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TNO report

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TNO Early Research Program Annual plan 2019

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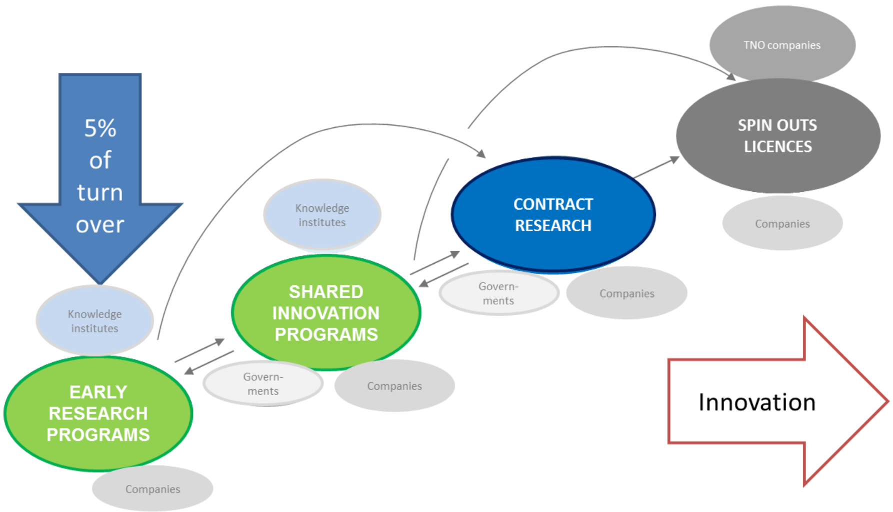
1 Introduction

The Early Research Program presented here reflects TNO's vision where to put our innovative research efforts in the coming years, so to be able to maintain and grow strong technology positions and to contribute, together with knowledge partners and stakeholders, to several grand challenges.
The major part of TNO's research, about 95%, is steered by TNO's stakeholders (clients, consultation by 'Topsectors' and Ministries, task financing by MOD, EZ, SZW). The 5% innovative research (ERP) is meant to build, renew and maintain TNO's knowledge assets (Kennis als Vermogen).



The main characteristics of the ERP portfolio are:
- Building and or renewing strong technology positions in the focus areas that are defined in the TNO Strategy Plan 2018-2021
- Use case inspired programs: ERPs feed the innovation roadmaps of multiple TNO units with common cross-unit requirements for low TRL technology breakthroughs. The output of ERPs is transferred to (higher TRL) shared innovation programs and contract research.
- A potential to give the research effort more mass through collaboration with knowledge partners and through additional investments by stakeholders (an average multiplier of 2).
- Programs with a substantial mass (on average 2 mln Euro per program), a running time of four years, and clear research goals. ERP funnel management (quarterly reviews by TNO CSO) is in place to monitor the progress and adjust and reallocate means where necessary. ERP programs are generally preceeded by one-year SEED projects that explores the feasibility of the topic, builds partnerships, and develops the full ERP program.

Together with EZ we inform Topsectors and Ministries of our approach of building our knowledge base, aiming at early involvement of companies and other stakeholders in public private cooperation.

Programs 2019

The ERPs in 2019 have been categorized with respect to TNO 'technology focus areas' (as listed in Table 3.3. of the TNO Strategic Plan 2018-2021) and described by a short summary and milestones ('Results 2019').

SP = Strategy Plan 18-21 ERP = Early Research progr.	Milestone 2019
SP: Nano- en quantum technology	
ERP: Quantum technology	Our ability to use previously untapped quantum effects in customized systems and materials is paving the way for a revolution in computation and communication. In QuTech, TNO aims to develop a quantum computer (fault-tolerant architecture, 17+ qubits, ms coherence, 99.9% fidelity, accessible online), and a quantum internet (4 quantum nodes with fiber connections). **Results 2019**: Improved qubit quality enabling the launch of (fault tolerant computing platform) Quantum Inspire (www.quantuminspire.com); establish first the two-city Quantum Link.
ERP: 3D nanotechnolgy	This ERP develops non-destructive techniques that are able to image, measure and characterize nanoscale production features through multiple and optically opaque layers, which is essential for production of the next generation of semiconductor devices. TNO has gained substantial experience in Scanning Probe Microscopy (SPM) as one of the promising solution for measuring defects, and dimensions of 2D and 3D structures. **Results 2019**: Sub-Surface Scanning Probe Microscopy (SSPM); Photo-Thermal-Acoustic Imaging (PTAI); Stimulated Emission Depletion (STED) Lithography.
ERP: Bionanotechnologie	This ERP aims to develop new technology for high-throughput detection and characterization of biomolecules at the single-molecule level. Precision in nanofabrication (nanotechnology and optics) enables the realization of molecular sensors interacting with only one molecule at a time. Nanopore sensors and single molecule fluorescence and spectroscopy enable new detection principles: in a collaboration with TUD we focus on protein fingerprinting and solid-state nanopores. **Results 2019**: proof-of-principle of enhanced throughput protein fingerprinting and design of protein-fingerprint instrument; demo nanopore sensor with optical DNA readout.
ERP: Optical Satellite Communication	This ERP contributes to the European Commission ambition to turn Europe into a Gigabit Society by 2025 by realizing a data communication infrastructure which is fast, secure and available everywhere. Satellites – and also aerial and naval platforms - will play a crucial role in the overall communication network by offering key capabilities such as: high data rates, instant and global coverage and ultra-secure links over long distances. The ERP focuses on optical satellite communication (10 Tbits/s, quantum -encrypted, long distance/deep space, multi-point)) building on technology advancements in optics, photonics, wave propagation through atmosphere, communication technology, satellite dynamics and quantum cryptography. **Results 2019**: modulation schemes and adaptive optics for high power laser beams through turbulent, free space; quantum key distribution schemes for ultra-secure optical links; Large field-of-view telescopes with limited aberrations over the full field.
ERP: Holst – Large-area ultrasound	Ultrasound for medical imaging and diagnostics have evolved into some of the most valuable medical diagnostic 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, now made of ceramic piezoelectric elements that all need to be addressed individually, a complicated and expensive process. This ERP aims to develop printed polymer ultrasound transducers that can be printed directly fabricated on top of a pixelated thin-film (flexible) transistor backplane.

	Results 2019: A first medical imaging demonstrator with polymer transducers operating at 5-10 MHz (either using thickness resonance of printed polymer piezoelectric layers or hybrid electrostatic piezoelectric transducers).
ERP: Holst – Self-adapting smart batteries	The Electric Vehicle (EV) market is challenged by battery performance (the driving-range limitation, charging speed in relation to safety, and price). Performance can be increased by monitoring and control of the temperature, pressure and charge state distribution across cells within a battery pack. Detailed cell-level temperature or pressure monitoring is not done today due to cost restrictions and integration complexity. This ERP aims to solve this. **Results 2019**: Prototype cell sensors and algorithms.
SP: Hybrid energy systemens	
ERP: Energy Strorage & Conversion	Energy conversion and storage becomes increasingly important to realize the vital transition from fossil fuels to sustainable energy. TNO developed plasmonic catalysts to reduce CO_2 to CH_4 using sunlight (Brightlands Chemelot Campus), and a process and reactor concept for the reduction of CO_2 to formic acid using renewable electricity (VoltaChem). Results 2019: reactor setup for photo-water-splitting for production of H_2 for CO_2 hydrogenation (H_2 + CO_2 > fuel) and photochemical conversion of CO_2 to C1 fuels (nanocatalysts for CO_2 > CO conversion).
ERP: Holst - Reliability and sustainablility of pv and thin film devices	Market introduction and growth of PV technologies such as silicon-PV and thin-film PV, is critically dependent on their cost, initial (rated) performance and other features, but especially on quantitative predictions of their stability, reliability and lifetime, preferably based on field data and on standardized laboratory tests. A collaboration between Holst Centre, Solliance and ECN Petten Solar. **Results 2019**: Basic understanding of failure mechanisms related to (inter)connection technology and interfaces in PV-devices by post-mortem analyses.
SP: Smart & green materials	
ERP: Submicron composits	This ERP focusses on the development of active and adaptive materials (versus static monofunctional materials). Specifically, TNO develops infrared regulating polymer foil and coatings (materials that capture light on large surface areas and guide it to a position where it can be used in combination with photovoltaic modules). **Results 2019**: Synthesis route for the production of monoclinic VO_2 nanoparticles (< 100nm, temperature 30C) and lab scale preparation of VO_2 doped polymer foils and coatings; validation of models to predict product performance and product lifetime and feasibility 3D printing polymers.
SEED: Autonomous pre-processing of plastics	The Dutch Climate Agreement requires significant reductions in CO_2-footprint. Implementation of a Circular Economy is required. Especially recycling of plastics is important, which is technically possible, but not yet applied commercially due to prohibitive costs. This ERP focusses on the autonomous pre-processing of (plastic) waste into a sustainable feedstock for industry, followed by central conversion into fuels & chemicals. Cost-competitiveness can be obtained by reducing labor costs locally through implementing efficient and intelligent technologies. **Results 2019**: state-of-the-art pre-processing plastic waste; specifying requirements autonomous preprocessing; experimental screening of potential technologies.
Decarbonisation	The Brightlands Sustainable Technology Center (BSTC) at the Chemelot campus in Geleen aims to become a hotspot and fieldlab for innovation in chemistry. Central is the ambition of a full decarbonistaion of chemistry by 2024. TNO focusses on the development, demonstration and integration of competing, sustainable and safe chemjcal process technology for a green Chemelot Campus, including electrification, recycling of plastics, CO_2 utilization, H_2 and use of heat waste.

SP: Smart megstructures	
ERP: Structural Integrity	TNO develops technology to make important macro-structures safe, increase their availability and limit the (increase in) cost to society. We do this by adding intelligence to the structures. Existing structures endowed with intelligence will assess their own condition, forecast their future state and, based on that, will signal the need for action. The agent doing this for the structure will be its digital twin. **Results 2019**: Automated construction of geometric models (improve sub-modelling by parametric models); interaction design digital twin; data/AI based self-learning digital twins with focus fatigue failure mechanism in a steel structure; demo generating digital twin of existing structure (with BAM); design of composite vehicle cabin using digital twin.
SP: Media-synchronisation	
SEED: Social VR	The foreseen Internet of Abilities (IoA) enables people to interact through augmented reality and tele-robotics. The goal of this ERP is to enable people to participate in shared events independently of their location, such as live concerts and sport games, online meetings and situational awareness operations, in which all participants can communicate and interact in a high-quality and realistic manner. Technologies developed for this purpose are 5G, point clouds, light fields and expertise on perceptual-cognitive systems.
SP: Artificial Intelligence	
ERP: Applied AI	Artificial Intelligence (AI) is rapidly becoming a transformative technology with an impact in almost every sector in society. Although current AI methods such as deep learning have achieved “super human” performances in demarcated local problems, it is not able to provide feedback to the user and unaware of its own functioning. When applying AI-systems in health, mobility and safety, they have to be controllable (self-aware), explainable, and responsible (function within legal and ethical frameworks). **Results 2019**: functional design for meaningful human control (MHC) framework (incl ethical and task-specific goal function, and self-assessment and self-management capabilities); proof-of-concept of intelligent system able to provide personalized contrastive explanations; proof-of-concept of a Hybrid AI method able to reduce discrimination in intelligent decisions while allowing for model transparency.
SP: Robotics	
iBotics	This ERP focusses on human-operated robotics (tele-robotics) in the domains of inspection and maintenance, and related exoskeleton developments. The goal for 2022 is: (1) a prototype of a full telepresence robot for inspection and maintenance with 3D remote augmented vision, audition, and touch, and intuitive bimanual control with haptic feedback, (2) a flexible robotic (exo)suit (for supporting physically heavy, mobile, and ‘difficult-to-automate’ situations, and as tracking and force feedback device for teleoperations). **Results 2019**: Intuitive control over a remote dexterous manipulator (four-fingered robotic hand); methodology for evaluating the biomechanical, kinematic and behavioural impacts of exoskeletons for support and as human-robot interface.
SP: Inside the Human body	
ERP: Organ on a Chip	Organ-on-a-chip models aim to mimick human (patho)physiology within an in-vitro system with simple readouts. Science and in particular drug development can greatly benefit from human functional organs-on-a-chip technologies (reliability, costs). TNO develops an organ-on-a-chip model 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. By 2022 we want to develop a population on-a-chip : a stem-cell based in vitro pre-clinical toolbox, enabling the introduction of population variability earlier in compound development (gut, and liver function). **Results 2019**: Validated gut and liver function-on-a-chip to study the impact of drugs, nutrition and environment on gut health.
ERP: Personalised Health	Lifestyle changes have a profound effect on life-style related diseases disease progression and can even cure (life-style related) diseases. TNO develops biology innovations (tissues and mycobiome/fungi role) and research methodology (AI/big data based interventions) for optimizing inflammatory resilience. **Results 2019**: inflammatory mechanism (human and mouse studies), methods to quantify inflammatory resilience, system biology intelligence to design mechanism based interventions or therapies; intervention methodology (ontology based reasoning for personal health advice, community driven health data marketplaces).
SEED: Body Brain Interaction	Knowledge about the complex interactions between our body and our brain can be used to optimize cognition and reduce stress, burnout and neurodegenerative diseases, as well as improve physical performance and decrease the burden of metabolic diseases and addictions. **Results 2019**: Determinants of cognitive decline in obesity and dysmetabolism; determinants of recovery from mental and physical overload in stressful situations Both topics involving a biochemical-molecular and a psychosocial component.
ERP: Exposense	Many health disorders are closely linked to exposures ranging from lifestyle factors, to chemical exposures, social interactions and stress. Many of these combined exposures can potentially be modified to prevent disease (personal early warning systems in unhealthy situations), if we would know complex interrelations between exposures, and were able to sense individual exposures. The long term goal of this ERP is to develop an integrated approach for assessment, interpretation and feedback of multiple external particulate matter (PM) related exposures and relevant internal biological perturbations. **Results 2019**: Improve TNO's PM sensor by adding chemical identification to the sensor; Integration of the environmental (outdoor and indoor) and occupational modelling into complete exposure profiles based on a person's activity pattern.
SP: Modeling and predicting integrated social systems	
ERP: Wise policy making	Decisions today are made in a volatile, uncertain, complex and ambiguous world stage where technological advances provide us with many opportunities, but equally as many threats. The goal of this ERP is to support governments, businesses and citizens in their policy making and daily choices, by enhancing their capacity to make wise decisions. Goals 2022 are: a multidisciplinary vision for enhancing wisdom in developing and implementing 'value driven' policy; support tools and methods that enable the realization and justification of wise and unbiased decisions; knowledge to predict and control human decision-making and the impact of new technology and linked policy.
SEED: Innovation Outlook	Due to technological complexity even large companies and governments are struggling with their future strategy. This complexity is even higher, as the political, social and economic factors for future trends are unclear, but have enormous impact on the actual innovation adopted in our society. Traditionally, foresight approaches focus on the process to create a common view among experts on future trends, but present technologies like sophisticated data mining and AI technologies can create more evidence based insights in future trends. This ERP generates methodologies and tools to enable this new type of data-driven foresighting providing insight in future innovations, and their potential impact on the Dutch economy and society at both the macro and micro level.

The tables below present the relations between the ERPs and the Top sectors and Social Themes.

ERP	TOPSECTOR								
	Horti culture and source materials	Water	Agri & Food	Life Sciences & Health	Chemistry	Energy	High Tech Systems and Materials	Logistics & Mobility	Creative Industry
Quantum Comp									
3D Nano									
Bionano									
Optical Sat Comm									
Holst –Ultrasound									
Holst –Smart bat									
Energy S&C									
Holst - Reliability									
Subm composits									
Preproc plastics									
Decarbonisation									
Struct Integr									
Social VR									
Applied AI									
i-Botics									
Organ on Chip									
Pers Health									
Body brain									
Exposense									
Wise Policy									
Inn Outlook									

ERP	SOCIAL THEMES				
	Environment and sustainability	Safety and security	Defense	Occupational health	Geological survey
Quantum Comp					
3D Nano					
Bionano					
Optical Sat Comm					
Holst – Ultrasound					
Holst –Smart bat					
Energy S&C					
Holst - Reliability					
Subm composits					
Preproc plastics					
Decarbonisation					
Struct Integr					
Social VR					
Applied AI					
i-Botics					
Organ on Chip					
Pers Health					
Body brain					
Exposense					
Wise Policy					
Inn Outlook					

In the next chapters the plans for the ERPs are described in a concise format agreed with the ministry of Economic Affairs, explaining the program development, the external connections with knowledge partners and stakeholders, the use cases, and the goals and activities for 2019 and beyond.

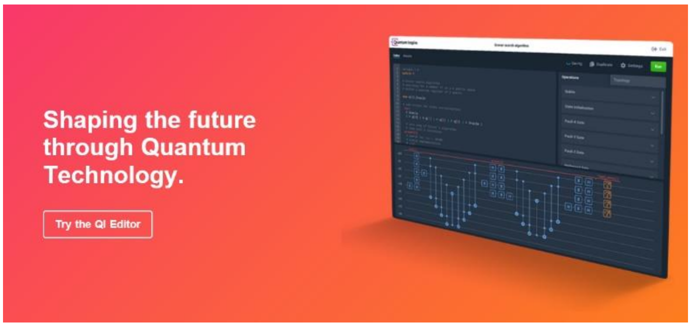
2 QuTech Quantum computing and quantum internet

General information	
Title VP/ERP	QuTech - Quantum computing and quantum internet
Contact person TNO (DM en VPM)	Peter Werkhoven Rogier Verberk
Contact person(s) government or topsector	Michiel Ottolander (EZK)
Programme 2019	
Summary	<u>Quantum technology at TNO</u> Quantum technology is seen as the basis for the “second quantum revolution”. 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 aim to exploit these effects in new systems and new concepts using our core quantum technology expertise: 1. Quantum systems engineering (QT department) 2. Nanofabrication of quantum devices (QT department) 3. Quantum encryption and protection (CSR department) 4. Quantum optics (Optics department) 5. Microwave engineering (RT department) <u>QuTech: developing quantum computing and communication systems.</u> *Long term goals* 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 second phase (2018 – 2022; Proof of Concept) will be used to demonstrate progress on key technologies (critical milestones) resulting to the following deliverables in 2022: - benchmarking, defining the requirements and system architecture, and by building or contributing to <u>pre-prototype fault tolerant</u> <u>quantum computer</u> based on three different qubit technologies (superconducting qubits, electron spin qubits and spin qubits in NV centers) accessible online - a <u>pre-prototype</u> <u>quantum internet</u>, with a 2022 milestone of a four-node internet between Amsterdam, The Hague, Leiden and Delft, accessible through an online portal allowing quantum communication between nodes. *Milestones 2019* In 2019 the Quantum Inspire platform (www.quantuminspire.com) will be fully launched (prelaunch took place in September 2018), making not only a quantum emulator available to society, but also qubit hardware developed by QuTech. It is envisioned that this platform will host different kind of quantum

computing qubits that have been developed at QuTech and will grow into a first proto-type of a Quantum Computing Cloud service.

Deliverable:

- **Quantum Inspire platform (www.quantuminspire.com) connected to the qubit hardware developed by QuTech.**



One of the most likely and interesting partners for technology transfer are Zurich Instruments, KeySight and QBlox. In 2019 B2B projects will be started up to facilitate room temperature electronics technology transfer from QuTech to industry.

Deliverable:

- **First QuTech spin-off technology licensed to commercial company.**

In 2019, the first 2 city Quantum Link will be established. Furthermore, the blueprint for the quantum internet will be developed in the Quantum Internet Alliance project.

Deliverable:

- **Quantum Link between Den Haag and Delft established.**

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The development of this blueprint will be based on QuTech’s NetSquid quantum internet simulator. In 2019 NetSquid will be extended to able to do so.

Deliverable:
- Release of NetSquid 2.0

Finally, first breadboard prototypes of non-existing key components, such as efficient quantum memory for light, of the quantum internet will be developed and tested in QuTech laser labs.

Deliverable:
- Breadboard prototype of quantum memory.

Embedding
The goals of this program are well aligned with the goals of the HTSM and the goals of the NWA route 18. Co-operation with various partners is taking place through ongoing co-operations, such as in IARPA and EU flagship sponsored projects.
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<tr>
<td>Short Description</td>
<td>
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 second phase (2018 – 2022; Proof of Concept) will be used to demonstrate progress on key technologies (critical milestones) resulting to the following deliverables in 2022:
- benchmarking, defining the requirements and system architecture, and by building or contributing to <u>pre-protoype fault tolerant</u> <u>quantum computer</u> based on three different qubit technologies (superconducting qubits, electron spin qubits and spin qubits in NV centers) accessible online
- a <u>pre-prototype</u> <u>quantum internet</u>, with a 2022 milestone of a four-node internet between Amsterdam, The Hague, Leiden and Delft, accessible through an online portal allowing quantum communication between nodes.

<u>Fault Tolerant Quantum Computing</u>
Surface codes use a 2D array of data plus ancillary qubits. Data qubits carry the quantum information, ancillas detect errors (via parity checks) induced on data qubits by decoherence and faulty gates, and classical feedback electronics analyze the detected error signals and issue all corrective actions.
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	The smallest circuits for demonstration of surface coding require 7 and 17 qubits. We pursue their realization with three approaches : superconducting qubits, electron spin qubits in quantum dots, and spin qubits in diamond. Superconducting quantum processors with 17+ qubits are already operational, with basic gate, readout and feedback operations demonstrated. Recently, the multiplexing of control technology to allow double-digit qubit numbers has been developed. Current emphasis is on qubit quality, which limits the applicability of surface codes. The overall goal with quantum dot spin qubits is to demonstrate and exploit millisecond coherence and qubit control, initialization and readout at 99.9% fidelity in a surface-code compatible architecture. In the third system, using electron and nuclear spins of atomic impurities in diamond, all basic gate, readout and feedback operations are in place. Increasing the speed of multi-qubit logic gates (via photonic coupling) is a major objective. This roadmap interacts with multiple industrial sectors. We collaborate with cryogenic equipment manufacturers (for example 'Blue Fors') to develop bigger and more powerful dilution refrigerators housing quantum processors and the classical electronics. Multiple connections are being established with manufacturers of digital electronics to explore cryogenic solutions. For the control of quantum processors, we discuss the tailoring of test and measurement equipment with leading manufacturers. The Fault Tolerant Roadmap is developing technology in close collaboration with Intel Research. <u>Topological Quantum Computing</u> Quantum states are fragile and tend to decohere quickly. This decoherence would be suppressed if the quantum state would somehow be stored in a topological variable. The roadmap "Topological Quantum Computing" aims at such topological protection. The five-year 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. A small circuit with Majoranas enables to demonstrate non-Abelian statistics. This involves exchanging, or braiding, Majoranas around each other. Braiding can change the quantum state in a controlled manner which constitutes a quantum gate operation. We will test the stability of this quantum gate and aim to demonstrate that conventional decoherence plays no role in topologically protected states. The Topological Roadmap is in close collaboration with Microsoft Research Station Q, located in Delft and headed by prof Leo Kouwenhoven. <u>Quantum internet & secure communication</u> Our goal is to build an optically-connected network of many (small) quantum computers. Such a network enables the exchange of quantum bits between any of the connected quantum processors in order to solve problems that are intractable classically.

	A quantum network in which the processors are located at different geographical locations is called a quantum Internet. Our goal is to develop the technology to enable quantum communication between any two places on earth. One application of such a quantum internet is to provide a fundamentally secure way of communication in which privacy is guaranteed by the laws of physics. Quantum processors can also be connected into a quantum network in order to assemble a large quantum computing cluster. This approach is called networked quantum computing and offers a natural path towards scalability. Combining a quantum internet and a networked quantum computer finally allows remote users/providers to perform secure quantum computing “in the cloud”. In 2019 the Quantum Internet Alliance EU flagship project will start. This alliance consist over 20 European universities and R&D institutes which collaborate to design a blueprint for the quantum internet of the future. The Quantum Internet Roadmap is using KPN’s fiber optic infrastructure in the Netherlands to realize a first Quantum Internet demonstrator.
Results 2019	<u>Fault Tolerant Quantum Computing</u> In 2019 the Quantum Inspire platform (www.quantuminspire.com) will be fully launched, making not only a quantum emulator available to society, but also QuTech developed quantum computing hardware. Its envisioned that this platform will host different kind of quantum computing qubits that have been developed at QuTech and will grow into a first proto-type of a Quantum Computing Cloud service. Qubit quality has to be improved and in 2019 several activities are foreseen to achieve this, from the nanofabrication as well as from the design perspective. Only limited partnerships can be pursued. Due the participation of Intel and Microsoft, ‘open innovation’ and pre-competitive research is no longer an option. Only partners that fit the ‘consortium’ can be invited, and only in close consultation with the existing partners. One of the most likely and interesting partners for technology transfer are Zurich Instruments, KeySight and QuBlox. In 2019 B2B projects will be started up to facilitate room temperature electronics technology transfer from QuTech to industry. <u>Topological Quantum Computing</u> The cooperation 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 the meantime, TNO has set-up a B2B relationship with Microsoft, providing quantum device development expertise. Most of the activities in the topological roadmap are cross-fertilization activities, where know-how from other QuTech roadmaps are used, such as: nanofabrication, data analyses, simulator developments, etc. <u>Quantum Internet & secure communication</u> In 2019, the first 2 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 2019 NetSquid will be extended to able to do so. Finally, first breadboard prototypes of non-existing key components of the quantum internet will be developed and tested in QuTech laser labs. Partnerships will be started based on 'open innovation' and pre-competitive research. In principle, every party could participate. KPN is foreseen to become a strategic partner of QuTech in 2019.
Dynamics	<u>QuTech cooperation</u> In 2019 the Business Development activities of QuTech will take off with the new Business Development Director in place, hired by TNO. The goal is to find new investors in Quantum Technology and start Quantum Technology transfer projects with industry as well as facilitating QuTech start-ups. Based on the mid-term evaluation 2018, it's likely that there will be changes in mission and vision statements and QuTech post-2025 strategy. One thing is for sure though, additional efforts will be spent in investigating the application side of quantum computing and communication, via reinforced activities to develop quantum algorithms, quantum simulation tools and re-inforcing the interaction between QuTech, TUDelft EWI and TNO ICT. This is in line with the ramp-up of TNO-ICT SMO contribution to QuTech from 250 kEuro to 500 kEuro from 2017 and further, as was planned at the start of QuTech. <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 2018, this could be having an effect on achieving milestones 2019. Probably this will lead to delays in Technical Readiness Level development and therefore expected market introduction of Quantum Computer or related (cloud-)services. <u>Topological Quantum Computing</u> The cooperation 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, especially in the context of TNO having started-up a B2B relationship with Microsoft next to being part of the QuTech – Microsoft collaboration. <u>Quantum internet & secure communication</u> In 2018 the quantum link between Delft and Den Haag was established. This field case will be available for quantum internet protocol testing in 2019 and a testbed for new components that are required to create a full quantum internet.

