthy Living (with equal contributions). In 2019 this program had seed-ERP status and started with 3 work packages which were brought down to 2 because we succeeded in defining common underlying mechanisms (shared knowledge development) and innovations (shared technology development) during 2019. This will allow to continue our research in 2020 in two work packages 1) Cognitive performance under multiple stressors and 2) Attenuation of cognitive decline in obesity as outlined above.

18 ExpoSense

General information	
Title ERP	ExpoSense
Contact person TNO (ERP)	Ingeborg Kooter (PL), Stefan Bäumer (PS), Anjoeka Pronk (Scientist)
Contact person(s) government or topsector	

Programme 2020	
Summary	*Program* description Our health is impacted by the environment we live in, consisting of a combination of 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. The concept ‘exposome’ – the total 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. Exposure to particulate matter (PM) is responsible for about 4% of the disease burden in the Netherlands. Air pollution therefore is one of the most important risk factors, in the same order of magnitude as overweight (5%). The long term goal of this ERP is to develop a personal ‘early warning system’ (e.g. integrated in a wearable / portable device) for PM related exposures consisting of new sensor technology and new interpretation of the data, tuned to each other for best performance. The new challenge in sensor development lies in added chemical identification to the PM sensor, which will allow for better source identification and the innovation in the data gathering / interpretation is concerning higher spatial and temporal resolution: from days to hours and km to m. This combination will warn people in unhealthy situations (e.g. heavily polluted area) and enable corrective actions which in the end should lead to a lower burden of disease. For this an integrated approach is needed for assessing, interpreting and providing feedback on multiple external particulate matter (PM) related exposures and relevant health effects. The first application domains of the technology will be occupational health and public respiratory health. *Plan 2020* The main planned results in 2020 include: (i) Two demonstrators combining particulate matter sensing and chemical identification for occupational and environmental applications. The design of a portable, accurate sensor device with data integrity over time is a core deliverable. (ii) Precise (data-driven) models for personal exposure profiling (‘exposome’) with functionality for source recognition and estimation of indoor exposure levels.
Short Description	The aim of the program is to deliver comprehensive equipment and models for the management of the impact of particulate matter (PM) exposure on air pollution-related human health. To this aim two important aspects are foreseen. First development of portable sensors (< 25 mm^3)

	and second an integrated model for the assessment and management of PM exposure. In a later stage the PM sensor and models will be complemented with other modalities for Volatile Organic Compounds (VOC) such as benzene and formaldehyde, which are on the list of substance of very high concern (SVHC). The following technology developments and knowledge breakthroughs are needed to achieve personalized assessment of external exposures, with a high resolution in time and space and in real time: *Sensor development for PM and VOC exposures*: Low cost and portable PM sensors are currently available. However, they suffer from major drawbacks: 1) both the detection limit and reproducibility are in general poor, and 2) they only can assess mass or size of the particles. To make a significant step to correlate particulate matter to effects on health, it is important to know the chemical composition of the particles. The proposed technology breakthrough is to discriminate the size of the particles (i.e. 2.5um /5 um / >10um diameter) in a low cost and small solution – 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 >10mg/m3 to 25□g/m^3 to be in agreement with the European Air Quality standard[8]. In parallel a platform for adding VOC's to the sensor will be developed to be able to measure those gases at a level <20 ppb (benzene) and <100ppb (formaldehyde). *Analysis and interpretation of external sensor data and integration with models (external exposome)*: Currently air quality and occupational exposure are being modelled completely independently from each other and for very different purposes. The resolution in time and space is low (often 8 hour time weighted average for occupational exposure and mostly annual averages for environmental exposure) and the predictive power for personal exposure levels is limited. Therefore exposure assessment can only be done at group level and in a time integrated manner. We aim to predict exposures at the personal level, being able to identify differences between individuals and within individuals over a (working) day. A higher resolution of exposure assessment methods in time (1-5 minutes) and space (1-10 meters) is needed to increase the predictive power to the individual level. Breakthroughs include improvement of time and place resolution of exposure models, methodology for data fusion with sensor data (challenges: difference in resolution and dealing with uncertainty) to increase precision, personalize exposure estimations and source identification to enable prevention. A dynamic data infrastructure that can manage these (sensor) data flows in real time is required. *Analysis and interpretation of internal exposure data and integration with models*. Presently, there is a lack of insight in how combinations of exposure patterns are related to personalized health effects at the individual level. Also, the effects of interventions (e.g. exposure reduction) cannot be directly monitored in relation to reduction of health risks or improvement of health. Internal exposure and effect data (e.g. biomarkers) and models can assist in bridging external exposure data towards health status. Thus, the development of approaches is needed that enable: (1) the qualitative and quantitative linkage between external exposure to markers of internal exposure; (2) the qualitative and quantitative linkage between

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

	markers of internal exposure and biomarkers of health effects. The technological breakthroughs consist of: (1) the development of methodology and data infrastructures for identification of these biomarkers from literature; (2) the (co)-development of detecting these biomarkers towards ultimate application into (personalized, minimally-invasive) sensors.
Results 2020	***WP1: Demonstrators*** In two demonstrators the combined developments of PM sensing and chemical identification together with updated and improved models will be tested and demonstrated. WP1.1: Occupational A PM sensor (either the PM sensor developed by TNO or a commercial one) in combination with the by TNO developed chemical identification unit will be deployed in an occupational setting (i.e. construction industry). Workers will be provided with a portable version of the sensor (~125cm^3) to collect exposure data during their working day or specific tasks. These data include (near) real time mass based PM exposure data and the fraction of crystalline silica in the exposures. This feedback can be given directly as such to the workers through an app on their phone, or the data can be interpreted first (averaged over the day/task or compared to threshold values; either afterwards or real time) to make the feedback more meaningful to them. Data flow options need to be explored and either result in implementation of algorithms in the app (smallest loop), or data transfer from the sensor to our data infrastructure (data storage and calculation capacity), application of algorithms and consecutive feedback to the worker's app (bigger loop). WP1.2: Environmental Next to an occupational demonstrator an environmental demonstrator will be planned. The field study planned with the city of Eindhoven could be used as basis. In this field study PM sensors (TNO and others) will be applied both stationary and personal. In this demonstrator personal environmental exposures will be estimated from a combination of air quality models (Urban Strategy) and stationary sensor data (data fusion) and personal tracking data. These personal estimations can be evaluated against personal sensor data. The field study in Eindhoven is in collaboration with the communality of Eindhoven and Areas (civilians participation). Together with them it will be decided which chemical fractions are important to focus on with our chemical identification unit. The environmental field study will next to the validation of the TNO PM sensor, validate the newly developed models for fast and local exposure prediction. ***<u>WP 2 Sensor development</u>*** The sensor development activities are geared towards the design of portable/wearable sensors which solve the major problems of today's low cost portable sensors: poor detection limit and accuracy and data integrity over time. There is also poor reproducibility amongst different sensors of the same type (resulting in current variability between and within sensors). The major breakthrough foreseen in the ERP with respect the PM sensing is enabling the in-line chemical and reactivity identification of PM, a feature that is lacking for current sensors. Chemical identification is introduced in two ways: FTIR identification to assess the unique molecular resonances of the chemical groups in the particles, and triboelectric

detection to assess the specific ionization energy related to the different particles.

Particles deposit in the respiratory tract depending on their aerodynamic diameter (figure 1). Size of the particles determines where and how they interact with the respiratory system. Next to size the chemical composition of the particles is important as well. This holds true for soluble and also for non-soluble PM. In the latter case the surface reactivity is more important. This reactivity can be related to the ionisation energy of the particles, using the triboelectric detection.

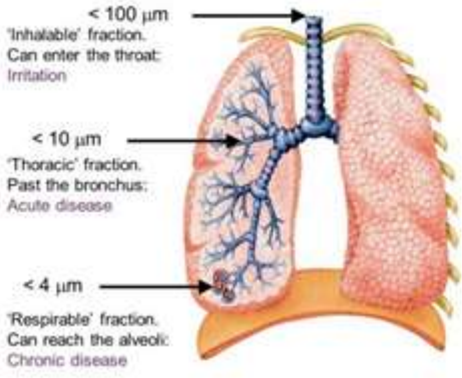
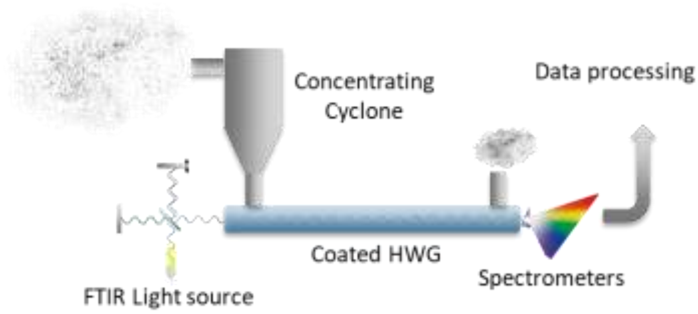


Figure 1: Deposition of particles upon inhalation in relation to their size.