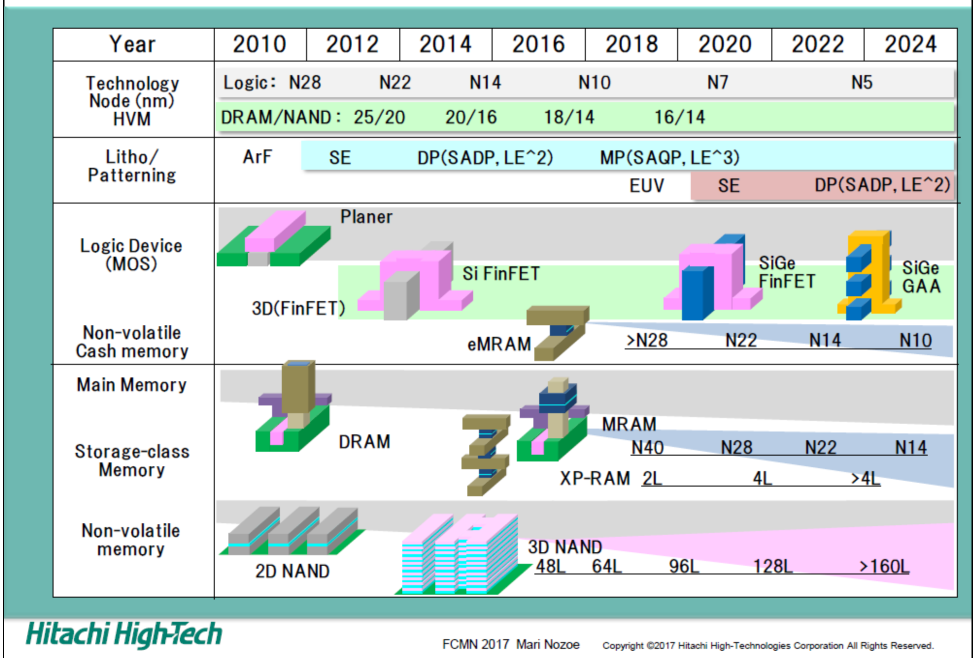
3 3D Nano manufacturing

General information	
Title VP/ERP	3D Nano-manufacturing
Contact person TNO (DM en VPM)	Stefan Bäumer, Rob Willekers,
Contact person(s) government or topsector	

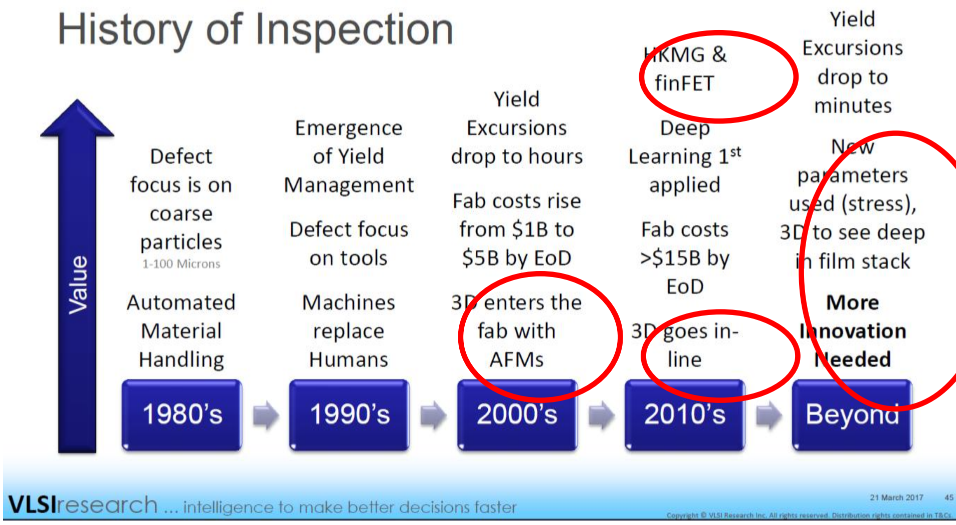
Programme 2019

Summary

There are already more connected devices than people on the planet, and the demand for these devices is steadily increasing: IOT, connected cars, immersed reality (virtual and real world overlayed). All of these products and applications rely heavily on semiconductor devices. With increasing needs for production of ever smaller and faster devices, the semiconductor industry is currently facing major challenges on manufacturing, metrology and testing. To accommodate the demands, the semiconductor manufacturing is quickly shifting away from planar device configurations and is moving towards 3D or stacked structures, such as multi-gate logics (e.g. FinFETs, Gate-All-Around FETs, and Nanowires) and 3D NAND memories.



However, due to the increased geometrical, processes and materials complexity, the conventional metrology and device testing techniques are quickly running into their limits in terms of both sensitivity and resolution. Therefore, development of non-destructive techniques that are able to image, measure and characterize nanoscale production features even through multiple and optically opaque layers are essential for production of the next generation of semiconductor devices. TNO has gained substantial experience in Scanning Probe Microscopy (SPM) as one of the promising solution for measuring defects and dimensions of 2D

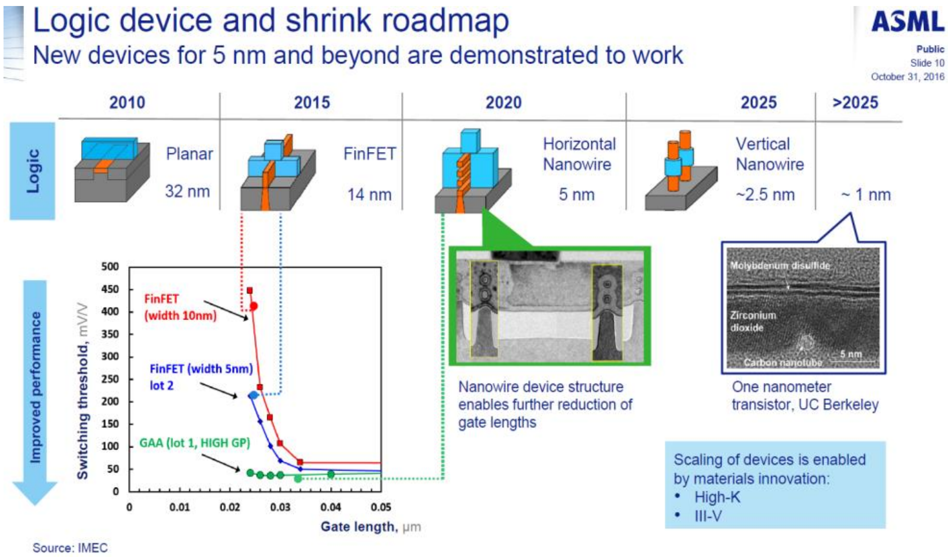
<table>
<tr><td></td><td>and 3D structures. Seeing that the devices have moved from 2D to 3D structures (see figure above) it is essential, that the SPM capabilities are being extended to 3D imaging and tomography. Developing the 3D capabilities will play a central role in the ERP. 3D imaging will be pursued through two complementary routes: Mhz and Ghz actuation of the samples and through Photo-thermal Acoustic Imaging (PTAI). Besides implementing 3D imaging, improvements are needed in protecting the samples from damage and also the repeatability of measurements have to be improved. Both can be achieved through specialized control mechanisms which will be developed and demonstrated in 2019.


As can be seen in the figure above the semiconductor industry is moving towards new parameters which need measurements as well. With a small exploration budget new parameters and techniques will be scouted and assessed on their feasibility.

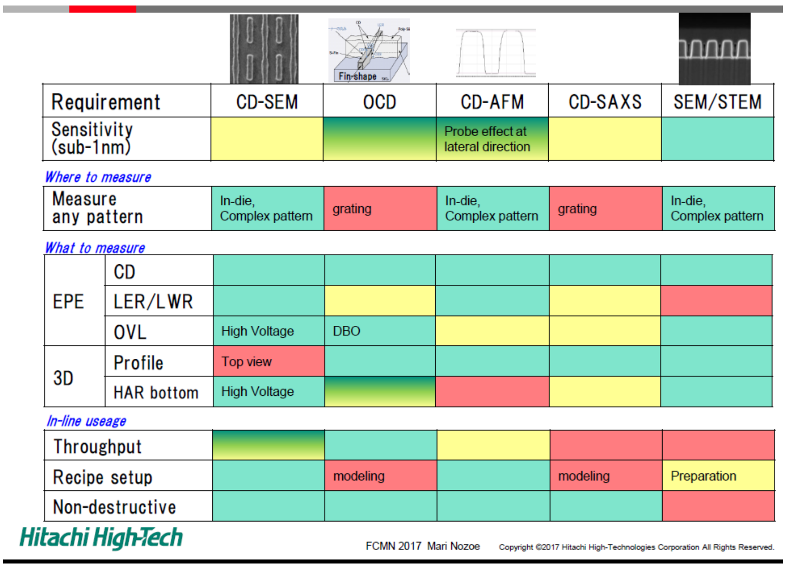
The problem of measuring x, y and z with high resolution and sensitivity is, of course, not exclusive to semicon industry. Highly sensitive nanometer resolution imaging will likely find applications on biomedical and biochemistry technologies (soft and sticky material characterization).

Summarizing the deliverable for 2019 in the ERP 3D Nanomanufacturing are
• Showing feasibility of *quantitative* 3D sub-surface imaging using MHz/GHz actuation and PTAI
• Develop a system architecture for advanced control and show improved repeatability to <1nm level
• Develop further the biology application of AFM technology by an improved flow cell development
• Scout and assess new parameters and metrology technologies for the semiconductor industry and involve complementary technologies (like AI).</td></tr>
<tr><td>Short Description</td><td>The main objective of the ERP 3D nano-manufacturing to develop solutions for
- True 3D metrology / tomography of advanced semiconductor devices aiming at 1nm resolution for new nanowire and gate all around devices as well as stacked memory.
- Making SPM based subsurface metrology quantitative and being able to detect up to >20um deep structures with a resolution of <100nm.</td></tr>
</table>

- Having implemented advanced control algorithms to make SPM technology for a large part more reliable, better performing, operator independent, and thereby HVM fab compliant..
- Next to the semicon industry the techniques of SPM will be expanded into other application fields such as bio-detection and photonic integrated circuits.
- Besides these main topics of the ERP there will room to explore new trends in metrology such as chemical imaging, quantum sensing and Artificial Intelligence (AI) for interpreting data.
- Having established a center of excellence together with partners in academia and industry.

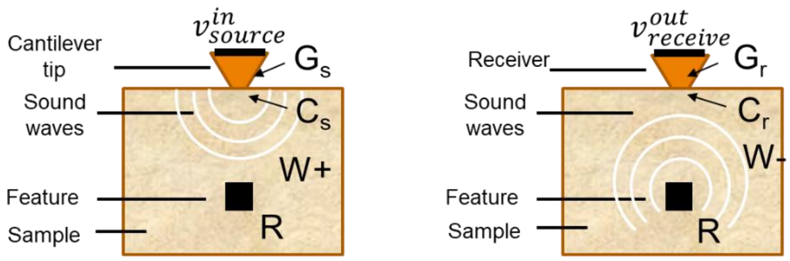


The above mentioned objectives are in line with the results achieved in previous years and also for the years to come. Looking at the figure above it is also clear, that two trends continue: shrinkages towards 2.5nm (1nm) and 3D features By shrinking the devices metrology issues will be some of the deciding factors in the entire fabrication process.



Requirement		CD-SEM	OCD	CD-AFM	CD-SAXS	SEM/STEM
Sensitivity (sub-1nm)				Probe effect at lateral direction		
Where to measure						
Measure any pattern		In-die, Complex pattern	grating	In-die, Complex pattern	grating	In-die, Complex pattern
What to measure						
EPE	CD					
	LER/LWR					
	OVL	High Voltage	DBO			
3D	Profile	Top view				
	HAR bottom	High Voltage				
In-line useage						
Throughput						
Recipe setup			modeling		modeling	Preparation
Non-destructive						

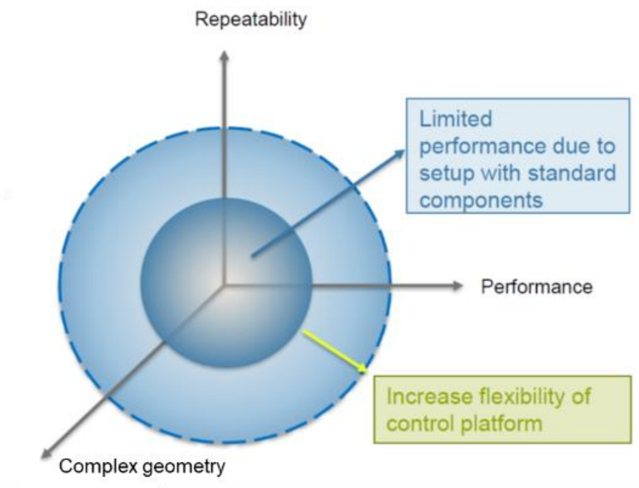
Figure: Overview on different metrology modalities

Results 2019	**Sub-Surface Scanning Probe Microscopy (SSPM):** SSPM can be divided in 2 main regions: the MHz regime, where the elasticity of a material is the main contrast mechanism and the GHz regime where the scattering contrast of the different materials is dominant. While the MHz SSPM allows for high spatial resolution but does not reach much deeper than ~500 nm the GHz SSPM will be able to penetrate several micrometers into the material with a reasonable spatial resolution. This enables Overlay and Alignment and CD metrology for next generation of Semiconductor devices, where current optical techniques fail. So far, experimental feasibility for GHz SSPM has been shown with a so-called bottom actuation scheme for frequency ranges up to approximately 5 GHz. For this technique to be accepted in the semicon fab, AND in order to be able to serve future applications, the excitation frequency needs to be increased and a top-actuation scheme needs to be designed and developed. The latter means that the excitation signal (in this case the high frequency acoustic wave) needs to be inserted from the top-side of the sample, preferably by the cantilever which also senses the response. In 2019 different top-actuation schemes will be investigated and the best one(s) will be chosen and experimentally verified. Top actuated GHz Sub Surface Probe Microscopy feasibility will be demonstrated. Simulations will be carried out to assess the feasibility of measuring real deep structure such as a depth 1 – 25 µm with resolution of <100 nm For the MHz SSPM platform the step from imaging of known subsurface nanostructures to quantitative imaging will be taken. Next to calibration of the setup the relation between depth and lateral resolution will be made quantitative by means of simulations and experimentation. After completion of the investigation, quantitative images in MHz mode can be taken.  Schematic view of subsurface top-actuation imaging. Left: actuation, right: receiving. **Photo-Thermal-Acoustic Imaging (PTAI):** In 2019 the feasibility of PTAI for Overlay and Alignment applications will be shown experimentally. Disadvantage of the current version of the PTAI setup is that the lateral resolution is limited to the pump and probe beam diameter, making the current system applicable where rather large structures need to be measured as in the alignment use case). In order to serve future applications like CD-metrology, increase of the lateral resolution is required. In 2019 we will work on this increase of the lateral resolution. For this increase, several options will be identified, analyzed and the

	best option for implementation will be selected. Finally, still in 2019 the increase of lateral resolution of PTAI will be shown experimentally on a representative use case sample.

Control technology:

Many AFM measurements suffer from rather long setup times and a low repeatability of the measurements. Both topics form an obstacle for industrial adoption of the technology in the semicon labs and fabs. TNO has in-depth knowledge of the AFM system and a long standing history of control technology and engineering. By applying advanced control technology and algorithms the set up time of the AFM system can be reduced and more repeatable results can be achieved. Also by choosing specific sample dependent modes, better performance of the system can be achieved, including minimizing sample damage. Designing a control architecture which is capable of accommodating various AFM modes, surface, and subsurface modes, at the required high bandwidth is rather novel.
In 2019 the following deliverables will be realized:



Contact mode:

- select z-position control algorithm and develop tuning algorithm based on provided measurement
- evaluate a) repeatability improvement; b) imaging performance

Amplitude-modulated AFM

- identify cantilever response to dither actuation & set dither amplitude & frequency
- select z-control algorithm and develop tuning algorithm
- evaluate a) repeatability improvement; b) imaging performance

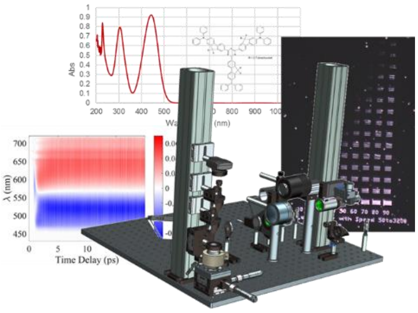
Frequency-modulated AFM

- perform FRF measurement from dither frequency to demodulated cantilever phase while in tapping mode
- select frequency control algorithm and develop tuning algorithm
- perform FRF measurement from z-scanner position input to demodulated cantilever deflection output (while in FM mode)

Stimulated Emission Depletion (STED) Lithography:

In 2018 the equipment for carrying out experiments on a new photo initiator has been built. Also several photo initiators have been investigated and one of them has been found to fulfill the requirements of high throughput (see figure below). IP has been generated on the fast photo-initiation. In 2019 the deliverables will include the testing of the new photo initiators and to establish, whether the predicted write speed of 1 m/s for high throughput applications can be reached. After this proof of concept the development of the applications for mask writing and photonic integrated circuits shall be continued in other programs.

Dye	$\lambda_{1P,abs}$	ε	$\lambda_{2P,abs}$	δ	λ_{em}	τ_1	η_1	$SE\tau_2$	λ_{SE}	$\varepsilon@\lambda_{SE}$	2P Stability	η_2	2PP @ 100 mW
Unit	nm	1/M/cm	nm	GM	nm	ns	%	ns	nm	1/M/cm		%	m/s
Requir.	<450	>40000	<800	>100	$\Delta\lambda$>50	<5	<30	<5				>2	>0.5
Method	Abs	Abs			Fl-Int	Fl-LT	Fl-Int	TA	TA	Abs	TA		Nanoscr-Amolf
DETC	425	91600		100	485(60)	1.8	2.5*	1.05	490	274	Medium	4.1	0.10
KETO	465	44800	800**	332**	520(55)	2.3	0.4	0.35	530	179	Poor	1.6	0.36
SPIRO	380	107000			425(40)	1.7	2.0	Not measured					0.18
99DiM	370	203000			495(125)	6.1	0.3	None	None	NA	Poor	NA	0.07
99DiH	350	165000			380 (30)	2.8	48	Not measured					X
PPBT	410	17700	780**	300**	515 (95)	1.2	0.9	0.44	540	500	Poor	0.12	0.43
MPPB	430	277000		200	463(48)	1.3	29	1.43	500	500	Good	7.5	0.37
AF455	445	92000	784**	400**	580(135)	4.2	0.6	1.65	640	<50	Excellent	3.7	0.39



Bio-Nano opto-mechanical measurements:

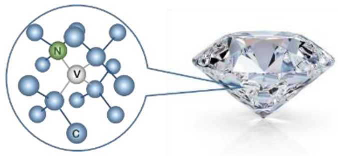
Mechanical model of the visco-dynamic behaviour of intestinal cells. The modelling is needed to further interpret and analyse experimental results. This activity will be carried out in cooperation with TU Eindhoven (NOMI JIC).
Experimental validation of the visco-dynamic behaviour of a monolayer of cells. Continuing the measurements of 2018. There is a cooperation with the ERP Organ on a Chip.
Concept development for Organ on a Chip continuous monitoring devices. The concept exploration will take into account input from the application and explore which systems are most suited for continuous monitoring given all boundary conditions. Here as well a cooperation with TU Eindhoven is possible (group den Toonder).

Exploration

Besides the main focus areas of the ERP there is room for scouting new trends and possible applications which could grow substantially in following years. Three trends have been identified, which will be sponsored by ~10% of the budget.

Quantum sensing

Quantum sensing will become an important discipline in the future. The promise of quantum technologies is that it can measure quantum behavior of matter at nano-scale. Applications of quantum metrology can be manifold. In the ERP a quick scan of possible quantum sensing technologies relevant for the semiconductor market will be carried out. A first design of a system containing an NV center on an AFM tip will be done for the application of measuring magnetic fields and small currents on a nm scale. (Image: https://spinnanoblog.wordpress.com/) The link to the Quantum technology department is established and cooperation either with ERP or VP around quantum sensing is established.



Chemical Imaging and identification

Semiconductor devices are becoming smaller and smaller but also new materials are introduced in the semicon process. In order to detect chemical composition, there are several technologies available such as variations on subsurface techniques with different readout and data processing aiming at material characterization. Other method includes Raman spectroscopy integrated into AFM technology or as Conducting AFM (C-AFM) or Scanning Microwave Impedance Microscopy (SMIM).

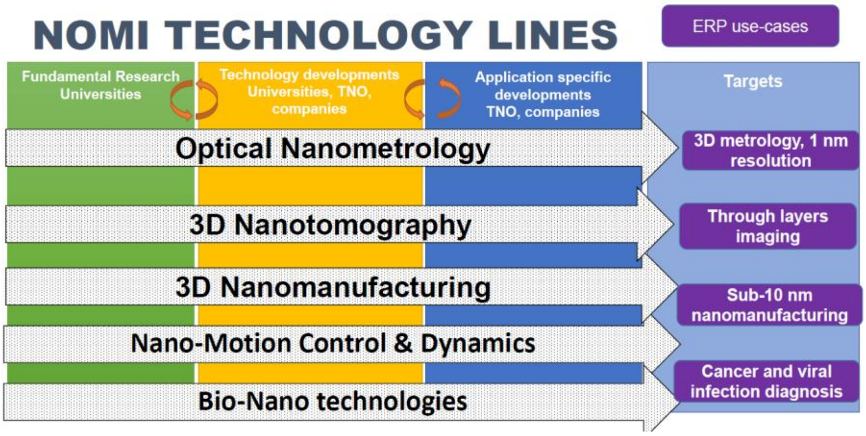
After scanning the application fields, the different techniques will be assessed regarding their applicability for the most promising applications. Then a system architecture will be sketched on how to implement these techniques onto TNO and later High Throughout platforms.

Deliverables will include:
Overview on application fields for chemical imaging
Technology assessment for the most promising application and
System architecture for the implementation.

AI (Artificial Intelligence)

Artificial Intelligence has taken its place already in data analysis of complex data (usually through deep learning algorithms). The advantage of AI is that for data interpretation of even complex data relatively little computation is needed. The issue usually is to have sufficient data for the training of the network. In an environment where physical models are available which can predict the outcome of experiments, synthetic data (which can be distorted) can be used in addition to measured data to better train the AI system. A second domain, where AI seems to be gaining ground is its application in system design. AI systems can be trained to aid in system design and the AI base designs sometimes show different results than what a designer would usually do. Having AI tools not only for the data processing and evaluation process but also for designing could be a real paradigm shift in new opto-mechanical systems. In 2019 first steps in applying existing TNO Deep learning to a select test case such as PTAI data or ptychography data will be initialed. The Link with ERP AI and VP AI will be established to make optimum use of the knowledge already present. The 3D Nano exploration will be used to test the

	specific application of 3D Nano metrology to deep learning algorithms and a roadmap towards physical models and prediction with AI.
Dynamics	In 2018 the TNO spin-off company Nearfield Instruments (NFI) has established itself further. Having first orders from customers to deliver a high throughput AFM platform has led to the situation that the lead scientist of the ERP 3Dnano manufacturing has left TNO and fully joined NFI. TNO is actively searching for a new lead scientist for the 3D Nanomanufacturing ERP. In the meantime the different teams within the ERP continue to update and execute the sub-roadmaps, as ample expertise is still present within TNO. In addition more business development support is asked for the 3D Nano activities. Since the business relations between NFI and TNO are further developed this leads to a valorization channel for TNO. Activities directly related to the parallel AFM platform have been slowed down, since NFI is commercializing this technology. Activities geared towards 3D nano-tomography such as PTAI and SSPM will be continued since TNO has unique knowledge in these fields which will have to be continued and eventually exploited in the next generation metrology tools (subsurface SPM, 3D HAR, and tomography), building on the HT-SPM platform. In 2018 PTA has seen first light and is an extremely promising technique for future tomography applications. Next to these semiconductor applications it appears that biological applications of nano-metrology become more demanding and interesting as well. Therefore the exploration in the direction of bio-metrology will continue in 2019. STED lithography has successfully been brought to a demonstrator level in 2018. Also next to the initial use case of 3D nano-lithography for mask writing a second use case has come across: STED and 2-photon lithography for customizing photonic integrated circuits, which has gained a lot of national and international interest. The work on miniaturized armless AFM heads has been put on hold, except for the photonics sensor feasibility study, which is a key element in the system development. The reason for this decision is that priority is given to the development of quantitative 3D imaging, which serves a higher market need. Since the system architecture of the magnetic levitation concept of the armless AFM has been worked out, only the most critical part was continued: the photonic sensor. The engineering of the technology will be carried on in differently funded projects. Cooperating with partners familiar with magnetic levitation technology is actively pursued. It is perceived that the work on the armless AFM will be picked up in such a cooperation. As new directions for semiconductor metrology making use of quantum technology has been added in an exploratory way. Measuring magnetic fields and currents at nanometer spatial resolution are enabled by quantum technology. Technology requirements together with market requirements will be explored. Another exploration will include the aid of Artificial Intelligence (AI) and Deep Learning for interpreting measured data. While the long standing expertise of TNO exist in the area of smart hardware design and manufacturing, the data side of metrology has to be emphasized strongly in the future.

	The 3D nano dissemination event, which was held in November / December in form of a symposium during the last years has been postponed to May 2019. This is agreed with the MT of the TNO unit Industry.  In summary, for the next period the integral picture of the NOMI eco-systems will stay as shown in the graph below. The main dynamics are that: - 3D nanotomography will become the focus of the ERP in 2019 - Optical nanometrology will be kept at very low level - And nano-manufacturing will be moved towards other funding opportunities.

4 Bionanotechnology Kiem – ERP 2019 and beyond

<table>
<tr><td colspan="3">General information</td></tr>
<tr><td colspan="2">Title VP/ERP</td><td>Bionanotechnology</td></tr>
<tr><td colspan="2">Contact person TNO (DM en VPM)</td><td>Rogier Verberk (DM), Sandra Guns (VPM), Arnold Storm (lead scientist)</td></tr>
<tr><td colspan="2">Contact person(s) government or topsector</td><td>Frank de Jong</td></tr>
<tr><td colspan="2"></td><td></td></tr>
<tr><td colspan="3">Programme 2019</td></tr>
<tr><td>Summary</td><td colspan="2">This program aims to develop new technology for high-throughput detection and characterization of biomolecules at the single-molecule level. This technology has ‘game changing’ potential: the capability to fully characterize every individual molecule in a sample means that there is no detection limit anymore. This will likely enable breakthroughs in biomedical research, diagnostics, chemical analysis and environmental monitoring. Additionally, it may enable the use of biomolecules as information carriers in computing and data storage.

This program focusses on two promising new technologies for single-molecule analytics; protein fingerprinting and solid-state nanopores. Figure 1 shows an infographic for our protein-fingerprinting project. For both options, we work together with the Bionanoscience department at TU Delft that was started by professor Cees Dekker. TNO has a strong background in optical design, systems engineering and instrument development and we will focus on design and realization of a demonstrator with high throughput in 2022. We foresee that the applications will require capability to detect and characterize at least a million molecules per sample.

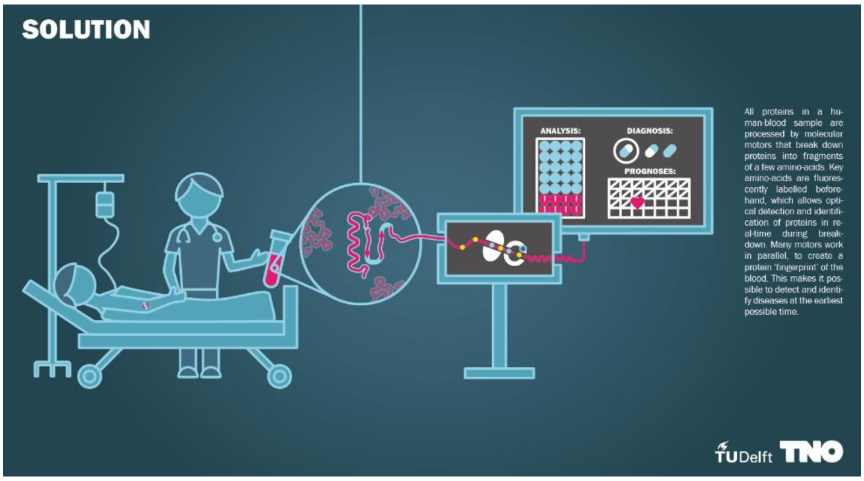
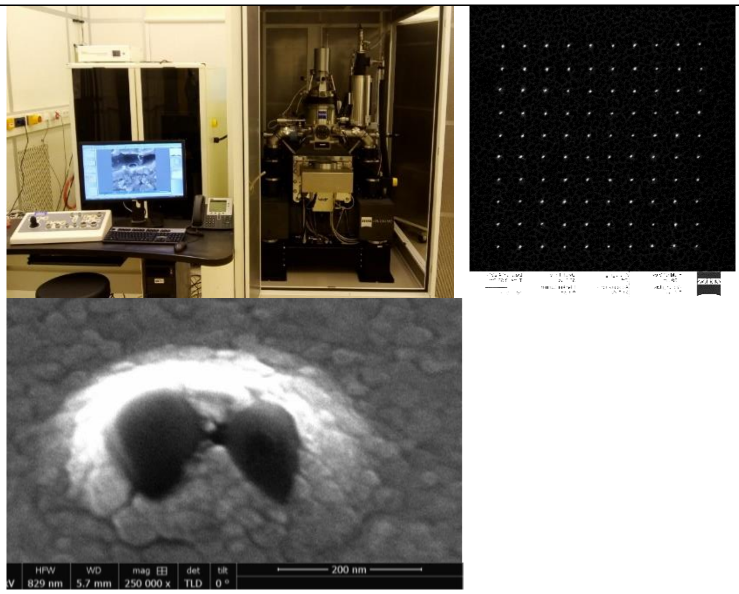


Figure 1. Infographic to illustrate our goal for protein-fingerprinting instrument

Goals for 2019 include:
- Demonstrate protein fingerprinting at proof-of-principle level.</td></tr>
</table>

	- Realize a nanopore-sensor with integrated optical nano-antennas for optical spectroscopy on biomolecules, and demonstrate nanopore-sensing of DNA experimentally. - Design the system architecture for an instrument capable of analyzing 1 million individual biomolecules in one sample. We are also actively looking for new partners to join or invest in these developments. This seed ERP brings opportunities for TNO on a new market: contract research for manufacturers of life-science equipment. Besides an economic motive, the developments can have a profound impact on improving human health.
Short Description	DNA and proteins are essential biomolecules for nearly every process in living cells. Each cell contains approximately 2,5 meters of DNA and there are over 20.000 different proteins active in the human body, with widely varying function, abundance and posttranslational modifications (PTMs). Genomics was the first step in understanding the individual response of humans to drugs, food and the general chance to develop certain diseases, skills and habits. Genomics has changed the life sciences, yet two main challenges remain: - DNA sequencing is still too expensive to perform routinely and does not have much diagnostic potential. - Analysis of a wide range of proteins with single-molecule sensitivity is not possible yet, but would provide valuable, ‘real-time’ information on the actual state of the human body. Our long-term goal is to develop instrumentation that will solve these issues with novel bioanalytic instrumentation. Developments in nanotechnology and optics are key enablers for single-molecule instrumentation. Current computer chips contain features with critical dimensions of approximately 10 nm. Within the coming decade, high-volume manufacturing with single-nanometer precision will likely be feasible. Such precision in nanofabrication enables the realization of molecular sensors interacting with only one molecule at a time. Nanopore sensors are a good example and have been demonstrated in academia. Advances in single molecule fluorescence and spectroscopy also enable new detection principles. Proof-of-concept tests at TU Delft show that single-molecule fluorescence has the potential to identify individual proteins one-by-one, using state-of-the-art fluorescence microscopy. We currently focus on two technology platforms for single-molecule analysis and detection. 1) Single-molecule protein fingerprinting using fluorescence microscopy. 2) Spectroscopy on individual molecules using solid-state nanopores with optical readout. Figure 2 shows some work-in-progress results for our nanopore fabrication project.

	 ***Figure 2:*** *left: TNO helium ion microscope used for nanopore fabrication. Middle: Array of nanopores etched in a silicon nitride membrane. Right: bow-tie nano-antenna fabricated in a thin gold layer.*
Results 2019	For 2019, we will continue with the two main technology lines running in 2018: Protein fingerprinting and solid-state nanopore development. Depending on the allocated budgets and the go/no go decision of the advisory board, we aim for following technical deliverables for next year: - Demonstrate protein fingerprinting at proof-of-principle level, preferably on the TNO setup that was built in 2018. - Realize a nanopore-sensor with integrated optical nano-antennas for optical spectroscopy on biomolecules, and demonstrate nanopore sensing with optical readout experimentally using DNA. - Design the system architecture for an instrument capable of analyzing 1 million individual biomolecules in one sample. Key components are a disposable cartridge for fluid and sample handling and a main unit with optics and analysis. - Develop essential technology and IP for high-throughput biomolecule analysis. - Identify at least three high-impact use-cases for protein fingerprinting and nanopore sensing. - Make a trade-off between nanopore and protein fingerprinting. Additionally, we will work on extending the ecosystem beyond TNO and TU Delft. - Contact with at least 2 potential customers/investors to align and fine-tune our roadmap. - Maintain and extend network in KIAs and NWA routes. This bionanotechnology program is aligned with several key NWA routes and the HTSM roadmaps Health and Nanotechnology.

	 *“Juist omdat ziektes veelal ontstaan door defecten op moleculair niveau kan nanotechnologie een belangrijk bijdrage leveren.”*  *“Eerste stip op de horizon: Een instrument dat de gehele elementaire en moleculaire samenstelling en dynamiek van een levend systeem … op niet-destructieve wijze kan bepalen.”*  *“Technologie gamechangers: “Whole genome sequencing, labs-on-a-chip, IPS cellen van patiënten, microbioom-analyse, liquid biopsies.”*
Dynamics	The bionanotechnology network is schematically drawn in figure 3.

5 FutuRe Optical commuNication by SaTellIte nEtwoRkS (FRONTIERS)

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

Programme 2019

Summary

SOCIETAL NEED for FAST and SECURE COMMUNICATION

Our Digital Society requires a data communication infrastructure which is fast, secure and available everywhere. Such an infrastructure enables our information-oriented society with Cloud Computing, the Internet of Things and Everything, and High-speed Connectivity. To illustrate this, 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 up to a Gigabit/s connectivity throughout Europe.

THE IMPORTANCE of SATELLITE LINKS and OPTICAL WAVELENGTHS

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.

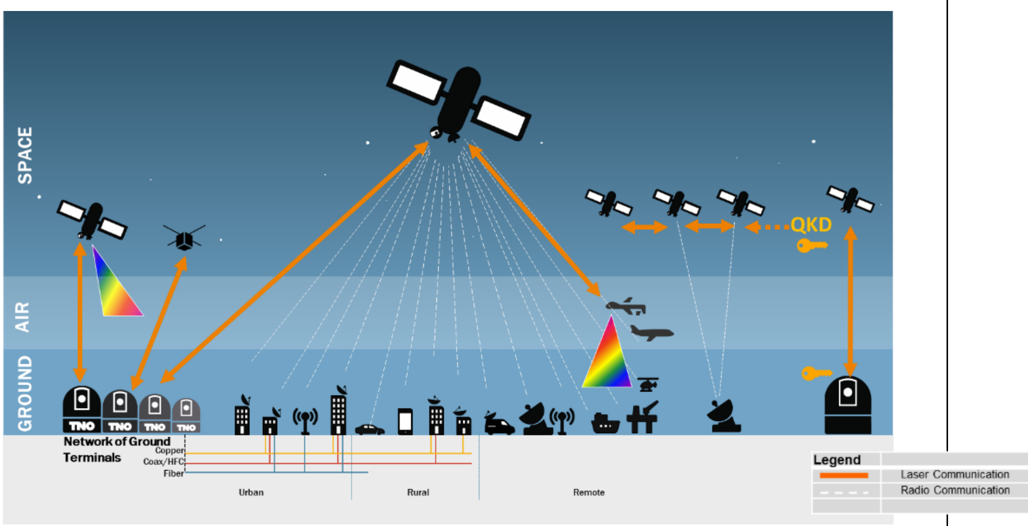


Figure 1 – Graph of various communication links with satellite and aerial platforms and the terrestrial network.

	RESEARCH PROGRAM The program focuses on knowledge and technology advancements in the specific areas of: optics, photonics, wave propagation through atmosphere, communication technology, satellite dynamics and quantum cryptography. The long-term (2022) 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. These future products comply with 4 key performance objectives: 1. Fast; order Tbits/s data throughput 2. Secure; quantum-encrypted links with ultimate protection towards hacking attacks 3. Far; data links over long distances, up to deep space science missions 4. Multi-point; communication with multiple access and multiple users links For 2019 the emphasis is on studying and analyzing promising, novel concepts and technologies which are required to meet the challenges of these future space communication links and networks. Specifically: - The minimization of turbulence effects on optical beams. - Advanced modulation methods to achieve an ultra-high spectral information density. - Optical transmitter and receiver terminals capable of distributing quantum keys from satellite nodes. - Optical and photonic system capable to transmit/ receive multiple beams at multiple angles. - Accurate pointing of optical beams in the presence of strong platform attitude instabilities. Network protocols for highly reliable performance and the integration into the core network.
Short Description	The principal objective of Optical Satellite Communication is the transfer of data by optical beams through free space. This transfer can take place between ground stations, satellites (GEO, MEO or LEO orbits), aerial (HAPS, aircraft, drone) and naval platforms. We have defined 4 key performance objectives, symbolized with a long-term target system. These are: **1) Fast** Description: ultra-high data throughput Long-term target: a 10 Tbit/s feeder link to a GEO-satellite. Application: broadband communication by businesses and citizens 2) **Secure** Description: communication links with ultimate protection, suitable for the post-quantum era. Long-term target: a Quantum Key Distribution service with satellite nodes, which is resilient to hacking attacks. Application: critical infrastructure with vital importance to society

3) **Far**
   Description: data links over very long distances
   Long-term target: a link to a deep space science mission, such as a planetary, asteroid or an L2 mission.
   Application: science

4) **Multi-point**
   Description: simultaneous communication with multiple senders and receivers
   Long-term target: a multi-beam optical space terminal in GEO-orbit, receiving data from various nodes (space, aerial, naval) and transmitting towards multiple users.
   Application: defense and commercial

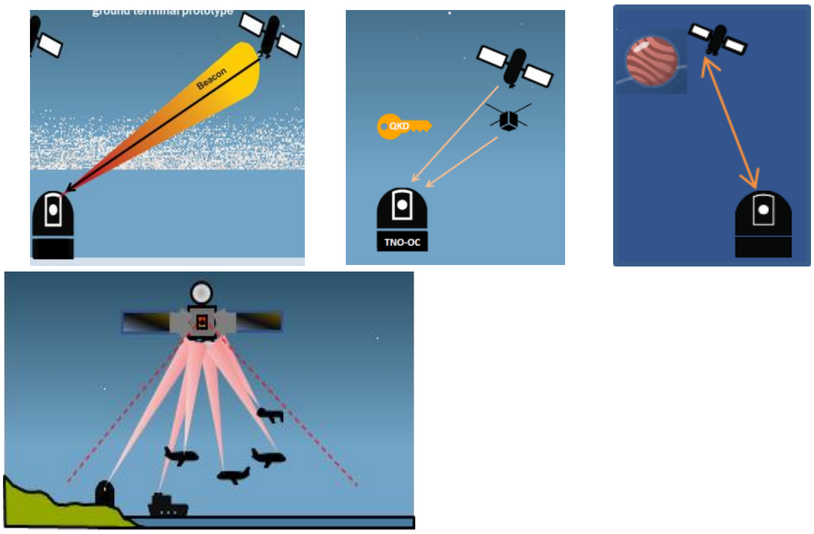


Figure 2 - Illustration of the 4 long-term target systems for optical satellite communication – 1) ultra-high data throughput, 2) ultra-secure communication, 3) long-distance link and 4) multi-point communication.

Besides the performance drivers, optical satellite communication needs to comply with specific and stringent boundary conditions:

- low Size, Weight and Power (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 4 target systems and the accompanying boundary conditions. The main knowledge areas of the ERP are:

a) Optics and Photonics with very low aberrations for single- and multi-point communication.
b) Full control of properties of optical beams, propagating over long distances through (potentially) turbulent and scattering atmosphere.

	c) Dedicated communication (modulation, coding, network protocols) technology for constellations of satellite, aerial and terrestrial nodes. d) Quantum cryptography for ultra-secure communication. The long-term (2022) 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 towards prototypes and products for Optical Satellite Communication. TNO will lead this next phase and will involve industrial partners, as active participants in a joint development towards TRL6 (demonstration of protoype in a relevant environment). Partial funding for this phase can 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. The knowledge development will be achieved in co-operation with research partners. Another objective of the ERP is to further uild the eco-system with university groups, applied research organizations and industrial partners. In further detail, the strategic 2022 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 photonics, free-space propagation, communication technology, satellite dynamics 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 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 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.
Results 2019	The research and development roadmap for the future target systems is shown below.

System		Development steps										
		2018	2019	2020	2021	2022	2023	2024	2025	2026	----	2029-2031
			TNO ROLLING HORIZON									
Ultra-High Throughput	precursor 1 Tbit/s	Outdoor test Adaptive Optics		Outdoor test Engineering Model			Ground station prototype					
	target system 10 Tbit/s	start	System Concept	Sub-system research and developments		Laboratory system verification	Horizontal link test		Ground station Engineering Model		----	10Tbit/s link prototype
Ultra-Secure Link	precursor QKD	BB84 system concept	LEO-sat system concept	Experimental proof	Laboratory system verification		In -orbit demo QKD					
	enhanced security QKD		start	System concept	Experimental proof	Laboratory system verification	Outdoor test		MDI-QKD engineering model	MDI-QKD in orbit	----	MDI-QKD service prototype
Multi-beam Optical Terminal	precursors (single-beam)		Cube-Sat terminal		LEO-Sat terminal				GEO-sat terminal			
	Multi-Beam GEO terminal	start	System Concept	Experimental (large FoV, beamforming)		Laboratory system verification		Qualification testing	Engineering Model Multi-beam terminal		----	Multi-beam optical terminal (in-orbit)
Deep Space	target system			start	System Concept	Experimental Proof	Laboratory System		Qualification testing		----	Long distance link (prototype
	TRL legend	1	2	3	4	5	6	7	8	9		

Figure 3 - Development roadmap for the 4 target systems of future optical communication systems with some prominent partners.

The research activities are organized along the same lines.

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 Terabits per second (Tbit/s) data. The knowledge and technology development is aimed at the minimization of the losses 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 2019 the particular research emphasis is on:

- High order modulation schemes, specifically QAM and APSK
- Adaptive Optics optimized for scintillation reduction and point-ahead-angle induced anisoplanatism.
- Forward Error Coding dedicated to turbulence-induced beam distortions.
- Coherent methods for improved detection sensitivity.
- High power sources, collimation and beam combination
- Advanced Traffic Steering, Switching and Splitting for constellations of ground stations and LEO satellites.

The output contains reports on the above research topics and a laboratory set-up for a single, critical technology in a multiple Tbit/s feeder link system.

Involved partners: TU Eindhoven, University of Leiden, University of Pisa, Industry: AirbusDS-NL, Demcon, and others

B. Ultra-Secure Optical Links

	The main objective is to arrive at an ultimately protected communication channel which is suited for the post-quantum world. Prominent research theme is Quantum Key Distribution (QKD) methods and protocols which have sufficient resilience to hacking attacks. Further, these QKD protocols have to yield a low Quantum Bit Error Rate (QBER), a high secure key rate and should be realizable with practically, feasible transmitter and receiver optical terminals. In 2019 the particular research emphasis is on: ▪ Various schemes for Quantum Key Distribution (continuous/discrete variables, phase/polarization modulation) and the impacts on the communication channel properties, the requirements on the optical terminals and the level of protection towards hacking attacks. ▪ Optical links, space and ground transceivers for the above QKD protocols. ▪ (Near-)single photon sources. ▪ Enhanced security QKD (measurement device independent), specific resilience towards detector attacks. The output contains reports on the above research topics and a simulation experiment for the secure key rate and the QBER for a satellite trusted node configuration. Involved partners: TU Delft, National University of Singapore, Industry/users: to be disclosed. **C. Multi-Beam Optical Space Terminal** This research topic is about wide-field, highly accurate and simultaneous receiving, processing and transmitting of multiple optical communication beams at a space terminal. Furthermore, the accurate and very precise beam pointing in presence of satellite and aerial platform attitude instabilities is addressed. In 2019 the particular research emphasis is on: ▪ Large Field-of-View telescopes with limited aberrations over the full field. ▪ Dynamic, multiple beamforming ▪ Optical phased arrays ▪ Integrated and high precision Beam Pointing 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: to be disclosed. Besides the research 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 The research activities in Optical Satellite Communication match with the technology roadmaps of 3 National Topsectors, being Photonics, Space and Security. Several industrial partners form 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). 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.
Dynamics	For 2018 this ERP has the seed-status ('kiem') and the main research activities have been on optics and photonic devices for ultra-high speed (Tbit/s) communication links and a quantum-key secure optical communication link. For 2019, these research activities for ultra-high data throughput and for ultra-secure optical links will be extended. Next, a dedicated activity on space optical communication terminals will be started, which has an emphasis on multi-point communication. This leads to higher efficiency, high flexibility, low cost, and low latency communication solutions. Furthermore, the application field of deep-space communication for science missions will be addressed. This application has very specific requirements because of the extreme, and variable link distance and the photon-starved circumstances.

6 Large-area ultrasound making medical imaging safe and affordable

General information	
Title VP/ERP	Large-area Ultrasound: making medical imaging safe and affordable
Contact person TNO (DM en VPM)	Jaap Lombaers (DM), Jan-Laurens van der Steen (pjl)
Contact person(s) government or topsector	Leo Warmerdam (HTSM Circuits and Components)

Programme 2019	
Summary	Ultrasound for medical imaging and diagnostics have evolved into some of the most valuable medical diagnostic modalities. The diagnostic imaging capabilities of ultrasound have spread across all clinical applications, from obstetrics and gynecology, orthopedics and cardiology, to emergency medicine, breast cancer detection and so on. The portability of ultrasound systems, speed, the absence of non-ionizing radiation and cost-effectiveness are some of the key attributes that have given this technology an edge over other imaging modalities when imaging anatomical structures. 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 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 current size of the arrays. The physical properties of today's ultrasound transducers make them bulky and rigid and in combination with a rapidly increasing cost for larger numbers of elements in the array, limits the usable size of the medical imaging ultrasound devices. This problem has stimulated us to start the development of printed polymer ultrasound transducers that can be printed directly fabricated on top of a pixelated thin-film transistor backplane. We intend to 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 offer higher image quality and much larger field of view. The mechanical flexibility enables complete new modes of ultrasound imaging. A first medical imaging demonstrator is foreseen by the end of 2019. First modeling results indicate that the polymer transducers can have 'sensing' performance in receiving mode, as good as ceramics piezoelectrics, but are less efficient in sending mode. Although the latter can certainly be improved by material and stack design, we want to focus in 2019 on the piezoelectric polymers as ultrasound sensors. We intend to demonstrate increased field of view when our flexible, large-area ultrasound array is combined with an existing medical ultrasound probe as acoustic source. The increased sensitivity should come from a larger number of sensors. Decoupling the

	ultrasound source from the 'sensor' is a radically new idea. For instance, it also implies that transmissive ultrasound imaging becomes possible. The technology will be further developed for specific applications in the years to follow.
Short Description	The TNO departments of Holst Centre and Acoustics & Sonar will combine in this project their know-how and expertise. Acoustics & Sonar has in-depth know-how on ultrasound imaging in a wide range of applications, incl. medical imaging. Holst Centre has a long expertise in printed flexible electronics and, guided by acoustic models made by Acoustics & Sonar, has started to develop the technology for monolithic fabrication of transducers arrays using printed low-temperature and lead-free polymer piezoelectric materials. In 2022 we want to be able to provide specialized ultrasound imaging solutions for different medical domains. To get to this technological level, acoustic modeling, array design, thin-film fabrication, and readout electronics need to be in harmony and established as a complete solution. Each application will likely require different designs and transducer array configurations but can be made using the same technology platform. Due to the different nature of flexible large-area arrays compared to conventional ultrasound devices, we also expect new medical applications to open up where imaging is improved using the scattered ultrasound detection and ultrasound in transmission, hopefully to replace CT and X-ray as preferred tools for imaging during interventional radiology procedures. The use cases have to be selected in collaboration with medical researchers, both academic and industrial
Results 2019	We will develop two different types of polymer transducers operating at ~5-10 MHz. 1. Type 1 uses the thickness mode motion of printed polymer piezoelectric layers. Modeling results show that this type requires thick polymer layers (>20 ・m). This implies technical challenges, in particular the voltages required to electrically pole the piezoelectric layer will be higher. For realizing demonstrators on a lab scale, this will not be a problem. For further scale-up in manufacturing we will engage with a specialized company. Because this transducer type is similar in architecture to that currently used in commercial ultrasound probes, the read-out electronic hardware will be charge-based. 2. Type 2 uses the flexural motion of a thin piezoelectric membrane. Here a combination of a piezoelectric suspended membrane above a cavity with a second electrode at the bottom is used. We are currently trying to patent this transducer geometry. The fabrication of the membrane is more complicated, but first membranes have been made. The thickness of the piezoelectric polymer can be thinner, compared to type 1, as readout will be based on detecting the change in capacitance due to small membrane deflection. Independent of the choice of transducer type, the fabrication process should be extremely reproducible to ensure identical transducer elements in an array and processing methods are preferable up-scalable to mass production. Once transducers have been designed and fabrication is successful, arrays can be designed for imaging. Initially we plan to match the receiving properties of the transducers to existing ultrasound probes as a sound

	source. At a later stage we will also investigate using a number of transducers in such an array as the acoustic source. The main target at the end of 2019 is a first demonstrator of a flexible printed polymer transducer array capable of medical imaging in combination with a conventional ultrasound probe as source. Imaging applications first have to be converted to technical specifications. For this we need to have a clear overview of current ultrasound medical imaging including details like the penetration depth of the ultrasound and field-of-view. Once these technical specifications are established, a clear design and process development of transducer elements and subsequent arrays can be performed. Task 1 – Modeling of discrete transducer elements (M1-2) In this task the modeling of transducer elements to achieve the required frequencies will be performed. The design of the transducer elements should focus on the 3 configurations present in the previous section. Furthermore, we will rank transducer designs from ideal solutions from an acoustic performance point of view and on solutions which can be readily fabricated with minimized process optimization. Task 2 – Fabrication and characterization of discrete devices (M2-5) The transducers from Task 1 will be fabricated and for this processes have to be developed. For example, the printing or coating method of the piezoelectric polymer is dependent on the required thickness, uniformity and lateral resolution required. For MHz thickness resonance much thicker layers are likely required compared current layers, requiring a different deposition methodology. Furthermore, thicker layers and accompanying larger step heights require different metal electrodes compared to the extremely thin (30 nm) Au electrodes used previously to ensure step coverage and good contacts. Discrete devices could be both on rigid (e.g. glass) or flexible substrates for characterization. We will check reproducibility of devices and investigate performance as a function of transducer area. Task 3 – Design of transducer arrays (M5-6) Based on the transducers designed in Task 1 and the actual performance measured in Task 2, transducer arrays have to be designed that can be combined with existing ultrasound probes used as source. The designs of the arrays have to include a solution for contacting and reading out the array by external electronics. Task 4 – Fabrication and characterization of ultrasound medical imaging demonstrator (M6-12) For the fabrication of the demonstrator based on discrete devices, the processing has to be optimal and reproducible between runs. The final demonstrator should be able to perform medical imaging. Both imaging of scattered sound and in transmission will be investigated with the array. To make it conformable to the human body the array needs to fabricated on plastic foils.

	D1: Selection of the fabrication method for transducers in the demonstrator array based on acoustic performance and fabrication possibilities (M4) D2: Design of transducer array for medical imaging demonstrator (M6) D3: Functional medical imaging demonstrator using printed transducer array as receiver and commercial ultrasound probe as source The printed transducer technology fits well within the 3F Roadmap since the technology focus is on printed, flexible and large-area electronics, where processing knowhow developed over the past years can be utilized for a new application domain. Furthermore, the (medical) imaging aspect complements the medical X-ray imaging and wearable health patch activities within Holst Centre. For optimal transducer design and acoustic characterization of the arrays a close interaction with the TNO Acoustics & Sonar (A&S) department in The Hague has been established, resulting in cross-fertilization between previously con-collaborating departments.
Dynamics	The worldwide diagnostic imaging market is expected to reach $36.4 bn by 2021, at a CAGR of 6.6% from 2016 to 20211. Geographically, North America holds the largest share of the market according to 2016 data, followed by Europe. However, the Asia-Pacific market is expected to register the highest CAGR during the forecast period. Factors such as increasing incidence of chronic diseases, rising awareness of the benefits of early disease diagnosis, development of new healthcare facilities, growing medical tourism in APAC countries, and increasing government initiatives for the modernization of healthcare infrastructure are driving the growth. Globally, the ultra-sound imaging segment is growing, and is expected to reach $6.9 billion by 2020 at a CAGR of 5.5% from 20152. Consolidated global market size prognoses for flexible, large-area ultrasound arrays are not available at this moment since this is basically a non-existing product. As stated in the HTSM Healthcare roadmap, imaging is an internationally renowned Dutch strength.3 TNO's activities are well aligned with the HTSM healthcare roadmap, with our focus on the development of diagnostic devices for applications along the healthcare continuum. It goes without saying that this activity has clear links with other HTSM roadmaps, notably Components & Circuits, High Tech Materials, and Nanotechnology and Photonics.

[1] Markets and markets – Diagnostic Imaging Market, February 2017
[2] Emerging applications and trends across medical imaging, Frost&Sullivan, 2015 ; Innovation in ultra-sound imaging, Frost&Sullivan, 2016
3 HTSM Roadmap Healthcare 2018

7 Self-adapting smart batteries

General information	
Title VP/ERP	Self-adapting Smart Batteries
Contact person TNO (DM en VPM)	Jaap Lombaers
Contact person(s) government or topsector	Richard Roemers, EZK Leo Warmerdam, HTSM roadmap director electronics

Programme 2019	
Summary	The Electric Vehicle (EV) market is booming thanks to recent battery price reductions and performance enhancement, but to attain the goal of 30% EV global sales by 2030[4], there needs to be a further drastic increase in EV adoption, driven by improved battery performance. Stationary storage for smart grids presents a similar huge challenge where batteries can play a major role. Next to new battery cell chemistry and materials, monitoring and control of temperature, pressure and charge state distribution across cells within a battery pack offers significant performance improvement, by enabling the Battery Management System (BMS) to deliver: • *increased cell safety, by avoiding thermal runaway* • *faster and safer charging by core battery temperature based charging* • *better utilization of storage capacity of individual cells while charging* • *extended lifetime (no. of cycles) of cells by more accurate monitoring* Cell-level monitoring needs integration of sensors in every cell in a battery pack. Cell-level temperature monitoring is not done today due to lack of suitable technologies and cost. In this program we will investigate integrated printed sensors combined with state-estimation and control algorithms that utilize the additional information optimally. Foil-based printed sensors for use in EV battery packs will be the application carrier. To take full advantage of the fine-grained sensorial information, Artificial Intelligence (AI) based battery state-estimation and control algorithms will be developed for smarter BMS. The program will lean on extensive domain expertise at TNO Automotive (Powertrains) and TNO Holst Centre. The combination of sensor and BMS technology will be the basis for a future differentiating proposition into the battery pack market for EV and stationary storage. The final demonstrator of the project (2022) is a functional 48V Smart Battery module.

[4] https://www.iea.org/media/topics/transport/3030CampaignDocumentFinal.pdf

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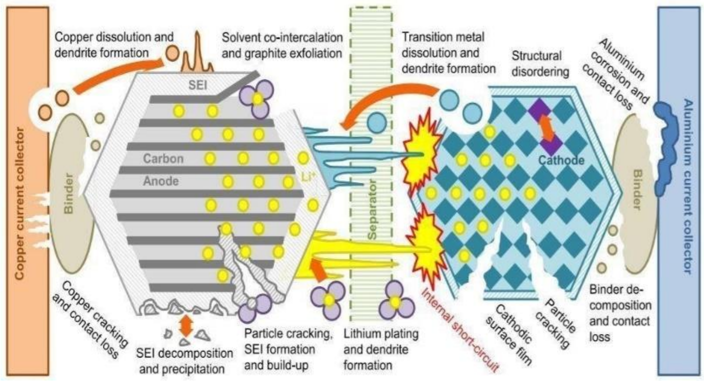

Complex physical processes influencing cell health and condition

Smart sensors require understanding of the multi-physics processes within the cell and fundamental insight into how and where which parameters can be monitored. Combination of pressure, voltage, and temperature presents valuable information about changes in crystal phase and entropy during operation. Measurements in or around the cell require innovations in sensor manufacturing and integration, and use of the measured data along with models to extract detailed knowledge of the cell in operation. Primary Research Questions are :

1. *What physical properties can be measured, and how do they relate to the overall chemical state of the cell?*
2. *Which sensor technologies are suitable for integration in or on battery cells?*
3. *How can a plurality of sensors be constructed at minimal cost and integrated in or around the cell?*
4. *How can the chemical states be used to infer non-observable characteristics (charge-state, health, capacity, discharge potential) of the cell?*
5. *Where parameters and states are variable over time, how can machine learning serve to support the various Gaussian processes?*
6. *What battery management operational parameters (e.g. charge rate, over-charging, discharge power) can be extended, and to what degree, through the inclusion of smart sensors?*

One set of 2019 deliverables and milestones (month 6) will establish the market needs and opportunities in the domain of battery monitoring systems in detail, derive system requirements, and decide about the target specifications of sensor technology, network topology and BMS algorithms. The technology status quo and roadmap outlook, and technology gaps will also be evaluated (month 6). The second half of 2019 will focus on development of sensor materials and devices, realization of the first sensor integration at cell level, including initial state estimation and control algorithms, and first implementation in module-level system, with the goal to gain early insights into technology development areas at all levels in the technology stack.

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The challenge

EV customer and OEM surveys show that price, driving range and charging limitations are key factors in adoption. These are linked to current limitations

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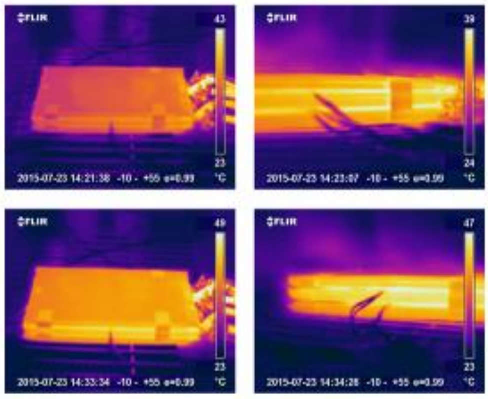
in batteries: usable storage capacity & no. of cycles under various operational conditions, cell safety & accelerated degradation, and total cost of usable capacity over battery life. Battery cell temperature is key in each of these. Temperature monitoring and control therefore plays a key role in multiple domains: thermal safety, ageing and life-time, and control. The challenge due to temperature uncertainty is not limited to automotive applications, but can also be found in other application domains (*e.g.*, grid-coupled storage solutions, consumer and industrial applications).