This elucidates the important reason for assessing the chemistry of air-borne particles in conjunction with size identification. By being able to determine chemical composition of PM, also the suspected source may be identified, enabling the end-user to more efficiently intervene and prevent exposure. In addition, current regulation is (and may remain) focussed on specific substance groups, e.g. diesel emissions, construction dust, crystalline silica, wood dust, outdoor air pollution, etc. which can be distinguished from other PM exposures if the chemical identity of PM is known. And last but not least, information on the chemical characteristics will help to define the external exposure in more detail from a chemical perspective which facilitates internal exposure and health effect marker selection and modelling of the internal exposome and health effects.

WP 2.1: Prototype integrated PM identification

In 2019 the proof-of-concept was shown for the in-line detection and



identification of air-borne silica. Particles were collected and concentrated using a micro-cyclone and in-line FTIR analysis was executed. This demonstrator was a bread-board set-up composed from separate components and demonstrated the ability to distinguish between amorphous and crystalline silica. This development will lead to a demonstrator showing the capabilities of the new technology. The individual components must be integrated into a single (portable) device that can be used for field test demonstration (~125cm^3). This requires a

	redesign of the hollow FTIR waveguides, and flow channels, including FTIR hardware connections, and flow control. It will also be assessed if the triboelectric detection can be integrated for additional data. Furthermore, the raw data from the FTIR spectrometers must be transferred to information about concentration and chemistry for integration with the exposome modelling. Deliverables: Occupational demonstrator 1.0. An integrated device will be developed and tested in the first combined demonstrator *WP 2.2: Miniaturization* The prototype that is used for the occupational demonstrator is a portable device, not suitable as a wearable multiparameter PM sensor. Some of the components required for the chemical identification, particularly the light sources and detectors, are currently expensive and large. Two approaches will be followed to evolve the PM sensor from a portable into a wearable device: 1) use of low cost components, combined with multivariate optical computing, in which smart tuneable optical filters will be used to improve the data quality; 2) miniaturization of FTIR spectrometers, suitable for a wearable device. It is expected that the first option will yield smaller and lower cost PM identifier, but may lack high sensitivity. This will be mitigated using suitable particle concentrator solutions, thus increasing the local particle concentration in the sensing element. The second solution will provide laboratory sensitivity, but may be too expensive for wide deployment. This approach will be followed in combination with academia and research institutes.  The implementation of miniaturized components will require some adaptations of the other essential hardware, such as the particle concentration cyclones, micro-channels and pumps. Furthermore, alternative data processing protocols must be developed, if the quality of the raw data becomes of lower quality than before. Deliverables: First building blocks of the miniaturized device will be demonstrated: i.e. integration of smaller optical components or a smaller FTIR component. These building blocks are required for the 2021 demonstrator for environmental PM identification. This demonstrator requires the measurement of multiple components, such as silica, black carbon, wood dust, etc. ***WP 3 Exposome modelling*** *3.1 External exposome modelling* *3.1.1 Environmental exposure modelling* The environmental modelling activities are aiming at the real time exposure profiling of individuals including source identification. The major improvements to be realised in the ERP are:

- Increasing the resolution in time and place of air quality models (currently year and 7x7km)
- Personal exposure estimations based on location tracking
- Data fusion with real time sensor data to increase precision
- Source identification of major exposures to enable prevention

In 2018 personal external exposure profiles were composed and visualised using Urban Strategy (US) technology either from improved high resolution air quality models in combination with GPS tracking or directly from personal sensor data (fig. 2).

In 2019 this approach was validated with a large dataset with personal black carbon data in collaboration with the Utrecht Exposome hub.

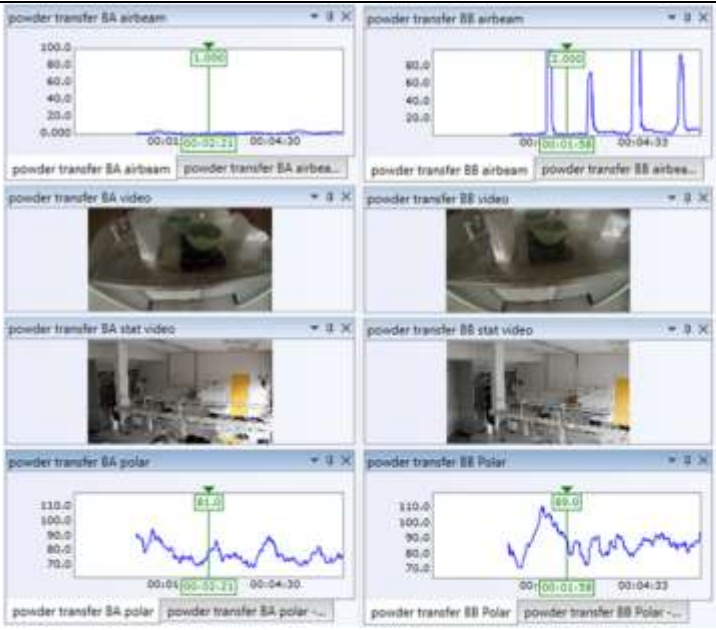
In 2020, this technology will be further developed and validated:

- Development of data fusion and/or assimilation methods for combining sensor and modelled data. This will lead to an Urban Strategy module that can automatically combine model and sensor data into a single personal exposure profile.
- Further improvement of environmental models in US platform to improve precision, to add the functionality for source recognition and for adding functionality for estimating indoor exposure levels.
- Validation of the system and new functionalities focussed on PM data (size fraction to be decided). A field study in the Eindhoven city sensor project will be performed. This will be done in collaboration with the sensor development of WP2 since the sensor will be validated in this field study as well. This will lead to a validation report in 2020 and a shared demonstrator in 2021.
- Scientific presentation on the US technology including BC validation. This will lead to TNO visibility in this field.

This work will be performed in collaboration with the UU Exposome hub and will build on the Eindhoven city sensor project which is performed with an extensive consortium including UU, RIVM, city councils and GGD. An assistant professor (expected start data 01-01-2020) funded by the UU Exposome hub and the ERP ExpoSense will contribute to these developments.

Fig 3: powder transfer in two scenario's: good (left) and poor (right) working practice. From top downwards time synchronized and visualized in EVADE: particle number concentration, personal video, stationary video, heartbeat

3.1.2 Occupational exposome modeling



Occupational modelling activities are mainly focused at understanding when, where and why exposures occur. Main activities include:

- Context sensors and technologies to inform exposure sensor data: exposure sensor data provide at best a graph of concentration against time. Without knowledge on where a person was and what he was doing, it is impossible to link this exposure graph to causes (sources, activities, etc) and hence to prevention actions. The use of context sensors and technologies can add this information. In the ERP it is explored when and how to use these technologies with the aim of prevention. Preliminary result in fig 3.

- Indoor dynamic concentration mapping: like for the environment, for work situations it could be beneficial to use stationary sensor networks to create dynamic concentrations maps. Based on indoor location tracking, personal exposure profiles can be compiled. Outdoor models use wind speed and direction, which can obviously not be applied indoors. New models (like CFD and kriging) are explored.
- Indoor location tracking is most meaning full if it can be displayed on a 2D or 3D indoor map.

In 2019-2020 in VP Sustainable Work (SW) field studies on the application PM sensors for occupational exposure assessment are being conducted in collaboration with NIOSH and HSE. Within this context, the ERP ExpoSense results can be directly applied, while the data gained from this study can be used to validate ERP results.

3.2 Internal exposome modelling

Ultimately, internal markers need to be used as markers of exposure and early health effects at the individual level, in direct relation to personalized time-resolved external exposure. In reality, this is quite complex, because internal markers are not very specific. Therefore, in most cases a set of internal markers will be involved, resulting in an internal exposome ‘fingerprint’. For PM exposure, it is even more complex, because PM may consist of all kinds of chemicals. Further, different types of PM are related to different (types and severities) of health effects. In 2019 a first step was

	made to develop approaches for identifying internal markers (‘fingerprints’) at group level using artificial intelligence (AI) based literature mining. This consisted of: (1) developing AI data mining technology to mine scientific literature and from these (2) proposing fingerprints of biomolecules indicative for PM exposures, originating from different sources (smoking, coal combustion, air pollution and nanomaterials). In 2020: • The AI/big databased literature mining and fingerprint big data approach will be further developed and validated by using biomarker datasets through collaboration with universities or knowledge institutes, e.g. Imperial College, Utrecht University exposome hub. Aside specific applications for PM, the AI/big data approach has the potential to also for other stressors, accelerate the hazard assessment procedure enormously, because a large part of the work will be computerized instead of performed by experts. Moreover, this technology contributes to increasing the understanding of how external exposures lead to disease. The results will be published in a scientific publication and presentation at a conference. • A collaboration with a (commercial or non-commercial) sensor developer for biomarker sensing will be set up. Within this collaboration, TNO will be responsible for identification of the appropriate internal marker set (as per AI/big data approach) as well as developing methods for interpretation of sensor data. This initial collaboration will lead to a shared plan for 2021-2022 on bringing the sensor technology forward for application and combination with the external PM sensor. <u>Development of collaborations:</u> - The collaboration with the UU Exposome hub is taking shape and a joined post-doc will start at 01-01-2020. - The collaboration with HSE and NIOSH has led to a signed MOU with external communication in 2019 and joined field studies in 2019-2020 (3 countries and 3 different industries for occupational health). - Collaboration on big data for exposome will be explored with Aarhus University and the University of Manchester Big data Center. - Collaboration with a sensor development company for internal biomarkers/fingerprint signatures will be set up. - Participation of TNO in EU initiatives HBM4EU, EU Exposogas continues, new proposals are submitted: the human exposome project (granted). - Collaborations on sensor development with University of Caen and Fraunhofer, that were started in 2018 should be revived. - TNO is well connected to the NWA route and startimpuls “Meten & Detecteren”. It will be investigated, how a follow-up to the cooperation within the Start-impulse can be given.
Dynamics	***Dynamics:*** While the contact with external institutes and research partners have developed in a positive way, business development in the area of ExpoSense seems difficult. The major lead Casella (for PM sensors) is delayed for many months and focus will be on bringing in other business partners for the valorisation of results. Integrating the work packages of sensor and model development has been more difficult than expected in 2019. However mutually aligned