IR camera images of a pouch cell (equivalent to ≈100 cylindrical cells) during ex-situ charge-discharge cycling.

For small battery cells in consumer electronics, cell-level monitoring is an integral part of the system. For multi-celled battery packs, however, this is lacking, even though the importance of temperature distribution inside large pouch cells and battery packs is known[5], primarily due to cost and integration complexity. Secondly, temperature (and pressure) measurement ideally is done *inside* a cell for optimal accuracy and pro-active pack management. Practical solutions for this do not exist today because <u>existing surface-mount thermistor technology is not scalable and too costly</u>. Also, a <u>system has to be designed</u> for read-out and processing of the sensor data while balancing system cost and performance. Thirdly, <u>smart strategies to improve battery pack performance</u> (safety, lifecycles, charge time) using the sensor data need to be developed and tested to prove the application value. Since performance at one level (*e.g.*, sensor location) bears upon possibilities at another level (*e.g.*, strategy to avoid thermal runaway), a concurrent approach with several technology iterations is required.

State-of-the-art temperature measurements for battery packs

Commercial EV battery packs deploy single temperature sensor at module-level consisting of several 100 cells. Usually measurement is done at the main contact pad, which does not provide a detailed thermal map of the cells. Only when the whole module heats up to unsafe temperature does the system shut off, which is too late should the temperature rise be caused by failure of a single cell. Adding to this, the cell core heats up significantly more than its surface[6], which makes it vital to measure cell core temperature. Without detailed cell-level thermal information, individual cell state monitoring is not accurate. As the state of the battery pack is directly dependent on the state of each cell, accurate state-monitoring can prevent pack degradation over time and lead to optimal battery capacity utilization. Summarizing, detailed temperature information would provide:

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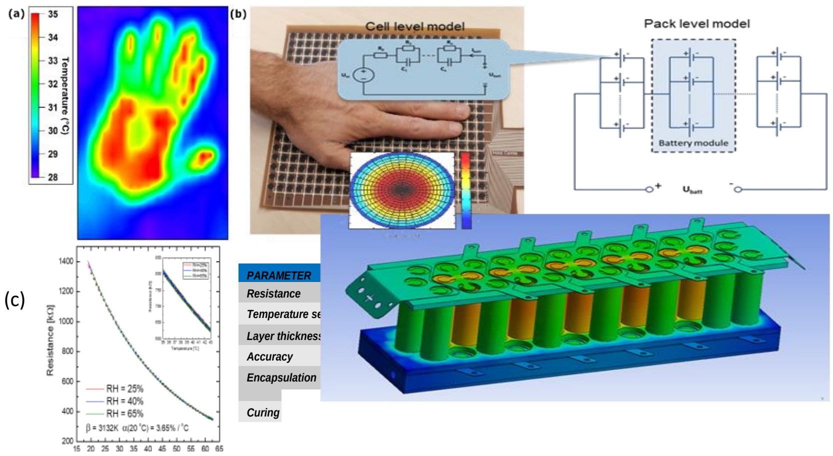
[5] Ning et al.: *3-D Temperature Field Reconstruction for a Lithium-Ion Battery Pack: A Distributed Kalman Filtering Approach*, IEEE Transactions on Control Systems Technology, 2017

[6] Richardson et al.: *On-board monitoring od 2-D spatially-resolved temperatures in cylindrical lithium-ion batteries: Part I. Low-order thermal modelling*, J. of Power Sources, 326, p.377-388, 2016

- *Earlier indication of cells that are over-heating (need not wait until the module is heated up)*
- *Better utilization of installed cell capacity, via more efficient (and localized) thermal management*
- *Increased battery pack robustness and utilization of module capacity by turning off mis-behaving cells*
- *Clearer cell-degradation picture during operation, enabling better balancing & longer cell life*
- *Faster and safer charging with higher currents*

Starting point for TNO's future technology platform
Printed electronics technology can deliver cost-effective and reliable sensors for other applications. The figure below shows an example of a printed demonstrator developed at Holst Centre. The thermal sensor uses a printable proprietary TNO material. Preliminary assessment of its performance by a partner in an IoT application showed the material to be state of the art. Sensor data will be coupled with predictive thermal management algorithms through collaboration with TNO Automotive Battery Packs (Powertrains). Various battery modelling capabilities at TNO Powertrains are shown at the lower right, covering electrical and thermal aspects and battery ageing. Based on extensive knowledge of cell, module and pack simulation, the sensor data can be effectively used to optimize the charging profile and develop advanced charge balancing algorithms. Thus, the program aims to lay the technological foundation for various potential benefits: faster reaction to unsafe scenarios; better capacity utilization; safe fast-charging (by DC Fast Charging); longer cell cycle-life; extended 2nd life and 2nd use; cost saving by less need for over-engineering the battery pack; faster time-to-market by shortening development cycles and decreasing product release testing.



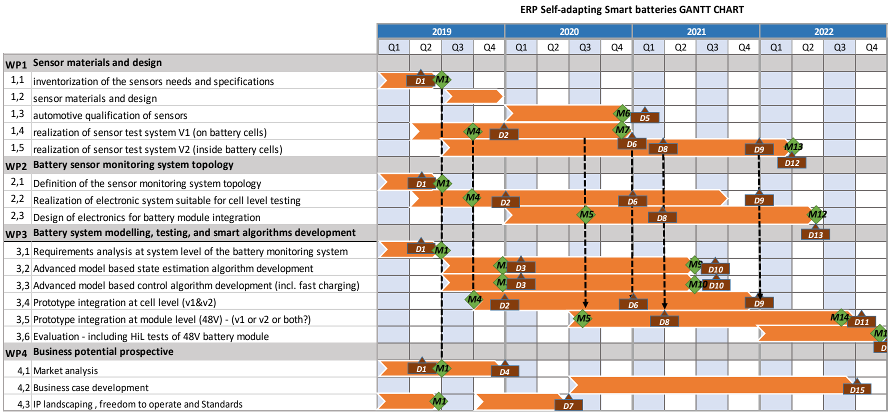
Printed temperature sensor for IoT application.
Temperature readout (a) of a hand on A4-sized sensor sheet (b), and performance of the sensors (c).

The Proposed program
The ultimate goal is to develop cost-effective and seamlessly integrated printed sensors in combination with state-estimation and control algorithms for battery systems. This program will investigate and develop required

building blocks and verify their performance in a demonstrator module comprising printed temperature and pressure sensor, system design, and advanced battery control strategies. We will develop competences in the domain of battery management and adopt a work package (WP) structure – see figure below.

<u>WP1 Sensor materials and design</u> will first make an inventory of desired temperature and pressure sensor specifications (*e.g.,* operating range, sensitivity, accuracy). A major topic will be development of a suitable sensor material system for the battery application, starting from the patented approach and including synthesis, processing and formulation of inks. Several sensor designs and measurement configurations will be investigated. Integration of sensors *inside* cells is of great potential value but very challenging, and concepts will be developed and tested for specific challenges such as solvent stability, electrode insulation, material stability, packaging, *etc*. Technology development for integration of sensors in packs is also part of this WP. Accelerated lifetime tests will be performed already in early stage to develop material and sensors that have the potential to meet demanding EV requirements. Several iterations of sensor development, integration and testing are foreseen.

<u>WP2 Battery sensor monitoring system topology</u> will look into definition of the sensor monitoring system topology, and tackle challenges in the electronics required for addressing and reading out the sensors and their integration into the battery pack. Key topics are the granularity of the electronic monitoring system and the interface between monitoring system, sensors and BMS. A first generation of electronics will be realized for cell level testing (signal conditioning, multiplexing). The next step will be combination with cell level logic to realize a larger system that can be scaled to the whole battery module and/or pack. Such system would ensure a high level of interoperability with the battery management system.



Time planning for overall programme , with split per Work Package and activity (owing to space limitations, details not discussed here).

<u>WP3 battery system modeling, testing and smart algorithms</u> will investigate system requirements for various vehicle types (*e.g.* BEVs, (P)HEVs) and applications (light duty passenger, heavy duty city transit) to determine the optimal use case for demonstration of the technology. This WP will also do requirements analysis for 48V battery module for the pilot demonstration,

	including sensor development and integration in the battery pack, and state estimation and control strategies. Prototypes will be validated at cell and module level with EV-relevant test cycles and for EV-relevant operational conditions (*e.g.* fast-charge). The final demonstrator will be a hardware-in-the-loop 48V battery module. WP4 business potential prospective will continually evaluate business development aspects, informed by the program technology progress and by external technology, market, IP, regulatory, *etc*. developments to make sure that the smart battery ERP can lead to successful valorisation through business partnerships. In this respect, IPR landscaping and filing of IPR will deserve specific attention. The program will be led by TNO Holst Centre but will be a team effort together with TNO-Powertrains. To execute the various activities will require contributions from scientific staff and engineers/technicians. In total we expect about 2.5 FTE of work, and some expenditures for materials and travel. A yearly project budget of EUR 500.000 will be needed to successfully execute this program. A number of new technologies and competences will be required to successfully execute this ERP. New and improved sensor materials, device concepts and integration approaches (esp. for monitoring *inside* cells) need to be developed that have the potential to meet demanding EV and stationary storage applications. Since no granular sensing system exists today, this needs to be developed from the bottom up, taking into consideration quality, cost-effectiveness, scalability and configurability, and interfacing with the Battery Management System, including communication. A technology platform with detailed battery model, advanced state estimation and predictive battery control tailored to the new sensor platform will need to be developed too. Finally, a thorough understanding of business opportunities in the domain of smart battery systems will be an outcome of this ERP.
Results 2019	**Detailed plan for 2019: Description of the intended results and deliverables** Before starting with the development, the system level requirements need to be clearly defined and translated into system specifications. This will be done using existing tools and experts within TNO. Since this activity is crucial to the success of the project, half a year has been planned for this, spanning all WPs. In WP1, focus will be on selecting the required sensor functionalities and specifications. The type of sensors suitable for battery monitoring and the specifications of parameters such as size, operating range, accuracy, cyclability and environmental specs will be investigated here. Integration into the battery pack will require detailed knowledge of the number of sensors as well as their location. WP2 will begin by tackling the challenges with respect to the electronics required for addressing the sensors and their integration into the battery pack. Key topics to be addressed are: the level of granularity of the electronic monitoring system and the way in which the

	monitoring system will interface with the sensors and with the battery management system. Furthermore, the level of computational power provided at each level, such as at cell, module and battery pack will be defined. WP3 will investigate Battery Monitoring system requirements for various vehicle types and automotive applications to determine generic and specific challenges. It will also analyse model-based requirements for a 48V battery module. In WP4, market analysis will be performed to gain a solid understanding of the future valorisation opportunities of the project results. This analysis will input on the main players active in this domain, the current state of the art, as well as the market and technology drivers that push the market towards a certain direction. The foregoing activities will result in two deliverables and is linked to two milestones: • A system requirement report (deliverable; month 6) • A market analysis report (deliverable; preliminary version month 6; final version month 12) • Target specifications (application, topology, functionality) defined (milestone; month 6) • Detailed, updated program plan for 2020-2022 (milestone; month 12) – this is also based on the outcome of the technical work described below. Technical work in Q1+Q2 2019 will focus on establishing the technology status quo: the detailed capabilities of in-house technology platforms and accessible external technologies, and potential future extensions. Comparison with the system requirements will provide the main performance and technology gaps that will be addressed in the later phases of the program. In the second half of 2019, when the key new required materials and technologies are established, the work towards development of a smart battery sensor system can commence in earnest. In order to learn fast about development topics at all levels in the technology stack and adjust program strategy accordingly, the program will produce feasibility demonstrators already in 2019. WP1 will start with fabrication of a range of temperature and pressure sensors with various materials and concepts to establish key performance parameters such as operating conditions, sensitivity and accuracy, as well as the technology limits. Promising sensors will undergo a limited set of automotive reliability tests (*e.g.* thermal and mechanical stress, temperature shock) to identify major challenges and development topics. First sensor test systems will be realized on the outside of battery cells. These will be combined with the first generation of the electronic system to realize cell level tests. These initial feasibility tests represent the first interfacing to the BMS and will verify that signals are properly conditioned for read-out and possible methods for multiplexing a large number of sensors (*e.g.* passive matrix) will be studied and developed. In parallel to the above, WP3 will investigate required algorithms for using the sensor information for advanced model-based state estimation of the battery cells (*e.g.* for core temperature estimation). To accelerate development, a pre-integration validation level will be used (Model-in-the-Loop). Likewise, first implementation of advanced battery control algorithm for battery control strategies (*e.g.* fast-charge) will be done by using a pre-integration validation level (Model-in-the-Loop). By the end of 2019, all results will be brought

	together in a prototype system with integration at cell level. Validation at cell level, including integration of the state estimation and control algorithms will be performed, as well as first testing with automotive specific cycles under realistic test conditions. The technical work will result in three deliverables and is linked to two milestones: • A report on the performance of the sensors including their integration at cell level (deliverable; month 12) • A Report on the algorithms for state estimation and control (deliverable; month12) • A report on technology status quo and gaps to be addressed (deliverable; month 6) • First cell sensor prototype ready for integration testing (milestone; month 9) • First module-level system ready with Initial state estimation algorithms and Initial control version (milestone; month 12) **Involved parties (present or future)** Potential partners from industry and academia/EU will be invited to become involved. We will explore the possibilities to partner up with EV expertise within the TU/e and the ERP proposition will be leveraged by using the gained knowledge and results to increase our value for participating within EU project consortia on the topic of battery management. On the industrial side, there are contacts with Sensata and Enmech about sensors for battery packs, and active contacts with partners such as VDL, BMW, GINAF, and Ebusco who could be involved as OEMs to help define or validate the application requirements. Companies like Heliox and ABB can help in defining the constraints from a charging infrastructure perspective. The program's results can also be explored with NXP who are active in (battery) sensor systems. Battery pack OEM's in the Netherlands (*e.g.* Cleantron, SuperB) or *e.g.* Germany (Akasol) may be interested in participating in a later stage. We see potential future collaborations with companies in the domain of printed electronics such as Henkel, Dupont for materials and SPG, ASMI for equipment. Since the sensor technology has a broad market potential, applications in other sectors than just battery packs can also be considered. Summarizing, we anticipate ample future interests, after technical and market feasibility have been proven, from amongst existing and new TNO partners. **External connections** The critical importance of creating a European industry along the battery value chain in order to retain millions of jobs in the EU has been recognized up to the highest levels in the EC. It is generally recognized[7] that the EU cannot compete against Asia in the manufacturing of incumbent technologies and that high performance, safety and sustainability are requisites for EU industry competitiveness. Integrating sensors in batteries is one of the means to achieve this: performance through increasing the utilization of battery packs; safety through avoidance of thermal run-aways;

[7] M. Steen et al, JRC Science for Policy Report, EU competitiveness in Advanced Li-ion Batteries for E-Mobility and Stationary Storage Applications – Opportunities and Actions (2017); European Commission, COM(2018)293, Europe on the move – Sustainable Mobility for Europe: safe, connected and clean

	sustainability through increased utilization, life extension, and second life opportunities. At the national level, there are many connections to NWA routes[8]. In the route 'Energietransitie' batteries will play a role in solutions for (i) building and vehicles as energy buffer to reconcile supply and demand, (ii) intelligent energy systems, and (iii) management of volatility. In the route 'Logistiek en transport in een energieke, innovatieve en duurzame samenleving' batteries are a key enabler in electrification of transport. Connections to the route 'Materialen: Made in Holland' are in the domains of materials for sustainable energy, high-tech systems and smart materials, and smart coatings. In the route 'Circulaire economie en grondstoffenefficiëntie' smart batteries can maximize the utilization of resources and their secondary use, and in the route 'Smart Industry' in the domain of smart products and services, smart batteries can open the door further to *e.g.* software updates of batteries and "electronic battery files" to create opportunities in secondary use. With regard to KIA's[9], 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[10].
Dynamics	This new program proposal sprouts from ideas that have been discussed in 2018. Initial assessment of the possible usability of the TNO Holst Centre sensor technology for Battery cells was performed together with TNO-Powertrains. The conclusion was that there is huge potential for this technology in the field of batteries. Sensor-enabled smart batteries seem usable for battery cell or pack development during the R&D phase (low-volume, high-margin application), and also for application in commercial battery packs (high-volume, lower-margin application). So, external developments in either application deserves monitoring, but the latter opportunity is, without a doubt, orders of magnitude bigger and more impactful. The EV battery market is expected to amount to ≈250 B€ annually by the end of the next decade, split between battery cells, battery electronics (including sensors) and battery management system. Even if the sensor system and related intelligence captures only a few percent of that, the opportunity for EV alone is sizeable. Thus, many players are evaluating or entering this domain because of its market size, but also because batteries are expected to develop into a crucial and lasting engine in electrification with future business opportunities that no one has yet thought of. It is, therefore, very important to keep track of outside developments, not only at the start of the ERP, but also during its course, as planned in the program. If

[8] https://wetenschapsagenda.nl/routes/
[9] Kennis- en Innovatieagenda 2018-2021, https://www.topsectoren.nl/publicaties/publicaties/rapporten-2017/december/11-12-17/kia-2018-2021
[10] Roadmap HTM Topsector HTSM, https://www.rvo.nl/subsidies-regelingen/high-tech-materialen-topsector-htsm

external work presents new paths or makes adopted paths less attractive, the program directions will be adjusted accordingly.

The topic of sensors in battery packs is gaining lot of attention from the battery community due to the extreme importance of intrinsic safety and reduced cost per usable kWh. Thus, the research community is also working on sensor solutions. Examples of these are listed in below Table. No one has successfully come up with a complete solution.

The present timing gives us a window of opportunity to develop new technologies that can address the application needs with a potentially differentiated offering. Our differentiation lies in our joint capability to design integrated, cost-effective printed sensors and control system, and test its performance under realistic conditions and good contacts and connections with companies in the value chain who can provide feedback on the usefulness and value of our approach. TNO has filed patents and possesses crucial know-how (patents fillings P115873EP00, p113392EP00) on the sensor materials and their application, and further generation of IPR will be actively pursued.

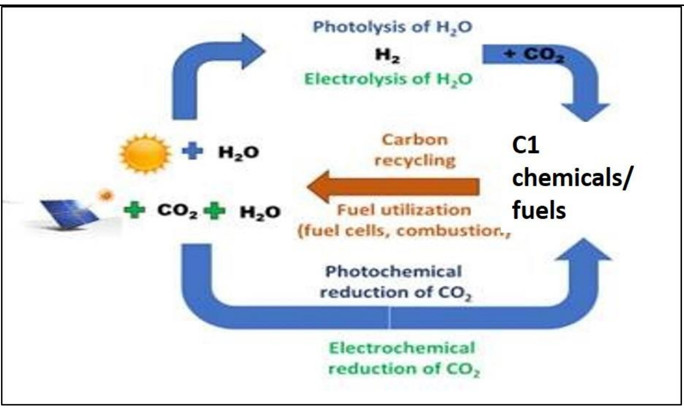
Organization	**Product**
Sensirion/EPFL	RFID T-sensors
Enfucell/NXP	Printed batteries temperature sensors
Fraunhofer IISB	Safety battery system
GE / PARC	ARPA-E project on Sensors
Taiwan Yuan Ze University	Internal cell temperature measurement
Enmech	Foil based battery management system

Table: Some organization working on (various aspects of) temperature sensors

8 Energy storage & conversion

General information	
Title VP/ERP	ERP Energy Storage and Conversion
Contact person TNO (DM en VPM)	Pascal Buskens/Peter Wolfs/Nicole Meulendijks
Contact person(s) government or topsector	

Programme 2019	
Summary	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. 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. 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. To date, 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, indirect: electrolysis of water) and on photochemistry (direct: photochemical reduction of CO_2 with water, indirect: photolysis of water to cost-effectively generate green hydrogen and subsequent use of that for hydrogenation of CO_2).

	 More information: https://www.tno.nl/nl/samenwerken/expertise/early-research-programma/ http://www.voltachem.com/ http://www.grensregio.eu/projecten/co2-voor-energie-opslag-enop
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 Photons-to-chemicals 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 concepts for production of C1 chemicals and fuels through sunlight-fueled hydrogenation of CO_2. • To develop and validate concepts for production of green hydrogen, which is needed for hydrogenation of CO_2, via photochemical and photoelectrochemical water splitting. • To develop and validate concepts for production of C1 chemicals and fuels through direct photochemical conversion of CO_2 and water. The research line Electrons-to-chemicals 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. 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 project EnOp, the starting 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.
Results 2019	**PHOTONS-TO-CHEMICALS:** **1. Photowatersplitting for production of green hydrogen for CO_2 hydrogenation:** In 2018, the potential of photowatersplitting as a technology to produce H_2 at lower costs than the conventional route via electrolysis has been investigated. These studies clearly elucidated which systems have the potential to produce hydrogen at lower cost than electrolysis (≤ 2 €/kg), and therefore contribute to a positive business case for CO_2 hydrogenation. The lab scale reactor equipment required for testing of the selected systems has been established in 2018. In 2019, the reactor setup will be validated, and the selected systems will be tested on laboratory scale (TRL 3-4). All materials required for that will be synthesized and characterized in the second half of 2018 and in 2019. Based on these lab scale results, technoeconomic feasibility studies will be performed to provide guidance for further lab scale optimization of these systems. Deliverables 2019: • Synthesis and characterization of materials (photocatalytic nanoparticles, photoelectrodes etc.) required for lab scale validation of selected systems for hydrogen production. • Comparative quantitative studies on photo- and photoelectrochemical water splitting at lab scale, providing input for first technoeconomic feasibility studies.

- Technoeconomic feasibility studies of selected systems at lab scale, and system optimization based on these results.

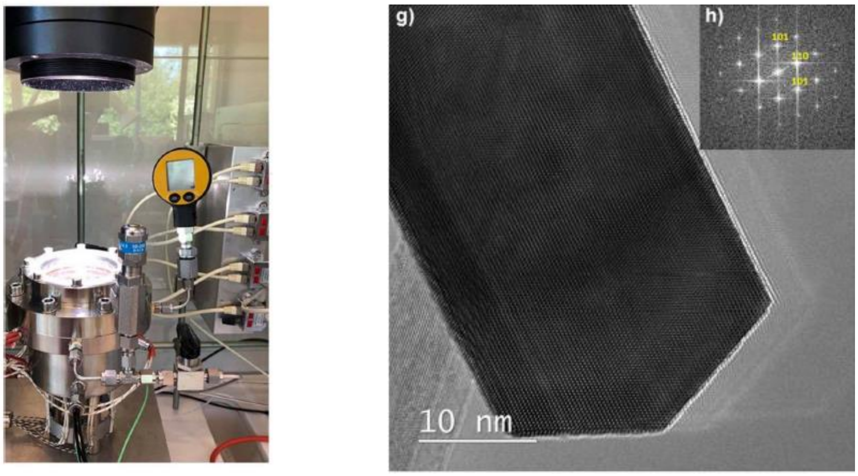
2. Photochemical conversion of CO_2 to C1 chemicals/fuels using sunlight as energy source:

In 2016/2017, we managed to successfully demonstrate the concept of plasmon catalysis in a model reaction, *i.e.* the Suzuki coupling of bromobenzene and *p*-tolylboronic acid catalyzed by Pd-decorated gold nanoantennas.

In 2018, we managed to successfully demonstrate the concept of plasmon catalysis for photochemical hydrogenation of CO_2 to methane. We designed and developed a Ru nanocatalyst, and demonstrated that it selectively converts CO_2 and H_2 to methane (CH_4) using the entire solar spectrum spanning from the ultraviolet to the near infrared. Using sunlight as energy source, we were able to perform this reaction, which normally requires a temperature between 300 and 500°C, at room temperature. For demonstration purposes, and comparative testing of various catalysts, a lab scale reaction cell was developed. This is not a suited reactor concept for scale up.

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 will focus on producing CO rather than CH_4. This conversion is expected to be economically more favourable. For that purpose, new metal nanocatalysts will be developed, characterized and validated. Furthermore, we will design and establish a reactor tailored for CO_2 conversion with plasmonic catalysts and sunlight as energy source.

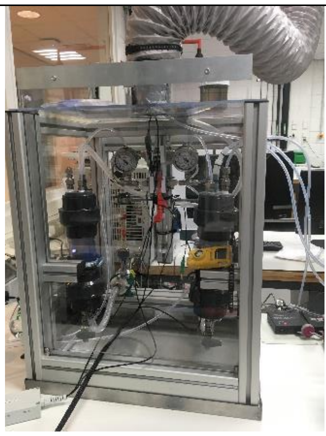
Deliverables:
- ♦ Design, develop, characterize and validate metal nanocatalysts for the hydrogenation of CO_2 to CO.
- ♦ Establish a reactor concept tailored for CO_2 conversion with plasmonic catalysts and sunlight as energy source.



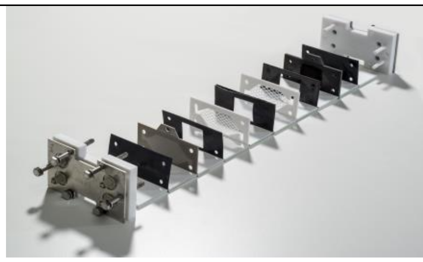
Established reaction cell for testing of plasmon catalyst (left), and developed plasmon catalyst (electron microscopy image, right) for conversion of CO_2 to CH_4.

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 fits to the NWA route Energietransitie, and relates to the topsectoren Chemie, Energie and HTSM. In 2019, no activities are foreseen in direct photochemical conversion of CO_2 and water to C1 chemicals/fuels. **ELECTRONS-TO-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: 1. Current density should be above 1 KA/m2; 2. Faradaic efficiency should be above 50%; 3. Power consumption lower than 500 kWh/kmol; 4. Electrode lifetime should be above 8000 hrs. In 2018, we successfully developed two different routes for CO_2 capture. The first route is an indirect route, which proceeds via the capture of CO_2 in the electrolyte followed by subsequent reduction of the captured CO_2. The second route is a direct route, using a gas diffusion electrode (GDE) to transfer CO_2 to the vicinity of the electrode followed by subsequent reduction of CO_2 at the electrode. The second route showed the most promising results in a first comparative technoeconomic feasibility study. In 2019, we aim to realize a proof of concept (TRL 4) for integrated CO_2 capture and conversion using an inhouse developed continuous flow reactor with an optimized three compartment GDE based cell (see Figure below).



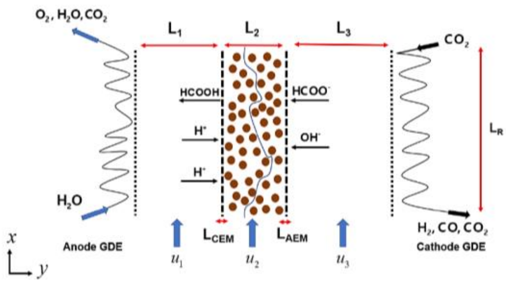
Low pressure continuous flow reactor



TNO's Electrochemical cell design

The concept that will be demonstrated, will be based on the use of a cathode comprising a GDE in a three compartment electrochemical cell. The GDE will be used as a membrane contactor to remove CO_2 from flue gas and subsequently convert it to a non-volatile chemical. This chemical will be a formate salt. Due to the fact that this has zero vapour pressure, no contamination of the treated flue gas can occur. Next to the GDE, the electrochemical cell will consist of a middle compartment separated from the anolyte and catholyte chamber by ion selective membranes (i.e. anion and cation exchange membranes). The produced formate will be combined with the protons produced at the anode in this middle compartment to FA. This FA will be enriched up to a concentration of ~10 wt%. Although FA can be a product of interest, the approach within the ERP considers FA as an ideal intermediate chemical for the production of high volume chemicals such as CO and formaldehyde because of the relative small market volume of FA.

Advanced modelling and dedicated experiments with in-house developed Tin based GDE already has shown potential for this approach in 2018.



The three compartment model

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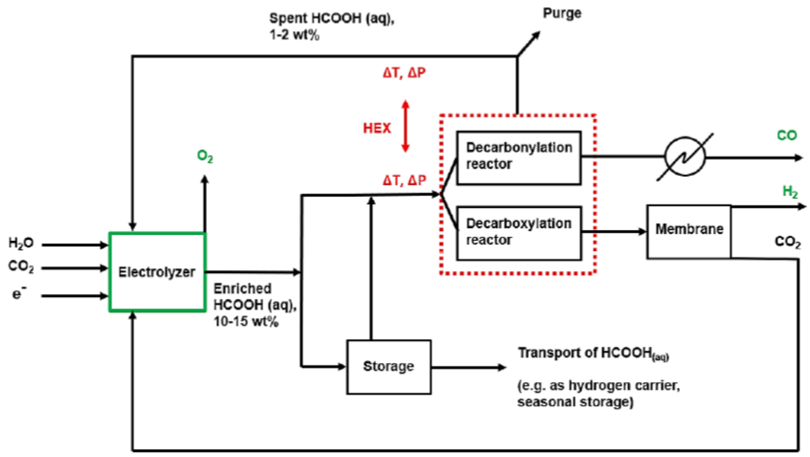

Overall concept

The aim for 2019 will be to demonstrate the integrated conversion of the produced FA to CO. The latter conversion will be done by heating the 10wt% solution to 200ºC in the presence of strong acidic heterogeneous catalyst. The produced CO will be obtained with a high purity at elevated pressures (>50 bar).
Deliverables 2019:
- Demonstrate an integrated CO_2 capture/conversion methodology
- Explore the efficiency of this concept for very dilute CO_2 sources (i.e. air capture)
- Perform a detailed techno-economic evaluation of the developed process concept

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.
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<td>Dynamics</td>
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The program has been carried out in accordance with the plan. We achieved the goals set for 2018 for the main research areas Photons-to-Chemicals and Electrons-to-Chemicals.

PHOTONS-TO-CHEMICALS:

○ In 2016/2017, we successfully demonstrated the concept of plasmon catalysis using a Suzuki coupling as model reaction
○ In 2018, we successfully demonstrated the concept of plasmon catalysis for sunlight-fueled hydrogenation of CO_2 to CH_4.
○ In 2019, we will focus on the development of plasmonic metal nanocatalysts for sunlight-fueled hydrogenation of CO_2 to CO, based on the input from industrial experts.
○ In 2019, we will not only focus on design, synthesis, characterization and validation of catalytic materials, but also on the design of a tailored reactor for plasmon catalytic conversions. This is required to establish a demonstrator that enables technoeconomic validation.
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	○ In 2019, we will validate selected systems for photochemical and photoelectrochemical water splitting for producing low cost green hydrogen. This is selected based on business case studies for hydrogenation of CO_2 that clearly illustrate that the high costs for green hydrogen from electrolysis negatively impacts the business case. **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 CO_2 flue gas. This result have changed our approach from decoupled CO_2 capture and electrochemical conversion towards integration of both. In 2019, we aim to realize a proof of concept (TRL 4) for integrated CO_2 capture and conversion using an inhouse developed continuous flow reactor with an optimized three compartment GDE based cell. **GENERAL:** 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 will explore such new technologies, e.g. heat storage. TNO started in the field of heat storage the multiyear project Dope4heat in 2018 and the multiyear project MAT4HEAT is planned to start in the second of 2018.

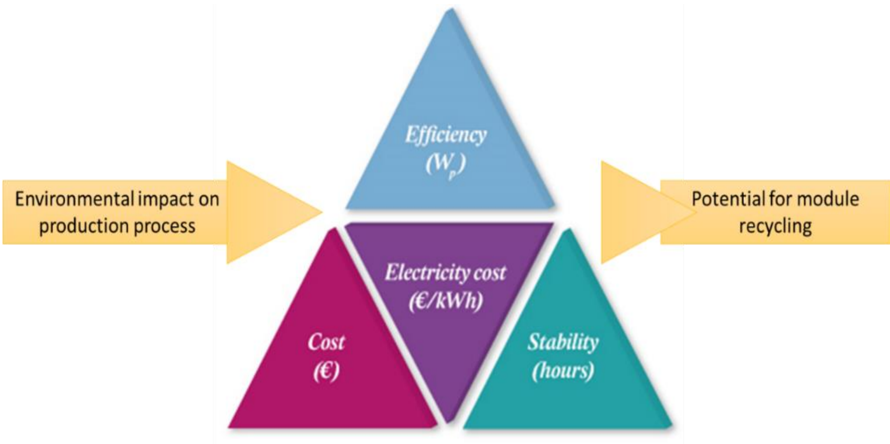
[1] Marrakech Action Proclamation for Climate and Sustainable Development (UNFCCC, 2016), https://unfccc.int/files/meetings/marrakech_nov_2016/application/pdf/marrakech_action_proclamation.pdf

[2] Directive 2009/28/EC of the European Parliament and the Council (European Union, 2009), https://ec.europa.eu/energy/en/consultations/preparation-new-renewable-energy-directive-period-after-2020

9 Reliability and Sustainability for PV and Other (Opto-) Electric Thin-Film Devices

General information	
Title VP/ERP	Reliability and sustainability for PV and other (opto-) electric thin-film devices
Contact person TNO (DM en VPM)	Jaap Lombaers (DM), Wim Sinke, Mirjam Theelen (pjl)
Contact person(s) government or topsector	

Programme 2019	
Summary	In the coming decades, worldwide utilization of photovoltaics (PV) as a clean source of electricity will grow by two orders of magnitude from its current level of 0,5 TW_p. This level already corresponds to thousands of km^2 of PV installations, and to maintain further growth PV will increasingly have to be integrated with other functions of surface areas. Therefore, TNO Solar Energy recently decided to focus its strategy on integrated PV. Here, PV semi fabricates will be integrated in building and construction elements, floating devices and concepts for dual land use in fields. This integration implies that PV materials will have to comply with more and very different external stress factors like mechanical and environmental loads in for example built, infrastructural or marine environment. The current market of PV is served by crystalline silicon modules (≈95%) and glass-based (rigid) thin-film PV modules (≈5%). Flexible thin-film PV modules (solar foils) have a small market share yet, but hold a great promise for the newly envisaged integrated applications, and for improved efficiency by integration into tandem cells. Moreover, they may be produced very efficiently in roll-to-roll processes. Market introduction and growth of new PV technologies such as flexible solar foils, however, is critically dependent on their cost, initial (rated) performance and other features, but especially on quantitative predictions of their stability, reliability and lifetime, preferably based on field data and on standardized laboratory tests. Lifetime, for instance, has a direct effect on the levelized cost of electricity generation. Therefore, understanding of the specific stress factors and processes that determine these parameters in integrated PV applications is very important, in addition to achieving a sufficiently high initial foil efficiency and a sufficiently low cost. One example is that better understanding of the reliability can lead to lower production costs: for (flexible) thin film modules, like CIGS, a large share (over 50%) of the module costs is made up by the protective/encapsulation materials, like a water barrier. Better intrinsic stability of the solar cells could reduce these costs. Similar arguments are applicable to other electronic thin-film devices on flexible substrates, like wearable sensors patches, X-Ray and ultrasound sensor arrays and devices for other Internet-of-Things applications, for example in healthcare and automotive. For all these devices, reliability questions are therefore very important. Many questions are related to

	interfaces in the material, either between interconnection materials (like wiring) and devices or at interfaces between (thin) films. In this project, we will focus on application specific aspects of long term stability, using generic aspects as starting point and reference. We are aiming to obtain fundamental chemical and physical understanding of the failure mechanisms of devices. A special focus will lie on devices failed under actual working conditions, which will clarify whether laboratory reliability tests yield representative information about the long term stability. This will provide a basis for new standards for testing integrated PV materials Moreover, the market opportunities and regulatory necessity of sustainability of photovoltaics will be studied. This is in line with ongoing European efforts to introduce ecolabeling for PV. An example of sustainability aspects is recycling, which is expected to be a billion euro market in a few decades: however, currently modules are not designed for optimal recyclability. In the end of 2019, a recommendation report will be presented. Additionally, in 2019, this project will result in improved, application oriented post-mortem test methods, improved knowledge about interface and interconnection stability in thin-film (opto-)electronic devices and several submitted publications and patents. The latter will be based on new low-cost, reliable product designs, which will result from the extensive link between the TNO device production lines and this reliability study.  Figure 1: The triangle displays the main parameters determining the cost competitiveness of electricity from a PV system. The yellow arrows indicate the additional factors that are relevant for the environmental impact of electricity produced by PV. A similar figure can be made for other electronic devices.
Short Description	**Reliability** The qualification and attractiveness of a solar panel or electronic 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. The robustness of the product towards external environmental conditions is strongly determined by the choice of the materials (polymers, composites, semiconductors, metals), their mutual interactions and the way they are processed together into a device. In order to understand and control degradation processes comprehensive research in relation to processing is thus required to go beyond the phenomenological level of knowledge that is currently hampering the progress towards development of accelerated life time test that can predict operation under practical conditions. Hence, in this ERP the long term goal is to be able to predict and prevent the occurrence of small and large failures in electronic devices. This will lead to a decrease of the degradation rate and an increase of the lifetime. This will be reached by: - An increase of the **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 at interfaces where components are joint and different materials are combined. The knowledge will be used to develop the materials and processes 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. - The development **accelerated test protocols** for new types of flexible devices in emerging application areas (like BIPV, Infrastructure Integrated PV, PV on water, PIPV, flexible sensor arrays and textile integrated devices) 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 by playing an prominent role in international task forces and platforms like PVQAT, IEA PV task 13 for PV and Photonics21, OE-A and EMIRI for flexible electronics. **Sustainability** The large scale introduction of photovoltaics 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 15.000.000.000 dollars in 2050 [5]. In order to address circular economy aspects and reduce the environmental footprint of PV and other electric devices, this ERP will be used in 2019 to define a long term TNO strategy for sustainability by identifying the key drivers, opportunities and market chances with the aim to initiate a separate R&D program for this theme.

Results 2019

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 and ECN part of TNO Solar Petten, several topics were selected which are generic between the selected technology lines:

- Potentially (semi-)flexible PV: CIGS and x-Si (higher TRL), perovskites and integration in tandems (lower TRL);
- (Semi-)flexible electronics.

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:
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 phenomenological description
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 mechanism with dedicated test samples and propose improvements

The focus will lie on failures that are related to **(inter)connection technology and interfaces.** 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.

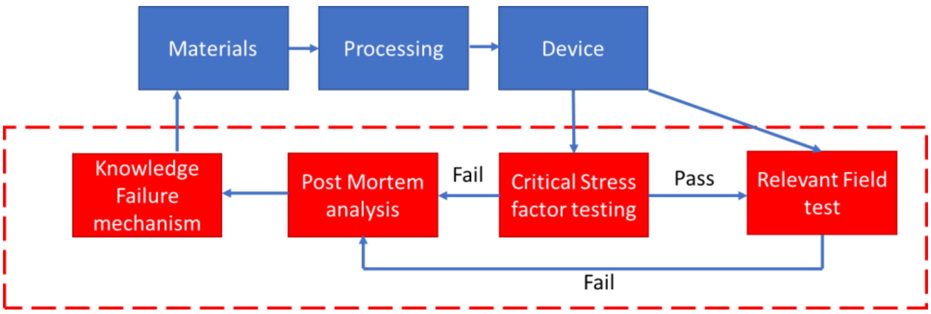


Figure 2: Proposal of the scope of this project displayed as the red blocks. Many activities within TNO focus on the production of layers and devices, while their long term stability and reliability is not studied. In this project, we will take already existing products and study their intrinsic (material related) and extrinsic (device and environment related) stability and reliability.

Cases

The general project will contain various sub-projects which are all focusing towards understanding cross fertilization:

- Stability and reliability of interfaces in (thin film) PV and electronic stacks, including CIGS, perovskites and interfaces between rigid and flexible/ductile materials in crystalline silicon modules (e.g. encapsulation, interconnection). The final goal will lay in the introduction of (semi-)flexible devices, while rigid devices can function as model.
- The influence of metal oxides (MO_x) deposited by s-ALD on long term device stability.
- Mechanical/electrical stability of transitions (interconnections) between materials with different mechanical, thermal, etc. properties under practical stresses (mechanical, thermal shock, exposure to solvents/vapors, etc.).

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, either from industrial partners after failures or within TNO.
- Competences in advanced microstructural (in-situ) characterization, chemical and physical processes, materials science.
- Development of non-destructive analysis methods and preparation methods for test samples, devices.

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 will execute a study to answer the key questions and 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. This report will allow a more sound decision whether a separate research program on this topic should be initiated.

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), both under development, for the discussion tables (in Dutch “sector tafels”) Electricity and Built Environment.

The project also connects very well to the goals set by the European Technology Innovation platform for PV (ETIP-PV). ETIP-PV is presently preparing 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. 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 to the M2i/NWO research program on material degradation will be studied, as it will offer good opportunities to team up with academia on this topic. If this appears relevant and achievable, participation in the grant submission will be pursued. Moreover, a personal Starting Grant application within the ERC Horizon 2020 research will be filed in order to fund in-depth research on long term PV stability.

Parties involved

The TNO teams involved in this project will be those of Solliance, Holst Centre and ECN part of TNO Petten (Solar). The project will combine 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 and university partners of these groups will be involved. A selection of national and international involved company partners will be Hanergy, AVANCIS, Solar Tester, Eternal Sun, EigenEnergie.net, DSM, Sabic, Energyra, Exasun Tempress, Levitech, Dupont, Philips, Solvay, BASF and Henkel.

Targeted project results

Table 1 shows the aimed project goals for 2019 and the responsible research group. Although a leader is appointed per result, naturally all groups will collaborate towards these goals.

Table 1: Project results with due date in 2019 and the responsible research group

Nr.	Title / description	Due date	Leader
R1.1	Validated innovative setup for post-mortem failure identification of PV (mechanical isolation of defects)	M4	TFT
R1.2	Progress report 1 – Identification of failures	M8	TFT
R1.3	Validated innovative setup for accelerated testing of PV under specific application related stress factors	M8	TFT

	R1.4	Progress report 3 – First proposal to prevent failures	M12	Holst
	R1.5	Test report of a first trial improved encapsulation material (replacement for EVA and PO), tested for >20years lifetime, improved resistance to physical/chemical stress in specific integrated applications, and improved release behaviour for disassembly. Strategies for improved encapsulation designs.	M12	TNO Petten
	R1.6	Test report of transparent conductive layers with improved corrosion resistance, enabling lower cost encapsulation at wvtr $>10^{-2}$ and improved resistance to physical/chemical stress in specific integrated applications. Strategies for improved encapsulation designs.	M12	TFT
	R1.7	At least 4 conference presentations	M12	TFT
	R1.8	At least 4 submitted scientific manuscripts	M12	TNO Petten
	R1.9	At least 2 submitted patents	M12	Holst
	R1.10	Submission ERC grant	M10	TFT
	R1.11	Studied participation in M2i reliability call	M10	TNO Petten
	R2.1	Initial report on market chances for sustainability within TNO	M5	t.b.d.
	R2.2	Plan for market approach Sustainability	M10	t.b.d.
Dynamics				

10 Submicron composites

General information	
Title VP/ERP	Submicron Composites
Contact person TNO (DM en VPM)	Peter Wolfs and Pascal Buskens
Contact person(s) government or topsector	Floris Lantzendörffer (EZ)

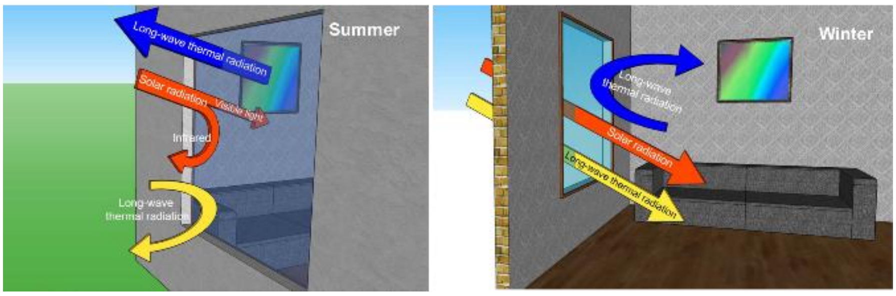
Programme 2019

Summary

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, in specific cases we aim to progress from static monofunctional materials 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 (BMC) and its partners. Within the framework of this ERP, we aim at facilitating a successful transfer of technologies delivered by academia at a TRL level of 2-3 to the applied research activities on a TRL level of 4.

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.



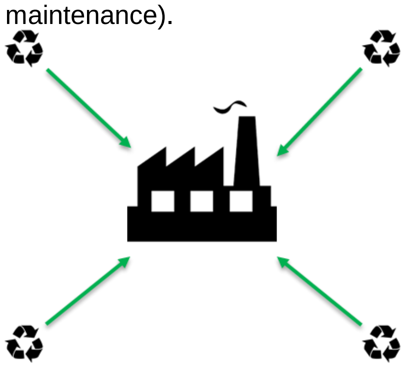
	In line with the BMC program Additive manufacturing (AM) , we aim to develop new materials and processes for the production of parts with high mechanical reinforcement as well as integrated thermal and dielectric functionalities, based on AM of fibre reinforced polymers. An example of an automotive part, that requires resistance against high thermal as well as high mechanical loads, which is the base of this use case, is an inlet manifold. This is 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. In 2019, we aim to show the first feasibility of 3D printing carbon fibre reinforced polymers to enable mechanical reinforcement in simple geometries. After that, 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 foils for glass lamination, to improve the energy efficiency of buildings. Focus of the ERP until 2022 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 2022, 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 2019	Sustainable Buildings: In 2019, we aim to achieve the following: • Synthesis route for the production of monoclinic VO_2 nanoparticles with a size below 100 nm and doped for lowering the switching temperature from 68ºC to 30ºC. • Lab scale preparation of nanocomposite PVB and other polymer foils comprising doped VO_2 nanoparticles. • Development of lamination procedure, and optical characterization of nanocomposite polymer foils integrated between to glass sheets. • Development of hollow/porous VO_2 nanoparticles to lower the refractive index in the visible (2019-2022, PhD at Hasselt University). • First nanoporous VO_2 coatings on glass realized. Additive Manufacturing: In 2019, we aim to achieve the following: • Extensive in-depth validation of the process-structure-property relations and models to predict product performance and product lifetime, as developed in the period 2017-2018. For these activities, we will strongly cooperate with academic partners, in particular Eindhoven University of Technology (TU/e). The Polymer Technology group at TU/e has a strong expertise in the area of polymer processing and design, through the use of experimental and computational tools in the modelling of the full thermo-mechanical history of materials during their formation, processing and final design, to quantitatively predict properties of processed objects. • Show the first feasibility of 3D printing carbon fibre reinforced polymers to enable mechanical reinforcement in simple geometries. After that, 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. • 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.
Dynamics	**Activities, deliverables and milestones 2018, Sustainable Buildings:** ▪ Liquid phase synthesis of monoclinic VO_2 particles with a size larger than 100 nm. In 2018, we managed to develop a synthesis route yielding monoclinic VO_2 particles with typical sizes between 500 nm and 1 µm. In 2019, we will focus on reducing particle size to less than 100 nm, and introducing dopants for lowering the switching temperature. ▪ Milling of monoclinic VO_2 particles with a size larger than 100 nm to a particle size below 100 nm. In 2018, we managed to develop a milling procedure to mill large metal oxide particles to obtain a size below 100 nm, as demonstrated for TiO_2. We have to scale up the batch size of VO_2 particles produced in our lab to produce sufficient material for milling, which will take place in 2019.

	▪ Characterization of VO_2 particles, including the thermal switching behavior. Together with the University of Hasselt, in 2018 we have developed characterization procedures to identify size, shape, composition, crystallinity and switching behavior of VO_2 nanoparticles. ▪ First polymer composites produced comprising VO_2 particles (together with Zuyd University of Applied Science). In 2018, we successfully prepared polymer composites with metal oxide nanoparticles, as demonstrated for TiO_2. We have to scale up the batch size of VO_2 particles produced in our lab to produce sufficient material for preparing polymer composites, which will take place in 2019. **Activities, deliverables and milestones 2018, Additive Manufacturing:** ▪ Model to predict product performance of polyamides process by PBF (with TU/e). In 2018, we have realized a model to predict product performance and product lifetime of polyamides processed by AM, in particular by powder bed fusion. Further in-depth validation will take place in 2019. In addition, in 2019 we will extend these activities to include processing of polyamides (unfilled and filled with glass and carbon fiber) by extrusion-based AM processes. ▪ Polyamide (PA) products produced by PBF AM process, and product performance tested (upon high mechanical and thermal load, together with TU/e). In 2018, we have realized PA-12 products by PBF AM and tested their performance. In 2019, we will extend the activities to include PA-6 and composite materials (based on glass and carbon fiber) that enable high mechanical and thermal performance. Processing of these materials will be by extrusion-based AM processes rather than PBF, as this better suits the envisioned use case in combination with improvements in new and future AM equipment, and further enable products with multiple materials and multiple functionalities. ▪ First accelerated lifetime tests performed on polyamide products produced by PBF AM process. Correlating short-term product performance and long-term product lifetime has been an important topic in the experimental and modeling activities performed in collaboration with the Polymer Technology group at TU/e. In 2019, the results of these activities will be implemented together with the product performance model to predict product lifetime for PBF AM products. ▪ First glass-filled PA-6 AM parts produced and validated. In 2018, the first series of glass- and carbon-filled PA-6 products were produced by extrusion-based AM and performance was tested. In 2019, we will extend these activities to increase filler content to enable high mechanical and thermal performance. Also, we will give additional focus to thermal and dielectric properties in 2019 (originally foreseen for 2020), based on feedback from industrial stakeholders.

11 Intelligent autonomous pre-processing plastics

General information	
Title VP/ERP	Intelligent autonomous pre-processing of plastic waste
Contact person TNO (DM en VPM)	Marinke Wijngaard, Ardi Dortmans, Esther Zondervan
Contact person(s) government or topsector	Oscar van den Brink (TS Chemie), Murk de Roos (MinIenW)

Programme 2019	
Summary	The Dutch Climate Agreement requires significant reductions in CO2-footprint, which can only be obtained with major changes in both industry and society. Implementation of a Circular Economy is required in the Dutch ambitions for a fully circular economy in 2050 and will contribute largely to this challenge. Especially recycling of plastics is an interesting topic, which is possible from a technological viewpoint, but not yet applied commercially due to prohibitive costs. Once implemented, it can account for a CO2-reduction of >1 Mton (>700 kton plastics). Vision for this ERP is an eco-system where (plastic) waste is locally pre-processed into a sustainable feedstock for industry, followed by central conversion into fuels & chemicals (see image below). Cost-competitiveness can be obtained by reducing labor costs locally to the absolute minimum (especially in developed countries) through implementing efficient and intelligent technologies. This ERP focusses on the development of intelligent autonomous pre-processing technologies that alleviate the need for labor (except for maintenance).  Long-term goal of this ERP in 2022: To develop autonomous pre-processing techniques for plastics recycling and demonstrate their potential at TRL4/5. The roadmap (see section “Resultaten 2019”) will be used to attain this long-term goal. The activities (both desk- and experimental studies) mentioned in the tasks for 2019 will be employed to result in the following deliverables: 1. Definition of starting point, required specifications and SWOT; 2. Conceptual process design of the intelligent autonomous pre-processing facility and definition of the experimental program;

	Mapping of potential technologies plus selection of technologies for experimental investigation and development in 2020.
Short Description	The chemical industry needs sustainable feedstocks as sustainable ingredients are demanded by brand-owners because of the desires of consumers for sustainable products. Different kinds of feedstocks are available, like biomass or plastic waste. The latter can be used as a feedstock directly (re-use) or after (chemical) work-up (recycling). Sustainable feedstocks (like plastic waste), unlike fossil feedstocks, are scattered and locally available. Due to the strong effect of economy-of-scale on cost-competitiveness, large-scale plastic recycling plants (e.g. based on chemical recycling as pursued at e.g. Chemelot) are required. Since long-ranged transport is costly due to the intrinsic low density (*e.g.* plastic waste contains a lot of air), cost-competitiveness requires local low-cost pre-processing of the plastic waste into a sustainable feedstock with a high(er) energy-density and subsequent transport of the feedstock to a large-scale central location for further conversion of the feedstock into fuels and/or chemicals (see image in summary). Ideally, pre-processing should be integrated in the current infrastructure for waste management (consumers: ~50 collection sites available; industrial: logistic sites of large brands like AH, IKEA). The appropriate technique should be added to existing equipment, possibly in combination with additional sorting/cleaning devices. The pre-processing technique can be mechanical, physical, thermal, or a combination thereof. It will be on-site, or possibly integrated in the waste-collection trucks. To enable the big picture (local pre-processing, central conversion), labor costs at local sites must be minimized (since there will be many local sites for pre-processing). Automatization & big-data is a trend, also in the waste management industry. Ultimately, this will result in intelligent and autonomously operated systems, meaning that the waste collection, sorting and pre-processing will run continuously (24/7) without labor (with the exception for maintenance). Fundamental research questions are two-fold: 1. Can a safe, low-cost pre-processing technology that fits with current infrastructure be developed that enables the big picture? 2. How to develop an autonomous and robust system (specifications in 2019) that can deal with the heterogeneity of plastic waste? Long-term goal of ERP in 2022: To develop autonomous pre-processing techniques for plastics recycling and demonstrate their potential at TRL4/5. The roadmap presented in the section “Resultaten 2019” will be followed in this ERP to achieve the long-term goal. It describes global activities over the years 2019-2022. Required knowledge/technology: • Insight in waste management industry (quantities, sites, etc.) • Overview of the penetration of sensing & smart industry in waste management industry • Automatization technology (control systems, artificial intelligence based technology)

	• (smart) Sensing technology (in-line sensors to assist automatization technology) • Process technology (liquification/densification/gasification of plastic waste) Techno-economics, sustainability & business models
Results 2019	To achieve the long-term goal of this ERP, the roadmap below will be followed.  **2019:** Definition of requirements autonomous pre-processing facility • Heterogeneity • Technology • Artificial Intelligence • Sensing Screening potential technologies • Processability • Process safety @ small scale • Process economics • Autonomous potential **2020:** Proof-of-principle on • Pre-processing technology • Autonomous processing Identification of bottlenecks • Economy of scale • Transport of intermediate product • Process technology • Robustness autonomous process **2021:** Solving bottlenecks by • Modelling to obtain insight • Experimental investigations • Technological improvements of AI, technology, sensors, etc • Working out business model Conceptual process design & preparing demonstrator **2022:** Engineering & Construction of demonstrator autonomous pre-processing facility at industrially relevant scale (TRL4/5) Demonstration of concept • Experimental program • Updating models • Techno-economic evaluation 2019 is the first year of this “kiem-ERP”. Therefore, the following three activities will be carried out: 1. Defining the starting position by preparing state-of-the-art overviews of: a. Plastic waste availability in terms of quantities, origin and composition; b. Current issues in waste management industry; c. Penetration of sensing & Artificial Intelligence in waste management industry; d. Technologies available for pre-processing of plastic waste; e. International developments in (pre)processing of waste. 2. Setting up requirements of the autonomous pre-processing facility (to be constructed in 2022) in terms of: a. Heterogeneity (what can be handled, what is out of scope); b. Technology (product properties, battery limits); c. Artificial Intelligence; d. Sensing. 3. Experimental screening of potential technologies on:

	a. Processability (yield, type of by-products, required process conditions); b. Process safety @ small scale; c. Process economics; d. Autonomous potential (suitability for autonomous operation robustly). Activities 1 and 2 represent desk-studies and interviews with (inter)national stakeholders and industry. Activity 3 is characterized by a combination of experimental studies and assessments (desk-study). These activities result in the following deliverables: 1. Definition of starting point and SWOT; 2. Conceptual process design of the autonomous pre-processing facility and definition of the experimental program; 3. Mapping of potential technologies plus selection of technologies for experimental investigation and development in 2020. These three deliverables culminate in a more detailed roadmap for this ERP with follow-up activities for 2020. TNO departments involved: Circular Economy & Environment (CAS, EMSA), ECN part of TNO (SPES, BEE), Industry (MaS), Strategic Analysis & Policy (SBA), Information & Communication Technology (ESI). The activities in this program are relevant for and will be connected to other initiatives such as: • Mission driven programs Climate and Sustainability, Circular Economy • Key technologies Materials, ICT • Topsectors Chemistry, Logistics, Creative Industry, HTSM, Energy. TKI BBE, ICT • NWA routes Circular Economy, Measuring and Detecting, Materials, Logistics • TI Coast, BMC, BSTC i.o.
Dynamics	This is a new “kiem ERP”, hence no dynamics compared to the 2018 situation.