	roadmaps are delivered reflecting the common goal. The introduction of context sensors has been proven to be useful and is a new component added in 2019. In 2020 the ERP will continue making use of theses sensors. Still more value should be extracted from the fact that TNO is vertically integrated, i.e. having both sensor and model development in the same organization. The discussion on which chemical identifiers are the most relevant for health effects has to be intensified. Efforts in this area will be increased in 2020.

19 Wise Policy Making

General information	
Title ERP	Wise Policy Making
Contact person TNO (ERP)	Josephine Sassen
Contact person(s) government or topsector	

Programme 2020	
Summary	*Program description* Policymaking that accounts for the wellbeing of our society as a whole, now and in the future, is essential to effectively manage radical changes. The Netherlands is at the dawn of several of these, driven by, among other things, climate change (the energy transition), technology (autonomous driving, AI, surveillance, cryptocurrencies), national developments (population aging) and international developments (migration). Steering towards wellbeing fits the global trend of ‘policy making beyond GDP’. We need a new set of indicators that capture a broader range of sustainable wellbeing. The state of the art is that various indicators are available to evaluate wellbeing in retrospect, with inductive speculations about the effects of policies on wellbeing. Currently only few and partial instruments are available to assess wellbeing prospectively. Moreover, most evaluation tools focus on objective parameters and scarcely take subjective (‘experienced’) wellbeing into account. At the moment, policy makers cannot assess the impacts of their proposed policies on wellbeing—not in terms of *individual and collective* wellbeing, *subjective and objective* wellbeing, *short-term and long-term* wellbeing. This ERP aims to fill this gap. Our aim is to develop a suite of instruments and methods to support policy makers to assess (ex-ante) the impacts of policy options on wellbeing. We aim to develop, test and validate this suite of instruments, in the course of 2020-2022, in an iterative process of prototyping, testing, evaluation and improvement. Our ambition for 2022 is to deliver a suite of instruments and methods that is tested and validated in practice, and is ready for use by policy makers. With this suite, policy makes will be able to *quantify* the impacts of different policy options on *wellbeing*, and also to *qualify* these impacts and have fruitful dialogues about these policy options and impacts with each other, citizens and other stakeholders. This will enable them to develop policies that promote wellbeing, based on scientific insights and legitimized by society. *Plan 2020* In 2020, the ERP aims to develop: 1. First “Expected Impact on Wellbeing Assessment” (EIWA) ex-ante evaluation instrument to support policymakers in prioritizing and steering policies towards societal wellbeing. The instrument will be based on utility functions and visual representations of scenarios to enable the assessment of the impact of policies on wellbeing. 2. A set of value-based reasoning methods to support policy makers in using the instruments in the complex real world of policy making. This set of methods will be gathered under the umbrella of the so-

<table>
<tr><td></td><td>called ‘Wise Tank’ – a knowledge base on state-of-the-art inventories related to policies for long term wellbeing.</td></tr>
<tr><td>Short Description</td><td>Our ambition for 2022 is to deliver a suite of instruments and methods that is tested and validated in practice, and is ready for use by policy makers. With this suite, policy makes will be able to quantify the impacts of different policy options on wellbeing, and also to qualify these impacts and have fruitful dialogues about these policy options and impacts with citizens. This will enable them to develop policies that promote wellbeing, based on scientific insights and legitimized by society. We envision the following three deliverables:

1. A set of instruments to assess the impact of policies on wellbeing—this will involve both the quantifying of impacts in terms of different aspects of wellbeing (how good or bad is this for this or that element of collective, long-term wellbeing?); and qualifying these impacts in dialogues (how do we value this impact, how can we compare apples and pears and bananas?). This work will be based on utility functions. A first instrument is the EIWA, which includes ways for people to ‘experience’ impacts on wellbeing, e.g., through visualizations (see Results 2020).