12 Decarbonisation

General information	
Title VP/ERP	Decarbonisation
Contact person TNO (DM en VPM)	Peter Wolfs
Contact person(s) government or topsector	

Programme 2019	
Summary	The program Decarbonisation will start in 2019 with a number of feasibility studies in order to determine the actual focus of the program on the longer term. This will be closely done in cooperation with the partners and the need of the industry.
Short Description	Within the context of the climate agreement discussions in the Netherlands and the targets that will be adopted by industrial chemical clusters in the Netherlands, TNO started discussions with the Brightlands Chemelot Campus, Sitech and the University Maastricht, to erect a center that focuses on the upscaling and development of technologies that can have a major impact on the carbon dioxide footprint of the Chemelot Site as well as comparable clusters nationally and internationally. In the meantime the province of Limburg launched a plan “Limburgs aanbod” to the dutch government in which amongst other topics the improvement of the sustainability of the Chemelot site is addressed. At present the Chemelot site is responsible for 30% of the industrial energy consumption and the connected carbon dioxide emissions. At national scale the site is also one of the major contributors of carbon dioxide emissions in the industrial field. The license to operate of the chemical cluster Chemelot is at stake. This will also effect the whole Amsterdam Rhein Ruhr Antwerp region because of its interconnection within the value chains and physical pipelines. The Chemelot cluster expressed an ambition in the Chemelot 2025 plan to become the most competitive sustainable cluster on materials and chemistry. Within this context TNO has the ambition to participate in the center and to develop technologies and knowledge that support the scale up of processtechnology that ultimately make “Climate proof Chemistry” possible. Within this context a fieldlab need to be erected at the Brightlands Chemelot Campus and/or Chemelot site. The scope of the center closely interacts with roadmaps of the units Industry, Circular Economy and Environment and ECN part of TNO. The center will focus on a number of transition programs that are energy related, circularity & alternative feedstock related, system integration related and process safety related. During the quartermaking phase and the startup the priorities will be defined in close relationship with the partners and the industry. The goal and focus of this ERP/VP is to develop the knowledge and technology that is necessary to reach the goals for decarbonisation. These goals are mainly energy and feedstock related. 1. High temperature heat

	2. Alternative feedstock, biobased & circulair 3. Hydrogen without emission 4. Electric conversion 5. Improved energy efficiency and process control end of pipe solutions 6. System and chain integration 7. Process safety
Results 2019	The first results of the program will consist of several feasibility studies which will help determine the further focus and scope of the program. After these first prioritization in close consult with stakeholders, partners and industry a further in-depth plan will be developed on the chosen topics. An important part of the program is to decide on the priorities. First which feasibility studies need to be carried out and in which order. Secondly to develop a method to choose between the outcomes of these feasibility studies. This will be one of the first results. The following feasibility studies within the context of the Chemelot site can be envisioned but will **not** be carried out all at once in parallel at the start of the program: Heat 1. High temperature heat by means of electricity through direct or indirect heating 2. High temperature heat by means of H2 combustion 3. Upgrading heat with heatpumps etc Hydrogen 1. Use of blue/green and internal/external hydrogen in relation to Chemelot and the national landscape. Electrification 1. Direct conversion of chemicals that fit in the eco system of Chemelot 2. Electrification of compressors, boilers and turbines Feedstock 1. Use of biomass for Chemelot processes 2. Decarbonisation of methane and the connection to existing and new processes 3. Use of Carbon capture of process gas or waste gas for CCU or CCS Chemical conversion 1. Scale up of processes with catalysts that eliminates greenhouse gasses Circularity 1. Next generation pyrolysis of plastic waste streams 2. Gasification of plastic waste streams 3. Solvolyses of plastic waste streams 4. Integral value chain integration and analyses

	Integration: 1. Life cycle assesments and sustainability impacts of chosen or to be chosen technologies Process safety 1. Integrated solutions that prevent unintended emissions with the help of digitization. Furthermore scouting of new technologies will be part of the program.
Dynamics	This VP/ERP Decarbonisation was initiated in 2018 to support the developments in the industry on decarbonization and in particular in relation to the Chemelot Cluster. It taps into the VP's related to the roadmaps Sustainable Chemical Industry, Circular Economy & Environment and Fuels & Feedstock and Energy & Industry. In Q4 2018 the focus of the program will be further defined and in 2019 a number of feasibility studies will be performed in order to determine and to support the priorities.

13 Structural Integrity

General information	
Title VP/ERP	ERP Structural Integrity
Contact person TNO (DM en VPM)	Peter Paul van 't Veen, Henk Miedema
Contact person(s) government or topsector	Duurzame Leefomgeving/Defensie
Programme 2019	
Summary	Early research program Structural Integrity (ERP SI) develops technology to make important macro-structures safe, increase their availability and limit the (increase in) cost to society. We do this by adding intelligence to the structures. Existing structures endowed with intelligence will assess their own condition, forecast their future state and, based on that, will signal the need for action. The agent doing this for the structure will be its digital twin. It will propose action plans, including suggestions for specific inspections, maintenance and, in case of deficiencies, recommend strengthening measures. Also in case of design or functional upgrading of a structure, its digital twin will facilitate the assessment of options thereby contributing to improved designs of structures. The digital twins for improving the structural (re)design will assist in investigating the potential of new materials and geometrical alternatives. Three important building blocks of digital twins have been identified. First, a digital representation needs to be generated, quickly, but with the right level of detail in the geometrical and material representation and in the models mimicking the behaviour of the structure, which are the core of a twin. Second, it must be possible to assess current performance and to run scenario simulations to assess alternative designs or future states. Also, a digital twin needs to learn from the information it receives e.g. from sensors on the structure or experiments carried out. Third, predictions need to be validated with lab experiments, field inspection, monitoring and big data. This information is fed into the digital twin so that it can 'learn' from it and improve its performance. In 2019 system designs will be made of the overall framework for the digital twins of existing structures and digital twins for designing structures. For the existing structures focus is on application to infrastructure and for design our focus is on composite military vehicles. For the proper performance of the twins, improvements will be realized with respect to automated model construction, visualisation and interaction, computational speed and the learning ability of twins. First prototypes will be made of twins for existing infrastructure elements and for a composite floor structure of vehicle cabin in a military vehicle. At the core of these twins are multi-scale models. Specific model improvements will be made for assessing loads of structures and the behaviour of steel, concrete and composite structures exposed to the loads concerned. Important is the feedback of information to the twins so that models in the twin can learn. For specific cases such dynamic model improvement will be realized. Also improvements will be made in acoustic and fibre optic sensing that enable the measurement of the critical input information, and laboratory experiments will be conducted to assess the validity of the model predictions.

Short Description	It is our vision that future intelligent macro-structures will self-assess their condition, forecast their future state and, based on that, will signal the need for preventive or corrective measures and, propose an action plan, including inspection and maintenance activities. Of course, such an action plan needs to be considered in the wider context of the management of the entire asset. When new structures are designed, this will be supported by an environment that enables easy evaluation of design alternatives with respect to materials and geometry. The agent connecting this intelligence to a structure will be its digital twin. A digital twin is the way to bring objects, usually machines, into the digital world by creating their virtual look-a-like representation that mimics their current as well as possible future behaviour, using data from sensors attached to the object and software models. The ERP SI aims at developing these capabilities for high value macrostructures with the purpose of safeguarding their structural integrity while reducing service life costs and maximizing the performance (e.g. availability) of the asset and optimizing the structural design. In the next four years period the focus will be on developing two types of digital twins: for condition-based asset management of an existing macro-structure (“existing structures”) and for (re)designing a macro-structure (“design of structures”), respectively. Their digital twin will endow macro-structures with the required intelligence: a computerized model of the real structure, that assesses the performance and can simulate future scenarios. Three important types of building blocks have been identified. First, a digital representation needs to be generated, quickly, but with the right level of detail in the geometrical and material representation as well as the models mimicking the behaviour of the structure. Secondly, it must be possible to assess current performance and to run scenario simulations to assess alternative designs or future states. These simulations may involve changes in loads, in material performance and structural changes. Also, of a digital twin needs to learn from the information it receives e.g. from sensors on the structure, experiments carried out or other data it receives. This means that input information is not only used for estimation of the parameters of the model, but also for updating the models themselves. This potential to ‘learn’ will be built into the digital twin. Thirdly, predictions need to be validated with lab experiments, field inspection, monitoring and big data. This information is fed into the digital twin so that it can ‘learn’ from it and improve its performance. Specific building blocks and their deliverables for 2019 are described in the next section under the headings DIGITAL TWIN – general, DIGITAL TWIN – existing structures, and DIGITAL TWIN – design of structures. We will combine a “fast track” approach aiming at prototypes of representative digital twins of macro-structures in relatively short time, with a “steady improvement track”. The improvements will concern the performance in terms of response times and visual representation of results as well as the functionality e.g. on degradation or damage progress processes and their effect on reliability, response to extreme loads, and service life performance. Both tracks will be followed in parallel.

	The ultimate goal for the technical development is to create a methodology for quickly generating high performing (response time and visual presentation plus functionality) Digital Twins of macro-structures enabling Condition Based Management (CBM) and Evidence Based Interactive Design (EBID). The deliverables to this end are specified for each 'work package' in the next section.
Results 2019	DIGITAL TWIN - general Automated construction of models. A large part of the geometrical modelling e.g. of a bridge or a vehicle can be automated. An important factor contributing to the time required for model construction is the large differences in scales between a structure (e.g bridge or vehicle) and its details (e.g. parts of joints). Sub-modelling is a suited technique to connect the scales, but is not often applied because of the large time involved in making the sub-models. This situation can be improved by making parametric models. In 2019, in order to explore the potential of making and utilizing sub-models, as a prototype, we will make parametric models of a few of joints including defects, allowing for variations in dimensions of the plates and joints and of the defects. The main deliverable is the prototype and its (generally applicable) algorithm. Visualization of and interacting with a digital twin. Part of a digital twin is a 2D/3D simulation of the structure showing dynamically the updated structural response to applied loads or prescribed load scenarios, the effect of alternative maintenance options and enabling visualisation of the sensor outcomes. It must be possible to explore scenario's with a user friendly interface. This is considered to be important to improve the communication of multidisciplinary experts engaged in a system approach to managing an asset or designing a structure, as well as facilitating decision makers and communication over the chain from modeler, inspection team and contractors. Much work is already being done in these fields. In 2019 we will make an inventory of the state of the art with a specific view to enabling fast creation of a digital twin. Computational speed. The development and operation of even a single 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 will be tackled from two fronts: hardware and algorithmic. The former encompasses parallelization on CPU and GPU, distributed, and cloud computing. The algorithmic approach will focus on increasing convergence rate that is intended to be achieved by leveraging on advances in computational statistics and machine learning. The focus in 2019 will be on the algorithmic front: (1) further developing the framework set in 2018 for systematic comparison of algorithms, and (2) advancing the application of automated differentiation to enhance the convergence rate of algorithms. The main deliverable is a tool that demonstrates that the computational time for reliability analysis and model updating can be reduced by at least an order of magnitude.

	Learning digital twins . Uncertainty in model predictions is not only a consequence of uncertainty in model parameters, but also of uncertainty regarding the model itself. A twin can learn and dynamically improve its models based on data. To do that, it is essential to establish the explanatory power of parameters that can be measured. Hence, it will be investigated on the basis of representative case studies, how well different parameters measured with alternative sensor configurations can improve model predictions of the structural behaviour, with a view to the relevant damage scenarios. The main deliverable in 2019 with respect to BMC will be demonstration of the methodology for fatigue failure mechanism in a steel structure, using a probabilistic method based on Bayesian inference and exploring the potential of AI and Machine Learning. The structural life of a joint is modelled and the random (stochastic) parameters in this model – and hence the structural life prediction – is updated with (artificial) information on crack size (inspections), crack activity (AE monitoring) and load measurements. Model updates over time will be generated. In a similar way, a case will be explored for improvement on the basis of a series of experiments of models predicting the performance of a design of a composite vehicle component. DIGITAL TWIN – existing structures System design. A design (method) will be made of a digital twin, i.e., a computerized model of the real structure that assesses the performance and can simulate future scenarios. Two aspects of the twin that need to be incorporated in the design are: a) digital representation which can be generated quickly but with the right level of detail in the geometrical and material representation as well as the models mimicking the behaviour of the structure; b) facilities to asses performance and to run scenario simulations. The simulations may involve changes in loads and in material performance. Also, of the digital twin needs to learn from the information it receives e.g. from sensors on the structure or experiments carried out. This means that input information is not only used for estimation of the parameters of the model, but also for updating the models themselves. This potential to ‘learn’ will be built into the digital twin. The deliverable will be the design. Digital twin existing structure -demonstrator. TNO and Bundesanstalt für Materialforschung und -prüfung (BAM) both are considering the development of the digital twin concept for civil structures. The target is to develop a common digital twin of a civil engineering structure to be presented in 2020. We envisage a digital twin setup consisting of 1) a tangible, physical structure sufficiently representative of a real-life structure but downscaled in size to ‘transportable’ dimensions, that can be subjected to loading conditions and 2) its digital twin consisting of a 3D visualisation of the structure showing near-realtime the load effects on the structure. The heart of the digital twin consists of a sensor system monitoring the loads and their effects and models, e.g. FE models, that use this data to calculate the behaviour of the object, and feed this near-real time into the 3D visualisation. The main deliverable will be a digital twin of a down-scaled civil engineering structure to be presented in 2020.

	Steel bridge as a Weight-in-Motion sensor. Reliable information about the traffic loads on the structures in an infrastructure network is essential for assessment of reliability and technical service life. The required information is implicitly present in the response of structures to these loads. We will develop a methodology to derive the dynamic part of the vehicle load (including the dynamic amplification by the structure) based on an individual truck level and deriving as much as possible relevant traffic load characteristics from non-ideal measurement layouts on various types of steel bridge components. The main deliverable will be a tool that can derive traffic load characteristics from various steel bridge layouts and an analysis of the feasibility to derive the dynamic part of heavy vehicle loadings from structural response measurements. The research will be based on strain measurements of various steel bridges. Vehicle load models The optimal management of infrastructures requires the coupling of a manifold of data and models. Amongst this is reliable information about the traffic loads on the structures within infrastructure networks. The required information holds a wide range of traffic characteristics ranging from e.g. number of (heavy) vehicles to individual wheel loads. The long term vision is a tool that geographically visualizes these load characteristics for infrastructure road networks. This best possible information is obtained by combining extensive data-sources about the actual measured traffic characteristics (e.g. Weight in Motion data, traffic intensities, etc.) with, amongst others, predictive traffic scenario and statistical models to enables extrapolation and prediction of future scenarios with sufficient reliability. The first deliverables will be an inventory of available data and models of traffic loads and intensities, the development of the methodology for coupling the different data sources and models and (3) a first crude demonstration of the tool. Material degradation models. For steel structures the most important material degradation mechanisms are fatigue and corrosion. Current fatigue life prediction models are based on the assumption of an abrupt transition between finite and infinite life. There is increasing evidence that this representation is incorrect: a more fluent transition seems more appropriate. This is of great significance for real structures as the majority of fatigue damage is created near the transition. The best recently published models will be selected and possibly improved by considering test data of a number of joints. In addition, modifications will be proposed in order to account for variable amplitude loads that represent traffic load effects. The main deliverable will be a more accurate model for fatigue life than the current state-of-the-art. In current assessments of concrete structures, the common approach is to use material properties of the original design stage as input parameters, when no major changes have occurred to the structure. However, concrete does age over time. To obtain insight in which material parameter is most critical in the assessment, a sensitivity analysis is performed on predictions from model calculations using different material parameter value combinations. Parameters in the analysis will be E-modulus, compressive strength, tensile strength and reinforcement (cross-) levels. The variations of

	model parameters shall also include variation of cross-relationships (e.g. increase of strength with decrease of stiffness vs. increase of stiffness with decrease of strength). When setting the scope of sensitivity study the concrete parameters that may be assessed by the acoustic sensing shall be considered so that the criticality of those for the assessment can be evaluated as well. This may require further development of multi-scale FEA analyses needed to make use of this type of measurements in the assessment to concrete structures. The main first deliverable in 2019 will be a ranking of the material parameters critical for an assessment of a typical concrete bridge structure. Acoustic sensing of concrete parameters. The current research within the ERP structural integrity is focused on characterization of concrete material, more specifically measuring the local Young's modulus using non-contact ultrasonic scans. The focus is toward assessing the material state, also known as material state awareness which involves knowing the relevant material properties and defects inside the structure. For complete material characterization and defect detection, the current narrow-band inspection system needs to be upgraded to a wide band inspection system. A suited, low-cost transducers has already been identified and preliminary tests have been conducted successfully. Using wide band data, the measured (frequency dependent) Rayleigh wave velocity can be translated to a thickness dependent Young's modulus. Using sparse sensing concepts, it will be investigated if it is possible to increase the spatial resolution of the DVM method. Moreover detection and sizing of other relevant defects like stress concentrations, cracks and delaminations will be investigated as well during the duration of the ERP-program. The focus for 2019 is on thickness dependent Young's modulus measurements and stress measurement using a wide band contactless inspection system. It should be noted that the developed technology is much more widely applicable to composite (Glass/Carbon fiber and fiber-metal composites) and steel components (under stress). Fibre optic sensing of concrete and composite parameters We have demonstrated fiber optic technologies for monitoring dynamic length changes along the fiber for dynamic strain sensing. At high frequency this can be used for measuring acoustic emission (AE) caused by stress, loading, or crack growth. Accuracy depends on the number of sensors and the signal interrogation system. We will optimize the combination of sensors and interrogation system with a view to detection of cracks in steel and concrete with sufficient sensitivity and speed by incorporating newly available components and technologies. Furthermore, proper installation concept and procedures will be developed to ensure reproducible and reliable measurement of the dynamic sensing with the optical fiber. Both, application as a monitoring system and as inspection instrument will be considered. Another fiber optic sensing technology which will be beneficial to the digital twin concept is the fiber optic distributed strain sensing system. Using this technology, the strain distribution along the entire fiber can be monitored to provide an overview of strain mapping of the entire structure. The advantages and the limitations related to our applications will be evaluated.

	Field site Bridge 705. For validation and demonstration of sensor and model developments regarding concrete structures a field site has been initiated in 2018. Focus has been on the assessment of present reliability. In 2019 this will be extended with evaluation of alternative scenario's for the bridge. The main deliverable will be illustration of the application of digital twin as support for the asset owner in decision making, e.g. in considering the effect of various maintenance scenarios and load scenario during the residual service life. DIGITAL TWIN – design of structures The design of a composite vehicle cabin resistant to mine blast has been selected as a benchmark for the development of the digital design twin. This design is challenging because of (i) the large number of variables and parameters involved, (ii) a new material application and no design procedures available and (iii) multiple and extreme requirements. Weight reduction and protection combined with modularity are key requirements for the design. The developed methodology and overall frame work of integrated models and decision criteria will be generally applicable. In the past years TNO developed a high potential full composite material solution for protection against severe impulsive loading, suitable for underbelly mine blast protection of a vehicle. A roadmap was defined specifying the further steps from this elementary material solution to application in a structure. The following tasks and deliverables are defined for the ERP program 2019 with focus on the required fundamental knowledge, evidence (experiments) and the models within the framework of the design twin that will be developed. System design of the design twin. This provides the overall framework of models and their mutual interaction. The system design gives the scheme of the modules at the various scale levels from the global design, the loading, global structural response, the load and response conditions of the structural elements up to the detailed models of the connections and material response. An important functionality in the framework is the interaction between the modules and the implemented models. The modules will be filled with available models and the interfaces have to be defined. The results from "Automated construction of geometrical representation" , "Visualization" and "Computational advances" contribute to this task. The core of the design-twin is formed by the models to predict the dynamic loading, dependent on the structure geometry, and the material and structure response under the extreme load conditions. The deliverable is the system design of the design twin, with the available models and software identified and the most suitable models selected for each scale level.. Global cabin design providing set of variables underbelly structure. After geometry and dimensions of the global structure are chosen, the structural design phase starts. Using the benchmark of the composite vehicle, the basic structural elements decisive for the cabin response will be defined. Based on the results of the task "System design of the design twin", existing experimental data and models will be used to identify, generate and develop

	necessary new/modified experiments and models to be implemented in the twin. The deliverable of this task is a global cabin design. FEM model for structural elements underbelly composite structure. A selection of structural elements identified on the basis of the global cabin design is modelled and analysed, for which engineering as well as detailed FEM models will be developed. In order to validate these models and evaluate the level of detail and accuracy they provide, reference tests are needed. (see "Blast tests on structural elements"). These tests are simulated and analysed. Blast tests on structural elements. In the previous ERP-SI instrumented blast testing devices were developed for ¼ and ½ scale panels. The ½ scale set-up offers the opportunity to test structural elements. The scaled set-ups will be used for reference test to evaluate the validity of the FEM models for the selected structural elements. The FEM models will be used for the full scale design, so that a full scale validation is also needed. A full scale blast test on a flat and curved panels are envisaged. The result of this task will be set of reference data for validation & modification of FEM modelsDemonstrator 1st version design twin. In order to judge the status and balance between the different modules in the drafted design-twin with the best available models and data, it will be applied for the design of a mine blast resistant underbelly of a vehicle. Results of all tasks will be implemented in the design-twin framework of which a system design has been made. The deliverable is the incorporation of the elements developed and used so far in demo setup made on the basis of the system design. This demonstrator is a 1st order design-twin suited for composite floor structures of vehicle cabins, which is a basis for extending this setup to other application areas. Advanced models of mechanism determining deformation capacity. Previous research revealed that the selected glass-fiber in the developed TNO-full composite laminate exhibited extremely high deformation capacity. The decisive mechanism leading to the high deformation capacity has not been identified yet. The multi-axial stress conditions, the high pressure and loading rate may contribute. In order to exploit this deformation feature, the mentioned conditions have to be covered in the FEM material models, which is not yet the case for the models currently available at TNO. Special attention will be paid to this aspect in cooperation with the Delft University of Technology. On the basis of the continuous interaction between experiments and numerical models we will identify the importance of different aspect so that we can concentrate on incorporating the most important aspects in the models they do not yet cover. Material characterization tests for these conditions will be designed and performed in the next years. R&D on digital twins so far mainly focuses on machines. Their development in other areas is in an explorative phase. For macrostructures explorative activities concentrate at academic centres and RTOs, e.g for infrastructure at Politecnico di Torino and University of Natural Resources and Life Sciences Vienna. When such parties make alliances with information companies such as IBM or Hewlett Packard, the present open communication may turn into competition. We are also exploring such alliances. Our main scientific partners will be major knowledge centers with respect to the content of the digital twins for macrostructures: TU Delft and Bundesanstalt für

	Materialforschung und -prüfung (BAM) in Berlin. The deliverables of the ERP in the preceding period were focused on building blocks (sensing, models) with demo's (field site bridge, full scale blast test new composite floor element) showing their very first integrations. The focus will now shift towards integration with further developments on essential building blocks. Together with our earlier ERP results, our network with other knowledge centers, our existing cooperation with NL/EU industry and end users such as MoD and RWS, and our alliances with high level partners put us in a front position with respect to digital twins for macrostructures. Our program is linked to three of the ten themes (Vervangingsopgave infrastructuur, Assetmanagement, Informatievoorziening) in Rijkswaterstaat's Innovatieagenda 2015-2020, herijking januari 2017. These themes are also important for ProRail, provinces and municipalities. An important contact for municipalities will be AMROR, in which Amsterdam and Rotterdam cooperate with Rijkswaterstaat. Our program is also linked to the Bescherming, Munitie en Wapens program of the Ministery of Defense (MoD). The approaches that we develop for Condition Based Management & Evidence Based Interactive Design (EBID) will have spinoff with respect to offshore wind structures (Topsector Energie) and water defense structures (Topsector Water). In addition to above mentioned end users, companies will be involved in the program, especially companies providing services for maintenance (in our work on Condition Based Management) and manufacturers of components and structures (in our work on Evidence Based Interactive Design). For the latter it is important that at international level there is interest of other MoDs and defence industry in lightweight, composite vehicles. Within the frame work of the EDA (European Defence Agency) a research and development program on this topic is currently defined in which NL participation will have a main role. The Dutch MOD (Ministry of Defence) and the EDA are interested in new solutions for improved military platforms. The ERP will be carried out in close cooperation with the related TNO roadmaps and these roadmaps will add additional funding to activities described here.
Dynamics	The main goal is digital twins for Condition Based Management (CBM) and for Evidence Based Interactive Design (EBID). The aim is to develop technology generally applicable to macrostructures. The present application focus is directed at civil infrastructure with spinoff in the offshore wind domain, and composite military vehicles with spinoff to application for composite components in civil infrastructure and offshore wind. Although the developments with respect to offshore structures and well integrity have been very successful (with respect to technology development as well multiplier) and they are addressing huge societal issues, our fundamental research with respect to these topics will be on hold for the year 2019 due to a decrease of the available budget while the spinoff from the work in the preceding period will be continued in our VPs and projects funded by external parties. The international collaboration with industry for the development of a composite vehicle is being further developed. The Netherlands, TNO, has the possibility and is in the position to take a leading role in these new

	developments. The development of a “design twin”, benchmarked with a composite, lightweight protective vehicle using the new full composite material solution, is an important contribution to take that position. In the research program a close collaboration is being developed with NLR for the production of composite samples and University of Delft on the development of material models and advanced material and structural testing. Also the ERP is the basis for extending our cooperation with Bundesanstalt für Materialforschung und -prüfung in Berlin.

14 Seed project Social eXtended Reality (SXR)

General information	
Title VP/ERP	Seed Project Social eXtended Reality (SXR)
Contact person TNO (DM en VPM)	Omar Niamut, Hans van den Berg
Contact person(s) government or topsector	Mariëlle Beers-Homan (EZK)

Programme 2019	
Summary	
Short Description	The digital transformation simplifies the sharing of knowledge and experience between people. We are moving towards an Internet or Abilities (IoA), which enables new ways for people to interact with each other through new major technological developments such as artificial intelligence, robotics, tactile internet and augmented and virtual reality (AR/VR). The TNO Strategic Plan 2018-2021 identifies the importance of media synchronization as an enabling technology for the realization of IoA, with a focus on the combination of XR (thesuperset of AR / VR), 5G and tactile Internet. In this programme, we aim to create a shared XR environment (Fig.1) whereparticipants get the feeling of being present at a remote location, referred to astelepresence. Telepresence is not a new idea, but existing telepresence solutions do not at all provide the feeling of being present. Avatar-based social VR has only recently emerged as the newest form of telepresence to share a virtual world. However, unlike the social space for consumers on social networks, however, participants in real-world applications are not avatars, but need to be volumetrically present. This distinction is incredibly important, and requires absolute photorealism, perfect camera alignment for eye contact, and augmented reality images (holograms). This creates an illusion of the remoteperson's physical presence in the local space, as well as a shared understanding of verbal and non-verbal cues (e.g., gaze, pointing), and touchbasedinteraction, as if they were there. More concretely, we currently miss photorealistic and volumetric human representation in a format that can beeasily captured, compressed and transported to current and upcoming AR/VRdevices to allow for shared and collaborative 6 DoF experiences; we miss orchestration capabilities for seamless and synchronized merging of real and virtual world human representations into a coherent experience, and for crosslayer and joint optimization across network and application stacks to enhance the quality of the overall experience; we miss low-latency capture, transport andrendering of tactile / touch information, and we miss capabilities to deal with the intermittent nature of ultra-high frequency wireless connections for achievinghighly reliable, high-speed, low-latency connectivity.

	 Figure 1: orchestrating networked social virtual reality experiences. Our ambition is to enable people to participate in shared events independently of their location, such as live concerts and sport games, online meetings and situational awareness operations, in which all participants can communicate and interact in a high-quality and realistic manner. This requires a new approach to vision and audition, (e.g. immersive and head-slaved) and expanding to other sensory modalities, starting with touch. We study and develop key aspects of mobile networks (5G and beyond), such as mobile edge computing and slicing, that have the potential to realize the required high video bandwidths (e.g. 1 Gbps for a mere single low-complexity point cloud consisting of 1 million points) and extremely low response times (e.g. under 20 ms for a system to feel responsive and where lag when moving in a virtual world is no longer noticeable, and up to 5 ms motion-to-photon latency to avoid cyber sickness). We integrate and extend media formats beyond 2D video, such as multiview-video, 3D meshes, point clouds and light fields, that offer opportunities to improve the quality and efficiency of the representation of the complex spatial data. We enable networked interaction beyond sound and vision, starting with the experience of touching someone as well as being touched at a distance. In 2019, our goal is to develop a hybrid shared XR environment, in which at least two participants in AR and two participants in VR share an experience, which runs on top of an underlying platform that resembles a (pre-) 5G network environment, and where at least two participants can touch and communicate with each other. Within this program, there is a strong collaboration with CWI (on volumetric media and networks) and University of Twente (on tactile interaction). Topsector HTSM expects technology breakthroughs in 5G networks and XR for Smart Industry, in line with the Nederlandse Digitaliseringsstrategie, the Actieplan Digitale Connectiviteit and the KIA ICT (2018-2021).
Results 2019	
Dynamics	

15 Artificial Intelligence

General information	
Title VP/ERP	Artificial Intelligence
Contact person TNO (DM en VPM)	Hendrik-Jan van Veen (DoS), Henk Jan Vink (MD), Program manager: Serena Oggero Lead scientist: Albert Huizing Steering scientists: Mark Neerincx, Cor Veenman
Contact person(s) government or topsector	Floris Lantzendörffer (EZ)

Programme 2019	
Summary	Artificial Intelligence (AI) is rapidly becoming a transformative technology with an impact in almost every sector in society. Although current AI methods such as deep learning have achieved statistically impressive results, in some cases “super human” performances, AI-enabled system are trained to perform very well in demarcated local problems, but are still unable to cope with new, unknown situations, unable to provide feedback to the user on the factors that contribute to their decisions, unaware of their own (correct or not) functioning. These are some of the major obstacles for introduction of AI in our society. Future AI-based Intelligent Systems need to acquire new capabilities to be able to act in the operational environments of the future and collaborate in a human society. The long-term goal of the ERP is to solve the following issues for society: - “**Controllable AI**”, enable meaningful human control and self-awareness of intelligent systems, - “**Explainable AI**”, enable intelligent systems providing meaningful explanations to humans; - “**Responsible AI**”, make intelligent systems capable to operate according to the (western) ethical principles of responsibility, such as the principle of non-discrimination and the principle of privacy preservation. Knowledge along these research lines is necessary -although not sufficient- to deliver solutions for current and future operational needs of AI-enabled intelligent systems in a broad range of TNO application domains. Defense, security, mobility and health are domains where these operational challenges are already identified by our market stakeholders. All three lines of research will need to merge knowledge on the current knowledge-driven and data-driven AI domains (e.g., reasoning techniques such as symbolic AI, and learning techniques such as deep learning) into a new form of AI, a “**hybrid AI**”. Hybrid AI represents the future of this field, it is necessary for TNO to acquire a knowledge position on this topic. In 2019, the line Controllable AI will deliver a functional design for the already developed meaningful human control (MHC) framework, discussing its general applicability to different domains. The MHC framework comprises an ethical and task-specific goal function, and will be extended to incorporate self-assessment and self-management capabilities. We will formulate and experimentally demonstrate an ethical and task-specific goal function for one of the application domains; we will develop the first proof-of-principle of such

	capabilities -yet missing in intelligent systems; and we will survey state-of-art literature on Hybrid AI techniques to identify those that can better enable an intelligent system to operate safely and at the maximum performance in unpredictable and unknown situations. The line Explainable AI will deliver the first proof-of-concepts of a hybrid-intelligent software agent that provides (1) personalized contrastive explanations for applications where the outcomes of a machine learning model need to be explained (e.g., for advices and decisions in health care), and (2) example-based methods that provide explanations on the underlying AI model's constraints (so that the human can interpret and apply the model outcomes adequately). For both methods, we will study and combine Hybrid AI techniques to improve the adaptivity of explanations, by incorporating knowledge-based resources, enabling human corrections, and reinforcement learning. The line Responsible AI will survey state-of-art literature on legal and societal limiting conditions of AI developments and outline the legislation innovation needed to define intelligent systems as legal entities. We will also deliver a proof-of-concept of a Hybrid AI method able to reduce discrimination in intelligent decisions while allowing for model transparency, and a secure-sharing design based on the exploration of generic modeling principles of various machine learning tools. All three lines of research will need to merge technical AI knowledge, with knowledge from the fields of law, ethics and behavioral science. Clearly **a multidisciplinary approach integrating disciplines at a system level** is required to combine methodologies and techniques in a cohesive solution. TNO is the right organization in this picture: we not only have expertise and a knowledge position on topics relevant for the 3 research lines, but also a strong experience on approaching applied problems from a multidisciplinary and system integrator perspective. To ensure integration between the three lines of research and consolidation of the TNO system approach, a small team of experts from the three projects will work together to deliver in 2019 a cohesive functional design for a Hybrid AI-based intelligent system, able to cope with challenges common to all three lines. This will form a base to work on a common demonstrator in the following years and to ensure collaboration across the three research teams.

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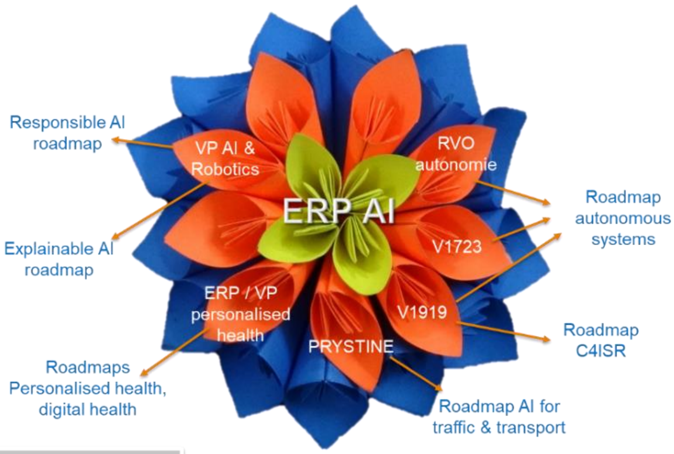
The broadness of the AI topic requires a strong collaboration with top research groups at academic level. Therefore, another objective of the ERP is to ensure collaboration through co-supervision of PhD students, professorships and shared research goals. In Fig. 1, left, links to academic teams already established or in consolidation are shown. The ERP will focus on knowledge building at low TRL. To ensure chances for valorization, we are teaming up with other TNO projects and programs focusing on the application of AI in specific domains, or on the research of shorter-term challenges of AI. These projects operate at higher TRL and are directly coupled to roadmaps (see also Fig. 1, right). The alignment will be based on a flow of knowledge (models, techniques, algorithms) from the ERP to the other projects, and vice-versa on the flow of use-cases (market problems for inspiration, real world representative datasets) to the ERP.



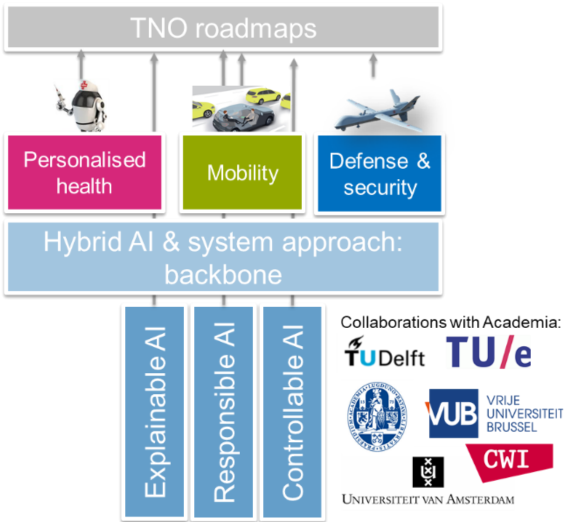


Figure 1: (left) Schematics of the ERP with academic partnerships; (right) schematics of the alignment with other TNO projects.
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<td>Short Description</td>
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AI trend in the outside world
Artificial Intelligence (AI) is rapidly becoming a transformative technology with an impact in almost every sector in society. Consider for example AI applications in computer vision, speech recognition, machine translation, robotics, decision support, fintech, strategy games, recommendation systems, self-driving vehicles, which are already part of our life. This technological progress is particularly driven by the fast developments in the area of deep learning where the ample availability of data and computational power has enabled superhuman performance in some applications. Consequently, technology companies such as Google, Amazon, and Facebook, and automotive industries such as Ford, Toyota and Mercedes are heavily investing in AI research to achieve a competitive edge.
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	Big challenges remain for AI in operational environments Although current AI methods such as deep learning have achieved statistically impressive results, results in individual cases show some disturbing signs of unreliable behavior. For example, recent studies have shown that state-of-the-art deep neural networks are vulnerable to adversarial examples, resulting from small-magnitude perturbations added to the input. Given that emerging physical systems such as self-driving cars are using deep neural networks in safety-critical situations, adversarial examples could mislead these systems and cause dangerous situations. Some of the problems of AI occur because they are trained to perform very well in demarcated local problems, but are unable to cope with new, unknown situations, unable to provide feedback to the user on the factors that contribute to their decisions, unaware of their own (correct or not) functioning. This is a major obstacle for future applications of AI. Future AI-based Intelligent Systems need to acquire new capabilities to be able to act in the operational environments of the future and collaborate in a human society. These operational challenges are common to various domains, from mobility to health, from security to defense. Coping with these operational challenges means meeting several new needs. The long term goal of the ERP is to solve the following urgent issues for the application of AI in our society: - “Controllable AI”, enable meaningful human control and self-awareness of intelligent systems, - “Explainable AI”, enable intelligent systems providing meaningful explanations to humans; - “Responsible AI”, make intelligent systems capable to operate according to the (western) ethical principles of responsibility, such as the principle of non-discrimination and the principle of privacy preservation. Knowledge acquired through these research lines can deliver solutions to address the operational needs. All three lines of research will need to merge knowledge on the current knowledge-driven and data-driven AI domains (e.g., reasoning techniques such as symbolic AI, and learning techniques such as deep learning) into a new form of AI, which we will hereby call “hybrid AI” (Battaglia, 2018). A hybrid AI combines the strength of knowledge-driven techniques to deduce specific information from domain knowledge and human common sense for instance to cover situations for which data is lacking, with the strength of data-driven techniques to induce new knowledge from acquired data. The three ERP research lines will therefore investigate methods merging these approaches into a hybrid form and the application of hybrid AI models to specifically realize explainable, controllable and responsible intelligent systems. Furthermore, all three lines of research will need to merge technical knowledge, with knowledge from the fields of law, ethics and behavioral science. Clearly a multidisciplinary approach integrating disciplines at a system level is required to combine methodologies and techniques in a cohesive solution. TNO is the right organization in this picture: we have expertise and a knowledge position on topics relevant for

	the 3 research lines; we have knowledge on expert-driven models in specific domains as defense, mobility, health, and we have experts on advanced data-driven algorithms as deep learning; we have been working on the first forms of hybrid AI systems (e.g., V1801 neuro-symbolic reasoning) and finally, we have a strong experience on approaching applied problems from a multidisciplinary and system integrator perspective. At the end of the ERP, TNO will be the ideal strategic partners in the domains of security & defense, mobility and health, to realize Hybrid AI based Intelligent Systems, able to reach more general-purpose goals, to operate in more unpredictable situations, to better collaborate with humans and to act in a legally and ethically responsible way in our society.
Results 2019	**Research Line: Controllable AI** Research questions (long term) 1. How can an Intelligent System be controlled through ethical and task-specific goal functions? How do ethical goal and task-specific functions look like? 2. How can an intelligent system assess its performance with respect to an ethical and task-specific goal function? a. Which measures can be used by an intelligent system to assess its own performance w.r.t. an ethical and task-specific goal function? b. How does the external world and the internal system configuration need to be modelled and represented to enable self-assessment and self-management? 3. How can intelligent systems operate safely in unpredictable and unknown situations (‘adaptivity’)? a. How can common sense and domain knowledge be represented and combined with data-driven methods in a form of hybrid AI to recognize new situations? b. How can the intelligent system subsequently decide how to operate in this situation? 4. Can a hybrid AI method be used to learn efficiently in a new, unknown situation? What are otherwise the best solutions to make intelligent systems capable to learn efficiently when lacking enough representative data in new, unknown situations? **Focus in 2019** A big challenge for intelligence systems is to achieve the goals that have been defined by humans in a complex environment in a safe and cost-effective manner while operating within legal and ethical constraints. Within the framework for meaningful control that has been developed by TNO, goal functions are used to specify the utility for each of the possible outcomes of the task the intelligent system must conduct (Werkhoven et al., 2018, Elands et al., 2019). The definition and elicitation of ethical and task-specific goal functions is one of the main research topics in 2019 (part of research question 1), which will build up on the research and experiments currently conducted within the V1723 program and starting within the VP AI&Robotics. The intelligent system uses the goal function to optimize its behavior by maximizing expected utility. For this purpose, the intelligent system needs to assess the effect and performance of different actions the system can take

	(self-assessment) (Aliman and Kester, 2018). These actions can include a change in the internal configuration of the intelligent system (self-management) (part of research questions 2a and 2b). In 2019 we will study methods to add self-assessment capabilities to an intelligent system, and we will proof their functioning for at least one application domain. In unpredictable and unknown environments, an intelligent system should behave in a safe and predictable way to avoid harm to people and damage to other systems or itself. Self-assessment and self-management are necessary capabilities in this context. Additionally, the system should be able to recognize a situation as new/unknown if encountered, and envision and assess the performance of possible measures to cope with this situation (act on the decision making). Examples of this action can be pausing and placing itself in a safe mode, acquiring data with a specific objective, ask for additional knowledge from a human assistant. In 2019, we will conduct a literature survey of AI techniques that can enable an intelligent system to operate safely in unpredictable and unknown situations (part of research questions 3 and 4). **Results and deliverables 2019** o Ethical and task-specific goal functions in one use-case and experimental demonstration of its feasibility, on the base of synthetic or acquired representative data, depending on the use-case chosen. **Results published in a research paper** o Proof-of-principle of self-assessment and self-management by an intelligent system w.r.t. an ethical and task-specific goal function in at least one use-case, with discussion on the generalizability of the method to other domains. **Results published in a research paper** o Generic functional architecture of an intelligent system, based on the meaningful human control framework and incorporating self-assessment and self-management capabilities. o Literature survey of (hybrid) AI techniques that can enable an intelligent system to operate safely in unpredictable and unknown situations. **Internal TNO report** The reference use-cases envisioned at this moment concern a case of self-driving vehicle (use-case in Prystine and adopted by the MCAS collaboration, see section ‘Collaboration’ below), an autonomous surveillance system (use-case in VP AI&Robotics), and an autonomous surveillance robot (use-case in RVO autonomy). **Collaborations** TNO, the University of Amsterdam (Informatics Institute and Faculty of Law) and Centrum Wiskunde & Informatica (CWI) are intending to collaborate in the area of Meaningful Control of Autonomous Systems (MCAS). The Research Line Controllable AI will contribute to the MCAS with the results of scientific research and a business plan.

The research on ethical and task-specific goal functions (1), will be conducted with a PhD candidate supervised by Prof. Peter-Paul Verbeek (University Twente), Prof. Peter Werkhoven (University Utrecht, TNO) and Leon Kester (TNO).

The research on intelligent decision making in unpredictable and unknown environments (3) will be partially conducted in the context of the EU project PRYSTINE, specifically for mobility applications.

The research on efficient learning in absence of sufficient representative data (4) will be conducted with two PhD candidates co-supervised with Prof. Max Welling (University of Amsterdam) and Dr. Bart de Vries (TUE), within the context of the NWO project Efficient Deep Learning.

Finally, TNO will possibly collaborate with TU Delft in AiTech, a TU Delft mission-oriented science, design and engineering initiative on Meaning Human Control over Autonomous Intelligent Technology.

Research Line: Explainable AI
Research questions (long term)

1. How can an Intelligent System provide explanations on its advices and decisions that are adaptive to the situation (time, content of information, place), to the goal, and to the human collaborator?
2. How can an Intelligent System provide adaptive explanations in a team of humans and other Intelligent Systems (i.e., provide explanations as a team-member while collaborating within the team)?
3. How can theory-of-mind (ToM) be implemented in an Intelligence System to realize AI-understanding of human's intentions and beliefs and to enable reciprocal AI-human explanations?

Focus in 2019
A concept for human-AI teaming has been worked out in an envisioned Perceptual and Cognitive Explanation (PeCoX) framework with some first building blocks (Neerincx, van der Waa, Kaptein, van Diggelen, 2018). In 2019, we will work out this framework, look for further complementarity with the hybrid AI models and framework developed in the Controllable research line, and study research question 1 in more detail. We will focus on two complementary explanation approaches which can enhance human-AI performance. First, contrastive explanations are often used by humans in a wide scope of situations, e.g. in responses to questions like "Why did you advise or decide for X, instead of alternative Y?" (the second part might not be formulated explicitly by the questioner). It is an effective and efficient explanation approach, because it focuses on the information that is relevant for the specific context. In the Kiem ERP 2018 project, we acquired a knowledge position on AI-mediated life style interventions (e.g., for diabetes self-management) by developing a method to identify the "alternative" (called "foil") and construct the consequential contrastive explanations (van der Waa, van Diggelen, Kaptein, Neerincx, 2018). First evaluations showed that useful explanations can be constructed, but that personalization is required. The research question on this topic for 2019 is therefore:

	1a) How to personalize perceptual-cognitive contrastive explanations (e.g., by reinforcement learning) in order to establish (a) adequate human understanding and trust-calibration, and (b) advanced human performance and learning? In the second example-based approach, explanations are derived from examples from the past, e.g., cases from the data-base that is used to train the machine-learning model, are used for explanations. When appropriate, the explanation should (a) disclose the constraints (i.e., possible voids and biases) of the model to the human, of such models in the explanations, and (b) provide an opportunity to add data or an interpretation (e.g., the relation of A with B is not relevant or has no meaning). The research question on this topic for 2019 is:1b) How to explain model constraints so that the human can unveil possible voids or biases, and how to enable human correction (i.e. adding data or interpretations)? This research line envisions two reference use-cases come from the health domain, respectively focusing on research question 1a) and 1b). The first use case is inspired by the H2020 PAL project and the ERP Personalised Health, centering on an ePartner-mediated lifestyle support system for diabetes. Explanations have to be provided to both the patients (for trust, uptake and learning), and caregivers (for trust, revision and learning). This generic lifestyle use case will be enriched with an obesity self-management scenario that aligns with one of the focal points of the “National Prevention Agreement” Nationaal Preventieakkoord, Ministry of Health, Welfare and Sport t[11], , to be implemented in 2019. The generic lifestyle XAI-research questions[12] aim at explanations for persistent behavior change: How to construct personalized, easy-to-interpret, recommendations with multimodal interactions (including conversational agents) How to incorporate knowledge-based resources (such as population statistics, hand-crafted medical models, background knowledge) with data-driven AI? The second use case centers on a system for psychological risk classification from patient-generated data (based on a dataset from the Curium hospital). Here, the explanations concern data and model understanding, to increase the understanding of the prediction for practitioners and domain experts. The use-cases will be studied with representative group of patients suffering from obesity, and data collection, data handling, analysis and reporting will be fully compliant with the GDPR. The use-case will also align with the research line Responsible AI: techniques and results from that line will be applied to ensure bias-free analysis, identity obfuscation and privacy. Finally, the applicability of results from the Explainability research lines will be tested on use-cases from other domains such as a self-driving vehicle and an autonomous surveillance system.

[11] https://www.rijksoverheid.nl/onderwerpen/gezondheid-en-preventie/nationaal-preventieakkoord

[12] Other research questions addressed in the use-case and co-financed by the VP AI and MinMWV will be: How to extract meaningful information and patterns from patient-generated data (self-measurement, life style reports)? Can we develop predictive, AI-based models for outcome prediction of life style choices (derived by (1)) for patients? What are adequate and transparent report facilities for the efficacy of AI-mediated life style changes on obesity (quantitative and qualitative)?

Results and deliverables 2019

- Proof-of-concept of AI providing personalized contrastive explanations.

Result will be demoed at a AI conference and presented in a research paper.

- Proof-of-concept of AI providing explanation on model constraints, for different type of data sources (different modes of explanations), e.g., text, images, structured data.

Result will be demoed at a AI conference and presented in a research paper.

- Extension of Hybrid AI framework to incorporate knowledge-based resources and enable human corrections.
  Internal TNO report

Collaborations

The research on Explainable AI will be conducted with a PhD co-supervised by Prof. Jonker (TU Delft) and Prof Mark Neerincx (TNO).

Additionally, Dr. Stephan Raaijmakers (TNO), who will conduct part of the research on Explainable AI within this project, will possibly hold a professor position at the University of Leiden (in progress).

Research Line: Responsible AI

Research questions

1. Which are the legal and societal conditions that limit innovations in artificial intelligence? How does legislation need to be changed to define intelligent systems as legal entities?
2. How can knowledge on legal and ethical values (e.g., non-discrimination principle) be made explicit in a hybrid AI model and used to make sure an intelligent system takes bias-free decisions?
3. How can an Intelligent System learn from different datasets without having the datasets shared / disseminated between parties involved? (multi-party learning, 'safe' learning)

Research questions 2019

Artificial Intelligence is an important enabler of innovation both for commercial applications and services as well as for improving governmental processes. With the availability of increasingly many open and closed data sources, measuring devices and sensors, the potential effectiveness of these developments grows accordingly. These developments can, however, been hampered by ethical, legal and societal conditions. The resulting challenges range from the attribution of responsibilities in intelligent systems to limitation in the use of data and the mitigation of societal biases in collected databases. The Research Line Responsible AI deals with pro-active developments towards current and future AI applications that respect laws and ethics in a transparent and evidence-based manner.

For the coming year the three research questions will be developed in the following way:

1. The definition of the state of affairs with respect to the legal conditions on data use and responsibility attribution is the first activity. Secondly, a

research outline will be sketched for the development of legislation that further enables AI innovations in a responsible way.
In order to do data intensive AI research as part of the foreseen hybrid responsible AI models, a suitable use-case with dataset is needed. Especially because of the legal and ethical conditions for data usage, such datasets are not readily available. There are several public domain datasets that have been used for the development and testing of discrimination free AI models. As long as no other use-cases are available, these will serve as starting point for the research.

2. Several results have been reported in the literature that enable representations of datasets in a way that sensitive attributes are suppressed. For instance, gender may not be used, neither directly nor indirectly as part of the AI model to predict suitability for a certain job. We will direct our research to the development of hybrid AI models that suppress attributes that may not be exploited, while allowing for transparency of the model, i.e. implementing the right for explanation to data subjects.
3. As part of the VP AI and H2020 initiatives, there are some AI models in development to enable secure regression among others. The standard toolbox for machine learning in various software environments (R, Python, Matlab) is filled with many methods that are not yet available for secure sharing. Within the Responsible AI research line, the aim is to extend the secure sharing machine learning toolbox by finding and exploiting generic modeling principles of existing tools.

Results and deliverables 2019

- Literature survey of legal and societal limiting conditions of artificial intelligence developments. Outline of legislation to define intelligent systems as legal entities.
  Result presented in a research paper / letter to the EU commission
- Functional design and proof-of-concept of Hybrid AI method to reduce discrimination in intelligent decisions while allowing for model transparency, for one data type or use-case. Datasets from public domain are considered for back-up.
  Result demonstrated at the AI symposium 2019 or external conference, and presented in a conference paper
- Secure sharing design based on the exploration of generic modeling principles of various machine learning tools.
  Result demonstrated at the AI symposium 2019 or external conference, and presented in a conference paper.

Collaboration

The research on consequences of attributing legal status to intelligent systems (1) will be conducted with a PhD supervised by Prof. Mireille Hildebrandt (Free University of Brussels) and Dr Albert Huizing (TNO).

Additionally, TNO collaborates on this topic with the Leiden Institute of Advanced Computer Science (LIACS), where Dr. Cor Veenman (TNO) is also senior researcher, and Prof.dr.ir Wessel Kraaij (TNO) has a chair on Applied Data Analytics

	Integration between research lines: system approach To ensure integration between the three lines of research and consolidation of the TNO system approach, a small team of experts from the three research lines will work together to deliver in 2019 a cohesive functional design for a Hybrid AI-based intelligent system, able to cope with challenges common to all three lines. In 2020, we will dedicate more effort to the integration of the results towards a common demonstrator between all research lines, based e.g., on the same use-case, and building upon the same Hybrid AI techniques and functional design. **ERP external ecosystem: links to academia, government and top sectors** The broadness of the AI topic requires a strong collaboration with leading research groups and institutes in the field of AI. This is needed to enable TNO to claim a prominent role in the field of AI and ensure/maintain a strong position in key markets. Therefore, an objective of the ERP 2019 is to start or strengthen collaborations through co-supervision of PhD students, professorships and shared researchers, and through direct participation in emerging consortia such as MCAS and AiTech. The following list collects all set-up links to Academia, as already mentioned in the previous paragraphs: TUDelft, UvA, UvA MCAS institute, AiTech institute, VU Brussels, TU Twente, TU Eindhoven, University of Utrecht, LIACS institute Leiden, CWI. The ERP AI connects to the NL Top Sectors and Programs through participation with industry, academia and TO2 partners in joint projects in dedicated tenders organised by the various TKI or EU-H2020. A number of important collaborations with European partners has already started and will be intensified. Through co-financing of the NWO program Efficient Deep Learning [13],, the EU ECSEL project Prystine[14], , collaboration with linked TNO projects such as ‘Uitlegbare en Veilige AI’ in the VWData program[15] and others listed in the following section, the ERP AI links to the top sector HTSM/ICT, High Tech Systems & Materials (roadmap automotive), the Maatschappelijk Thema Maatschappelijke veiligheid, and to the Dutch Digital Delta. Additionally, the mentioned projects ensure not only a link to world leading institutes in the field of AI, but also to top players in the application domains. Examples are: NXP, Nvidia, Nokia, Bosch, Thales, Siemens.
Dynamics	Content-wise, the main change between the plan presented in this document and the proposal that was formulated in 2017 for the ERP Applied AI concerns the insertion of specific research goals on ‘Responsible AI’. Additionally, the last year saw increasing attention in the field of AI for Hybrid AI techniques; we deem these techniques important, because they show potential to address the challenge of balancing high performance, adaptability and safe behaviour in unknown situations, a challenge which is common to Explainability, Controllability and Responsibility. Therefore, we believe

[13] https://www.nwo.nl/en/news-and-events/news/2017/32-million-euros-for-top-level-technological-research.html#zelflerend
[14] https://www.ecsel.eu/projects/prystine
[15] https://www.dutchdigitaldelta.nl/big-data/alle-projecten/vwdata-uitlegbare-en-veilige-ai

	necessary to dedicate knowledge development budget to acquire solid expertise and a position on this topic. As a consequence, less room is made available to research other challenges of intelligent systems, which are still important for some TNO units and roadmaps: - AI methods dealing with uncertainty, a goal which was set in 2017; it will be now partially incorporated in the research line Controllable AI (self-assessment goal) and Responsible AI (eliminate discriminatory bias); - AI methods capable to deal with 'data-starvation', another relevant challenge for the application of AI in different domain and relevant for TNO to acquire a competitive position next to the 'big data giants' (Cock et al, 2018); it will be now partially addressed through research on efficient Deep Learning methods in absence of large labelled datasets, in the context of the NWO project Efficient Deep Learning. No room is available to dedicate budget to goals not directly related to knowledge building, such as external profiling (with exception of presentations and contributions to conferences and symposia) and investigation of use-cases from market stakeholders. The latter will be possibly conducted in the VP AI&Robotics and we will seek maximum collaboration on use-cases with other TNO projects. **References** - Aliman N-M., Kester L., "Hybrid Strategies Towards Safe Self-Aware Superintelligent Systems", AGI Conference 2018. - Battaglia et al., "Relational inductive biases, deep learning, and graph networks", arXiv:1806.01261v2 11 Jun 2018. - Cock H., Cox E., Koot L., Kaas B., Oosterwijk A., Wilmer M., "AI within TNO - Concept of a roadmap", Deliverable of traineeproject Ai in TNO, Aug 2018. - Elands P., Kester L., Oggero S., Peeters M., Huizing A., "Governing ethical and effective behavior of intelligent systems. A novel framework for meaningful human control in a military context". TNO whitepaper, 2018 - Neerincx, M. van der Waa J., Kaptein F., van Diggelen, J., "Using perceptual and cognitive explanations for enhanced human-agent team performance", EPCE Conference 2018. - Raaijmakers S., and Brewster C., "Exploiting ontologies for deep learning: a case for sentiment mining", Semantics Conference 2018. - van der Waa J. , van Diggelen J., Neerincx M., Raaijmakers S., "ICM: An Intuitive Model Independent and Accurate Certainty Measure for Machine Learning", ICAART Conference 2018. - van der Waa J., van Diggelen J., van den Bosch K., Neerincx M., "Contrastive Explanations for Reinforcement Learning in terms of Expected Consequences", XAI Workshop IJAI Conference 2018 - van der Waa J., Robeer M., van Diggelen J., Brinkhuis M., Neerincx M., "Contrastive Explanations with Local Foil Trees", WHI Workshop IJAI Conference 2018 - Werkhoven P., Kester L., Neerincx M., "Telling autonomous systems what to do", ECCE Conference 2018.