2. A set of methods to support policy makers in using these instruments in the ‘messy’ reality of policy making—the ‘policy cycle’, which also includes politics, power, vested interests etc. We envision methods for ‘value-based reasoning’, for scoring, weighing and interpreting diverse impacts on wellbeing, for understanding impacts across time and across stakeholders, for advanced forms of ‘argument-mining’ (e.g. in discussions, forums, etc.), and for dealing with complexity and circumventing (cognitive and evolutionary) biases in decision making. Additionally, we plan to develop methods that facilitate interactions and dialogues between policy makers and citizens, e.g., in discussing, interpreting and decision making. This set of methods will be gathered under the umbrella of a so-called ‘Wise Tank’ (see Results 2020).

3. An online archive that documents the knowledge we generate and makes it available to others, both in policy making and in academia. This is intended as a scientific evidence base that provides the backbone of our research and the developed tools and methods. This will involve knowledge on different levels:
• On the content level e.g., regarding developed tools (such as the EIWA)
• On the process level, e.g., regarding developed process methods to support policy making (such as the Wise Tank)
• And on the meta-level of transdisciplinary research and innovation, e.g., with regards to teamwork, lessons learned and Responsible Innovation

The instruments and methods in the suite will meet the following requirements:
• Based on scientific knowledge, evidence, data and models
• Applicable to a broad array of policy areas, e.g., energy transition, sustainable mobility, security
• Applicable to multiple levels, e.g., national, regional, local</td></tr>
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	• Clear added value to policy makers, compared to current policy making practices During the 2020-2022 period, we plan to actively seek collaborations with both prospective clients in the Dutch government and other actors and stakeholders in the policy making process (e.g., BiZa, CPB, CBS, PBL), and with experts from (international) academia (e.g., MIT, TUD) along with national and international research agenda's such as the KIA of the 'topsector creatieve industrie'[9] and with the Nationale Wetenschapsagenda, in particular with the Routes Energietransitie, Logistiek en Transport, and Veerkrachtige Samenlevingen and with the NWO program for Responsible Innovation. We envision different options for bringing our results into the world—in the order of increasing complexity and efforts involved, please find below several possible options (to be further explored and developed during the 2020-2022 period): a) The creation of a Program Office to organize these collaborations (with clients and academia) b) The creation of Shared Research Centre to organize these collaborations c) Contract research for a Ministry (e.g., BiZa) to further develop the support suite d) Contract research in the form of secondment (working on their premises) for a Ministry (e.g., BiZa) or other actor (e.g., PBL, CBS) further develop the support suite e) Contract research for a private (strategic consultancy) company to apply this support suite f) TNO offers the support suite to the market, e.g. to governments or authorities (internationally) g) TNO offers the support suite to the market, e.g. to governments or authorities (internationally), in close collaboration with a private (strategic consultancy) company (as a back-office service for these companies) h) Further research, e.g., in the context of EU projects and funds i) Establishment of an independent organization, which deploys the support suite (e.g., spin-off)
Results 2020	**MILESTONES 2020** ***Phase 1: Ideating*** **Activity 1: Series of interviews** We plan to conduct a series of interviews with stakeholders and actors in policymaking, and explore thought experiments ,to investigate the challenges of ex-ante assessing the impacts of policies on sustainable wellbeing. Based on this, we will create a framework that clarifies:

[9] "[…] het centraal stellen van de mens en haar welzijn, het ontwikkelen en verbeelden van visies, het integreren van uiteenlopende belangen en disciplines, het aansturen op breed gedragen innovaties en het methodologisch inzetten van creativiteit." Excerpt from the summary of the KIA for creative industry.https://assets.ctfassets.net/h0msiyds6poj/38l7iJZb2t6G30s23mt0HM/ace08a82103232c95dfa2514513b5baf/KIA2020-2023_20190701.pdf

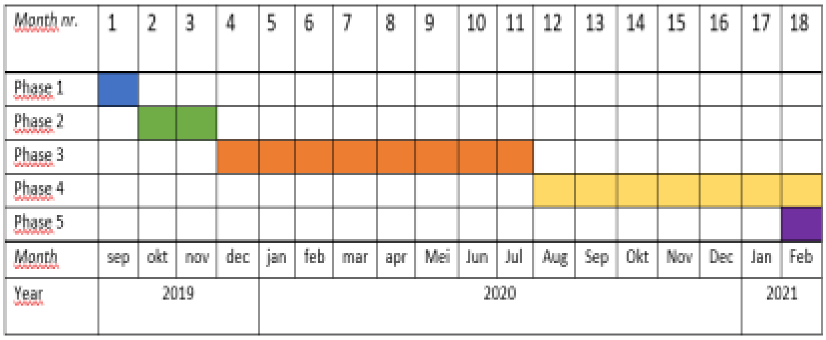
	• What is meant by sustainable wellbeing? And what are determinants of wellbeing? • What are feasible time-lines for assessments of future impacts? And How to handle second order, third order(etc) effects? • How assessments of impact on wellbeing relate to other types of impact (e.g., economic prognoses) • How policy makers can practically use and benefit from assessment of impacts on wellbeing? What problem does it solve? How does it help policy makers in their daily work? ***Phase 2: Concepting*** **Activity 2: Parameterizing and quantifying wellbeing** We plan to parameterize and quantify the impacts of policy options on a series of wellbeing indicators so that they can be made measurable, based on the aforementioned thought experiments. This entails the selection of relevant wellbeing indicators and hence the development of questionnaires that measure both objective and subjective elements of wellbeing. **Activity 3: Visualizing and qualifying wellbeing** We plan to create visual representations of different policy scenarios, which we can use to enable, e.g., policy makers, to experience and qualify these scenarios in terms of impacts on wellbeing. The aim of this activity is to provide a representation of the results of a wellbeing assessment using the EIWA. A first ('paper prototype") version of activities 2 (Parametrizing and quantifying) and 3 (Visualizing and qualifying) will be presented at the 4TU-Ethics Bi-Annual conference (7-8 November 2019, Eindhoven). ***Phase 3: Committing*** **Activity 4: Demonstrate the applicability of the EIWA** We will demonstrate the practical applicability and flexibility of the EIWA by parameterizing, calculating and making visual representations in other policy areas (max 5), per case, with appropriate wellbeing indicators. **Activity 5: Engage and involve policymakers** We will create a bold presentation (think 'TED Talk') to present first versions of our instruments and methods to policy makers: the added value of the EIWA instrument, and methods for using it in policy making. This presentation will entice policy makers to invest time and effort in an EIWA evaluation. ***Phase 4: Field testing*** **Activity 6: Prepare a field testing of the EIWA** We will further develop, fine-tune and streamline both the EIWA process and the visual presentation (in iterations). **Activity 7: Proof of concept** We will test the EIWA in different concrete policy proposals / issues (max three), in which policymakers can actually apply the results in

their policy making practice. This will deliver a ‘proof of concept’ and practical examples of a (successful) application of the EIWA.

Phase 5: Maturing

Milestone 8: Strengthen EIWA forecasts
We will develop and document the EIWA instrument and Wise tank method, in order to strengthen the validity, reliability and feasibility of our support suite.

The aim is to gain three new practical examples in which the Wise tank has been successfully applied to strengthen the EIWA. The result should be that the Wise tank actually adds something of value to the policy process in concordance with the EIWA (or not).



The EIWA and Wise Tank decision support tools are relevant for all the TNO roadmaps that incorporate policy issues in their domain. We are currently exploring practical applications in 3 domains: energy transition; mobility; National Security.

USE CASES
Use case 1: KIA energy transition and sustainability
In 2030 the energy transition will have resulted in an increase in the use of sustainable energy in order to mitigate climate change. The Dutch Climate tables have defined several policy measures on different domains. The impact of these measures have been assessed by PBL and CPB, calculating the cost and expected CO_2 savings. The impact of the proposed policy measures on sustainable wellbeing has not been assessed.
The energy transition is complex and to comprehensive to assess, so in the use case the focus will be on one of the building blocks to prevent further climate change: the transition towards sustainable neighborhoods. In this transition households will have to change their behavior, buy different products and make investments.

- For the assessment on sustainable wellbeing the relevant indicators defined in the EIWA will be selected. Together with the stakeholders, for instance households in a neighborhood, we define and assess the impact of three transition options on short and long term, using both objective and subjective measures (for example: air quality (objective) and the influences on peoples experiences (subjective).
- During the assessment the stakeholders will get insights about wellbeing and biases to broaden their perspectives and help

	them to make an informed decision about the different transition options. • The outcome of the assessment of the three selected options will be visualized in order to get a good understanding of the implications and development of sustainable wellbeing over time. **Use case 2: KIA Mobility** In 2030 the way we view mobility and the role it will play in our lives will have changed significantly. People will travel using sustainable modes like electric vehicles, bike and public transport. The new mobility concepts Mobility as a service (MaaS) and Automated Driving are already emerging, slowly resulting in a mindset shift from traditional owning to using shared transportation modes. During this transition towards sustainable mobility difficult and complex assessments, choices and tradeoffs have to be made. One can think, for example, of how to assign different weights to the conflicting views of (different) stakeholders and travelers, and how to take into account the impact on environment, accessibility, infrastructure, spatial development etc. The impact of electric vehicles, MaaS and AD is dependent on the acceptance of the users, and the way they use these concepts has its own impact on multiple domains. For instance: the use of electric vehicles has a positive effect on CO_2 reduction, but MaaS and AD may increase the number of trips, thus contributing to more congestion in cities. A possible side-effect of MaaS and AD is that they are likely to replace public transport, possibly increasing the social divide. There are currently few tools or methods that aim to assess the long term impact on societal wellbeing of these interacting developments. Nor do current tools and methods take human biases into account that inhibit effective decision making. • EIWA will be used to explore, determine and visualize relevant parameters of wellbeing and short- and long term impacts on sustainable wellbeing, in addition to economic, financial and technical criteria for multiple users. EIWA will combine SOTA knowledge from different scientific area into a comprehensive tool that is able to tackle this kind of complexity. • The Wise Tank methodology will be used to help different stakeholders to value parameters, engage in effective dialogue, and score positive and negative impacts of transition scenarios towards sustainable mobility. **Use case 3: KIA Surveillance and Safety** In 2030 autonomous surveillance of criminal activities will have increased, security organizations will sense and collect new and better data, and as a result criminality will become more risky and less attractive. Better intelligence and more effective interventions will be enabled by big data analytics and artificial intelligence. • Together with interested stakeholders like police, municipalities, event organizations, etc relevant safety issues and new surveillance and intelligence concepts will be defined. • The EIWA tool will be used to explore, determine and visualize short- and long term impacts of alternative concept on indicators of objective and subjective safety, wellbeing and ethical criteria (e.g. privacy, confidentiality, proportionality, misuse, etc)?

	The Wise Tank methodology will be used to help different stakeholders to value positive and negative impacts of surveillance and intelligence concepts on wellbeing, to engage in effective dialogue about trade-offs and dilemma's and to apply methods to mitigate cognitive biases.
Dynamics	In WP 2 (wise human) and WP 3 (wise institutions), we have several extra deliverables that we had not promised in the original plan, or had not promised in 2019. And in WP 5 (Wise experiments) we had anticipated to do research that in retrospect did not appear to be fitting yet. In WP 2 we added a literature study on "retention and transfer on debiasing interventions" and we speeded up the drafting of a report addressing "critical biases in the sustainability domain" (this was supposed to be delivered in 2020). We also set up an internship literature study on "incorporating biases in predictive behavioral choice models". The reason to speed up this work package was that we needed the knowledge as a basis from which to work on the EIWA concept. In WP 3 we have three draft reports that were not foreseen in the plans for 2019, but as the focus shifted towards wellbeing, we acknowledged a gap in our SOTA that needed to be filled. This resulted in 1) Draft SOTA report of policy studies and public administration literature 'Innovation policy and policy innovation: identifying policy needs for ERP WISE'. 2) Draft SOTA report 'Participative methods for ensuring well-being and autonomy in data-driven and AI-supported policy making'. 3) Internship paper leading to the report 'The ethics of nudging' (an ethical evaluation of nudging by Dutch policy actors). In WP 5, we had anticipated to elaborate on the idea of policy labs. It appeared however, that it was still a bit too early to start testing and experimenting. We first needed a good idea of the playing field of policy making in relation to wellbeing. And we needed an idea of what we (TNO) could contribute that is unique and innovative. Now that we have developed the idea of the EIWA embedded in a Wise Tank method, we can start relating these concepts to the policy lab innovations. Finally, though not explicitly planned as a deliverable yet, we are currently developing a concept for an assessment tool based on multi-criteria, multi-actor & utility-based analysis (the EIWA tool). The tool supports the user in aligning wellbeing-parameters with policy-goals and produces a visual representation (a wellbeing landscape) of its expected impact on sustainable wellbeing for society. To further the development of a minimal viable instrument in 2020, we will start engaging a dashboard-designer and software programmer to make the first steps towards a mock-up of the EIWA that can be demonstrated. This was also not foreseen.

20 Signature

The Hague, 31 October 2019

Jaap Lombaers
Director Knowledge Management & Partnerships TNO