16 i-Botics

General information	
Title VP/ERP	i-Botics
Contact person TNO (DM en VPM)	Dr. H.A.H.C. van Veen (Director of Science) and Drs. C. Jansen (project leader)
Contact person(s) government or topsector	

Programme 2019	
Summary	<u>Goals for 2022</u> Robotic Technology will affect many aspects of our professional and private lives: it will raise efficiency in industrial production, increase safety levels in amongst others transportation and it will provide enhanced levels of service at home. Robotic technology will become a significant element in solving societal challenges posed by an ageing population, the need to bring manufacturing back to Europe, the demands for more efficient, clean transportation and energy, and the desire for a safe and secure society. Indeed, in the National Science Agenda of the Netherlands (NWA) as well as in the European H2020 program, robotics is seen as an important and promising development that will have a significant impact on society in the near future. The ever changing society itself as well as the technological developments shape the future role of robotics in society. It is our vision that the human robotic interaction is an important element of the robotic technology, in order to fully seize the future opportunities of these developments for society at large. Many research and technology endeavours on robotics focus on increased autonomy of robots. i-Botics however is focussing on interactive robotics, hence ***<u>i</u>***-Botics: integrated robotic systems that remotely enable us to see, hear, touch and interact with physical environments and other people. Both R&D tracks, autonomy-based robotics and interactive robotics, are needed for achieving the above mentioned societal goals. Since the interactive development is not so much in focus with other competitors, we have chosen to focus on these developments. One of the most important challenges in robotics both tracks are facing is: how to fully exploit and scale the combination of the cognitive- and motor intelligence of humans with the power, speed and accuracy of robotic systems. Current interactive robotic systems are often restricted to vision and often have no manipulation capabilities and if they do, they are cumbersome to employ losing big on task performance and efficiency.In this ERP we have two goals for 2022, having this challenge in mind: (1) First to develop the knowledge and technology demonstrations for a full telepresence robot for inspection and maintenance with 3D remote augmented vision, audition, and touch, and intuitive bimanual control with haptic feedback, important goals in the e.g. the Sparc roadmap[1]. The human-robot interface will be designed to evoke the illusion of ‘telepresence’ (I am present in the remote environment) and of ‘body ownership’ (I am the robot). This allows the operator to build superior situational awareness, transfer his or her skills and cognition over distance, and to act and perform as if being present at the remote location. The main deliverable for 2019 is a demonstrator (TRL<3) with state-of-the-art Augmented Reality technologies in our tele-presence vision system, as well as intuitive control over a remote dexterous

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<tr><td></td><td>manipulator (four-fingered robotic hand), including a feedback scheme for critical haptic cues.
  
(2) The second goal is to develop the knowledge and technology demonstrations for a wearable robot or flexible robotic suit (exosuit) for two types of application: first, to provide mechanical support to workers that are involved in physically heavy, mobile, and ‘difficult-to-automate’ situations, and second, to serve as input (tracking) and (force) feedback device in telepresence robotics (i.e. as human-robot interface for (1)). The exosuit should act as a non-obtrusive, second skin, sense the human intention to move, track actual movements, add mechanical power and stability, provide haptic feedback, use seamless integration with different levels of robot intelligence, and be highly adjustable to the individual preferences and industrial or remote control context. The main deliverable for 2019 is an improved methodology for evaluating the biomechanical, kinematic and behavioural impacts of exoskeletons for support and as human-robot interface.</td></tr>
<tr><td>Short Description</td><td>Our goal for 2022 is to have all scientific knowledge generated and collected for designing integrated interacting 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 and control device for manual control of the telepresence system.

According to SPARC[16], 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:</td></tr>
</table>

[16] The SPARC roadmap (The partnership for robotics in Europe): http://sparc-robotics.eu/

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[17]:
(1) intuitive interaction using remote environment virtualisation
(2) bimanual control with haptic feedback through a wearable robot / exosuit
(3) telepresence through (robot)body ownership
(4) Wearable robots / exosuits for mechanical support

Intuitive interaction using remote environment virtualization
Approach: create a full 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
Approach: use exosuit technology to track the operators intentions and actual motions to control the two arms and endeffectors (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

[17] Please note that partners in the Joint Innovation Centre i-Botics focus on other targets.

	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 2019	*Intended results and deliverables* 1. We will demonstrate TRL<3 state-of-the-art Augmented Reality technologies in our tele-presence vision system, as well as intuitive, bimanual and dexterous manipulation capabilities. In 2019 we will have intuitive control over a remote dexterous manipulator (four-fingered robotic hand), including a feedback scheme for critical haptic cues. These remote manipulation capabilities are combined with augmented, intuitive vision of the remote environment by mixing real-life footage with virtual information, amongst others rendered on the robotic hand. This setup allows unique opportunities to experiment with and optimize body ownership of the robotic hand expected to lead to increased performance and decreased vulnerability for mismatches between the (form, size, capabilities of the) robot and the operator. We will identify factors that affect body ownership of the robot and the hypothesized effects on task performance. We will employ and validate the TNO dexterous telerobotics task battery covering the subtasks that are critical in tele-inspection and –maintenance. In addition, we will be able to build a virtual 3D model of the remote environment using (pre-recorded or live) multi-sensor data. This virtual model allows fast and accurate (platform) navigation and robot control despite e.g. low visibility or a low bandwidth connection. Live camera images can be stitched onto the virtual model employing a new approach to augmented reality (i.e. where virtual images are added to live camera images). These technologies will greatly improve the situation awareness of the operator. 2. We have an improved methodology for evaluating the biomechanical, kinematic and behavioural impacts of exoskeletons for support and as human-robot interface. We will have a model (OpenSim) to simulate the biomechanical and kinematical impacts in terms of user effort, joint loading, tissue stress, motion freedom and anthropometrical fit and we will have experimentally validated the model predictions. We explicitly make the shift from lower extremities (2018) to the upper extremities (arm and hand) to move closer to our goal of applying exosuit technology for robot arm/hand control and intuitive force feedback to the operator. We will integrate different approaches to predict movement based on EMG, EEG and kinematics. *Parties (to be) involved and links to roadmaps and knowledge agendas* 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 and the new initiative for a physical hub; 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 (both approved August 2018). Robotics and especially interaction robotics is explored as topic for close collaboration between TNO and Fraunhofer Germany.

	Several stakeholders are actively involved in monitoring and updating the technology roadmap, both external (industrial as well as governmental) and internal (roadmap / market directors). The latter ensures the fit with VPs on Maritime & Offshore, Renewable Energy, Defense, Social Innovation and Sustainable Employability (concerning safety of robotics development in industrial settings). This increases the opportunities for i-Botics knowledge and (concept) products to be adopted by the various VPs. Connection to national agendas are in place for amongst others the Maritime Cluster: 'Winnen op zee', 'schone schepen', 'Slim en veilig varen' and 'effectieve infrastructuur', Smart Industry and the Ministry of Defense's 'Strategic Knowledge and Innovation Agenda 2016-2020 (SKIA) with Man-Machine Teaming related to (un)manned systems as one of the seven top priorities for innovation. i-Botics is also closely linked to MoD research programs (doelfinanciering) V1719 on 'Behavorial Impact of Humans – Nonhuman-Intelligent-Collaborators Teaming, a V1717 project on telemanipulation for Countering IED and EOD applications, and NTP project exobuddy, and several projects on Telepresence control, including a collaborative TNO-Fraunhofer participation in the ELROB 2018 robot competition. These projects mutually benefit from transfer of knowledge and R&D equipment. The program is linked to the goals of the topsectors HTSM, Logistics and Life Science and Health. The excellent link to the various activities is also shown by an increasing portfolio of i-Botics related projects, for instance the EU H2020 projects HORSE (human robot collaborative systems) and TRADR (Urban Search & Rescue Robots), the TKI Dinalog proposal Man and Robot in the Warehouse about Man-Robot collaborations in warehouse operations, the TTW perspectief project on exoskeletons, and the TKI LSH project on reducing physical impact and danger in specific operations in maintenance activities.
Dynamics	i-Botics started in 2018 as a full ERP project and is running for six months now. The workplan for 2018-2019 was based on the i-Botics technology roadmap 2017. The tech roadmap will be updated in Q4 in 2018, but we foresee no major changes in the targets or the planning. To further integrate the activities and focus them on the 2022 goal we will move all involved research facilities to one central i-Botics laboratory in 2018 and shift the exosuit focus from the lower extremities to the upper extremities.

17 Human organ on a chip

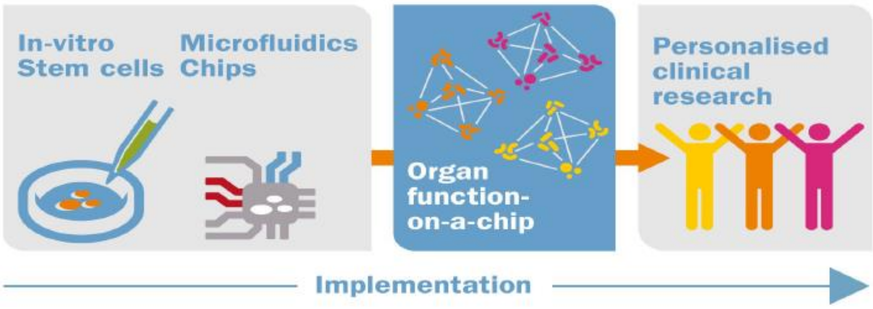
General information	
Title VP/ERP	Human Organ on Chip
Contact person TNO (DM en VPM)	Evita van de Steeg/ Ivana Bobeldijk
Contact person(s) government or topsector	(EZK) Rene Bok

Programme 2019

Summary

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 simgle 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 2022 we will develop a stem-cell based in vitro pre-clinical toolbox, enabling the introduction of population variability earlier in

	compound 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, an ideal fit with the national focus on “Nederland wereldleider proefdiervrije innovatie in 2025”. Deliverables for 2019 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 application. Integration of on-line read-out technologies of these models. In addition, a first step towards introduction of populational variability will be included by application of individual stem cells and combination with individual sera or microbiota.
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. In 2017 Organ function on a chip started as a full Early Research program with a four year program. It 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 on two different organs, i.e (liver and gut, with their own use cases. In both use cases we initially started the development of relatively simple, cell-based *in vitro* models with relevant readouts, which can as such already be used by industrial partners. In the coming years, we will gradually evolve these models into more complex “organ function on-a-chip” models which will mimic specific organ functionalities in health and disease. In addition to these two use cases, a third line of the ERP focuses on the development of state-of- art organ on-a-chip hardware easily applicable for various imaging and readout technologies for applications within the focus use cases, but also applicable for other organs and disease areas. By 2020 we plan to have the developed technologies implemented in Roadmap Biomedical Health. **Goals for 2022** Technology that is and will be developed will be embedded in Roadmap Biomedical Health by 2020. The combined achievements will be :

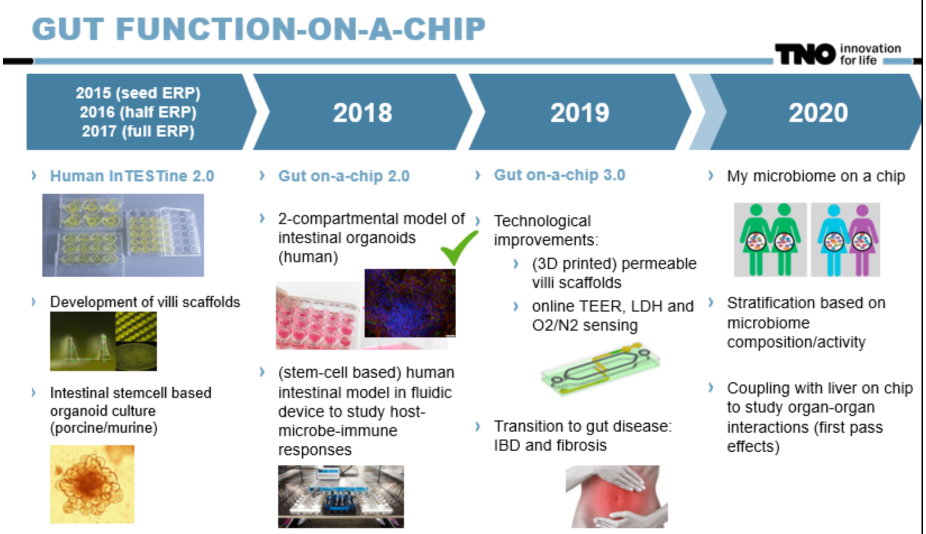
	• Partnership with at least 2 top 10 pharmaceutical companies for application of the developed better predictive preclinical models (organ function on-a-chip models) for drug efficacy or toxicity screening in order to select the right drug candidates and reduce attrition rates • Together with at least 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 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 an 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. The ability to study (personalized) interactions between intestinal microbiota, gut epithelium and immune system is an important aspect of the model and will be of high relevance for both pharmaceutical and nutritional industry. By 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. **2. Liver** Within the use case liver function on a chip we focus on addressing patient variability using translational preclinical advanced cell models, thus introducing patient variability already in preclinical efficacy screening. The approach will be either by using stem cells from a large number of individuals (mimicking the population variability which is usually encountered in the clinical trial phase) or by using serum from individuals/patients. By thorough characterization of the stem cells using the signatures and knowledge on disease mechanisms developed in Roadmap Biomedical Health, we will be able to define patient subgroups. In this way, we will be able to study why drugs often only work in a limited number of patients and how the right drug can be selected for the right patient. **3. Technology** In addition to these two use cases, a third line of the ERP will focus on the development of state-of- 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 applicable in other (disease) areas as well as measurements of environmental exposure (link to ERP Exposense).
Results 2019	✓ **Gut function-on-a-chip in 2019**

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 intestine 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) cultured on (3D printed) permeable villi scaffolds combined with (micro)fluidics 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. This gut on-a-chip model will therefore have its application in the pharmaceutical and nutritional industry by providing a high physiological predictive human *in vitro* model to study intestinal absorption, digestion, and metabolism of compounds. In the end 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. Moreover, gut on-a-chip will be combined with developed liver-on-a-chip models in order to study cross-talk between organs and more accurately predict human oral bioavailability of compounds.

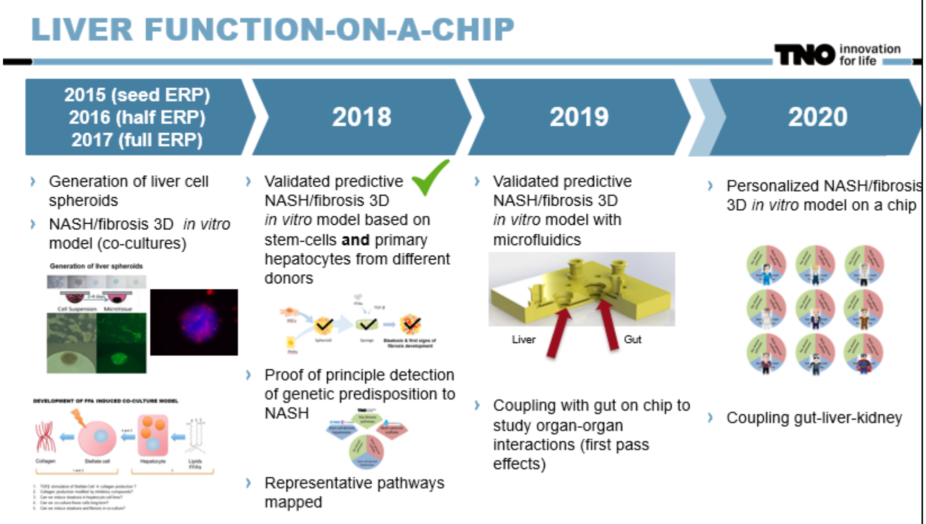
Deliverables 2019:

- ✓ Validation report human intestinal tissue on-a-chip
- ✓ Validation report human intestinal stem-cells on-a-chip,
- ✓ Publication on (validated) application of human intestinal tissue on-a-chip,
- ✓ Publication on (validated) application of human intestinal stem-cells on-a-chip,
- ✓ Demonstrator study for anaerobic-aerobic incubation platform, and if feasible patent application,



2: Liver function-on-a-chip in 2019

The “liver-disease-on-a-chip” will be a predictive *in vitro* disease mimicking (i.e. non-alcoholic steatohepatitis; NASH) model using co-culture of human pluripotent stem cell-derived hepatocytes or primary hepatocytes 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. This is of high relevance both for the pharmaceutical industry as well as the nutrition industry. 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.



Deliverables 2019:

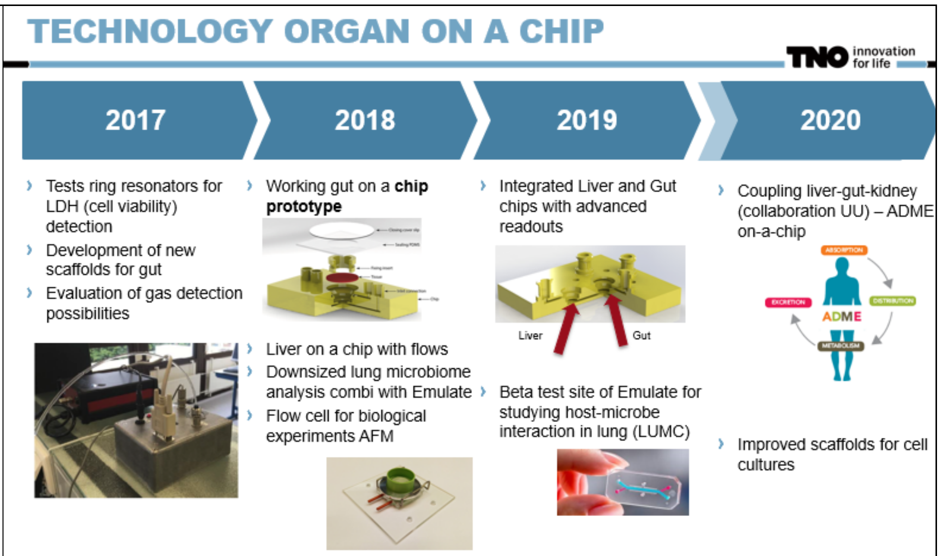
- ✓ Demonstrator that co-culture models using stem cells from different individuals show variation in response on disease induction
- ✓ Proof that 3D in vitro model responds to current clinically used compounds
- ✓ Proof whether human patient sera can predict populational variability
- ✓ PPS initiated on “targeting clinical trials models”
- ✓ Publication on application of human liver on-a-chip

3: Readouts, microfluidics main activities in 2019

We develop standardized organ on-a-chip hardware and scaffolds for easy, accepted and general use within industry, with focus on the population on-a-chip applications. We will do this together with, or based on our experience with, current chip providers and in close collaboration with end-users.

Deliverables 2019:

- ✓ Microfluidic chip with general ‘click-in system’ for tissue, general scaffolds or trans-well membranes
- ✓ First demonstrator coupling liver and gut
- ✓ Integrated sensors/electrodes for readout: TEER



4: Dissemination, communication and transfer to Roadmaps

Deliverables 2019

- ✓ Plan on technology embedding in Roadmaps, IP strategy
- ✓ Program management and internal communication
- ✓ International symposium
- ✓ 2 newsletters
- ✓ PR material: presentations, website update, animations, graphics (see example below)
- ✓ White paper on population on a chip

Internal and external collaboration

This program will only be successful if we 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.

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"

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, Maag Lever Darm stichting.

<table>
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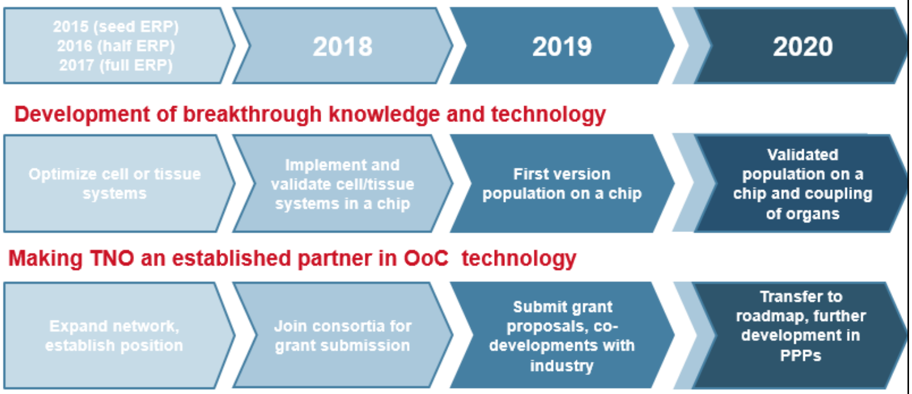
<td>Dynamics</td>
<td>Over the last 3 years, the ERP Organ function on-a-chip evolved from a seed ERP (2015) into a full ERP (in 2017). The program started with three use cases: gut-, liver- and lung-function on a chip, and for all three subprograms important technical developments as well as ecosystems development were achieved in 2015-2018, see figure below.



In 2017, use case lung 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 collaboration with Emulate, the leader in lung models, to which we will contribute with our expertise on host-microbiome interactions. We aim to become a partner in a collaboration with Emulate and LUMC and be an expert on host-microbe interactions 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. The focus of the OoC team was defined during Business case boot camp sponsored by the TNO Board of Directors: development of population on a chip for better (stratified) candidate drug selection for gut on a chip and liver on a chip. For technology, in 2017 we started the development of several readout and imaging technologies that will be implemented in the two use cases, and in 2018 two new postdocs started developments of chip and stem cell technologies. In 2019 we want to combine all these aspects into a first version of population on a chip for both use cases. In 2020 we will start with validation of these systems and gradual transfer of the Organ on a chip development and validation activities into Roadmaps. For this, in 2019 and 2020 we aim to generate sufficient opportunities through participation in consortia for grant requests (NWA call, EU projects, ZonMW, TKI and others).</td>
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18 Personalized health

General information	
Title VP/ERP	Personalized Health
Contact person TNO (DM en VPM)	Dr. Ben van Ommen (a.i. Dr. Jildau Bouwman en Dr. Andre Boorsma) Dr. Marjan van Erk
Contact person(s) government or topsector	Floris Lantzendörffer (EZK)

Programme 2019

Summary

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 life-style related diseases, evidence is mounting that lifestyle changes have a profound effect on disease progression and even disease cure is possible.

ERP Personalized Health develops 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.

Biology innovation: We will 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 will consider the roles of different tissues and the mycobiome using model systems. Moreover, we will research how we can reprogram inflammation or optimize inflammatory resilience.

Research Methodology innovation: In order to bring together all knowledge and data and connect this to the needs of citizens, personalized health advice models will be developed. These models will be based on data (Bayesian) as well as knowledge (system dynamics). This will be intertwined with activities and innovations in ERP Artificial Intelligence.

We will build a prototype community to investigate its value in empowering citizens and patients in their lifestyle changes: the ‘research and health community’. Within this community, behavioral change innovations will be combined with innovations in data collection and volunteer study methodology.

	Deliverables in 2019 will include proof-of-concept on improved inflammatory robustness measured by innovative plasma biomarkers and proof-of-concept on reversal of organ inflammation in mouse studies (biology innovation) as well as a next version of the PHAS that implements the ERP PH output of 2018, a framework for ontology based reasoning (as innovation to the PHAS) and 1-2 health data communities in which the community framework and PHAS will be tested. The innovations from this ERP PH program will land in future PPS projects that will implement personalized health innovations in real-life.
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 a systems and personalization approach towards metabolic processes. This established TNO as world leading with our personalized intervention strategy, as was shown by the fact that Habit/Campbell selected TNO as a strategic science partner for their product development. This ERP will focus 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 will build the biological basis for prevention, reversal and cure for diseases with a chronic inflammatory component (WP1 of the ERP PH). The by TNO developed PhenFlex challenge test technology will be 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. The combination of metabolic knowledge with innovative knowledge and application of inflammation within this ERP will take the personalized systemic approach of health optimization to a next level. To achieve personalized health optimization, research methodology innovation is needed. In the program, we will 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. These 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 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.
Results 2019	**WP1 – Biology innovation: towards inflammatory mechanism and robustness** WP1 will obtain knowledge about new personalized intervention strategies to optimize low-grade inflammatory resilience. Low grade chronic inflammation is a key hallmark for dysmetabolism and metabolic disorders, such as type 2 diabetes, cardiovascular disease, cancer, COPD, rheumatoid arthritis. In fact, low grade chronic inflammation is the key process that is common to all chronic lifestyle related diseases. Being able to treat or reverse low grade inflammation is therefore of great interest to industrial companies as well as to society and health care. However, chronic low grade inflammation, when present in one or multiple organs, often is not yet detectable in the circulation (blood). It is now amenable that the response to nutritional challenge test (result of previous work) may magnify these functionalities on the tissue level causing an overflow of inflammatory markers into the circulation and hence allow detection of early low grade inflammation without the need for biopsies. This allows the design of new therapies and lifestyle solutions, which was not possible earlier. In combination with (earlier developed) personalized interventions for optimizing metabolic health this will help in preventing, reversing and curing lifestyle related diseases. The figure below represents the knowledge and innovation areas that WP1 aims to develop for the coming period within ERP Personalized Health.

The results from WP1, will be used to prepare for a new public private partnership (PPS) which will implement developed technology and knowledge in a human volunteer study focusing on training of inflammatory resilience as a strategy or treatment to improve low-grade inflammation. Alongside human studies, mechanistic mouse studies will be performed to gain understanding of the mechanisms underlying reversal of low grade inflammation and efficacy of lifestyle and other interventions on long-term health endpoints as well as effects at organ level. Key to the technology that will be developed is that it will be mechanism- and biomarker-based. 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.

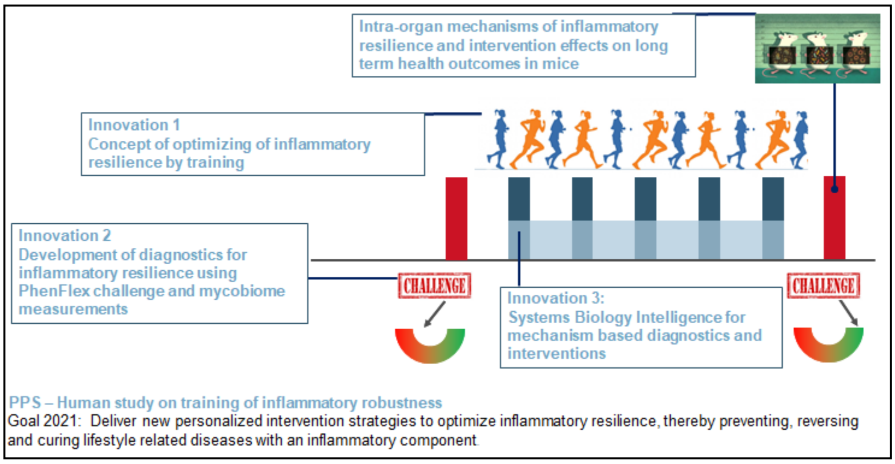


Figure EPR PH WP1. Overview of important aspects, innovations and their interplay within WP1 – towards inflammatory mechanisms and robustness

Three important innovations will be developed in WP1; **the first** is focused on the concept of training of inflammatory resilience. Literature is providing more and more indications that the inflammatory response may be "trained" by regular mild inflammatory as well as metabolic triggers that are regulated through epigenetic modifications. In 2019 we will combine the knowledge on metabolism and inflammation and how they trigger mild inflammation. We will incorporate knowledge on how immunity can be trained and how stimulating resolution can effect chronic low-grade inflammation. On this we will build new strategies to optimize dynamics of inflammation. **The second innovation** will focus on the development of new sophisticated diagnostic methods to quantify inflammatory resilience. In conditions of chronic low-grade inflammation the concentrations of inflammatory factors are overall slightly higher than in healthy populations in plasma, however, in isolation these concentrations are considered to be in the healthy range. Although inflammation in multiple organs can be present, often this is not yet detectable in the circulation. It is therefore difficult to determine whether a patient exhibits low-grade inflammation on basis of blood measurements. Human studies that applied TNO-developed PhenFlex

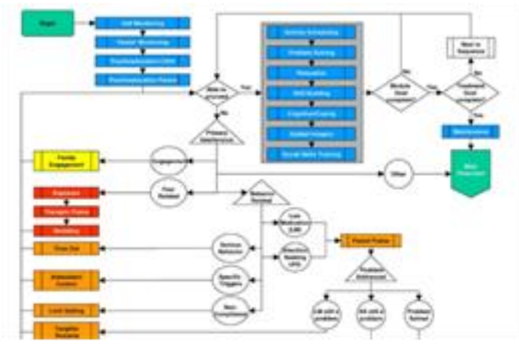
	challenge test provided first indications that the challenge test may allow detection of disturbed inflammatory resilience via quantification of dynamical inflammatory response profiles as well as via micro- and mycobiome measurements. **The third innovation** focuses on the development of so called Systems Biology Intelligence (SBI) for mechanism based diagnostics and interventions. This is a pipeline of in-silico technology that can be used to scout for established and exploratory biomarkers as well as to design mechanism based interventions or therapies. This innovation will also include the technological development to extract and store knowledge regarding co-morbid disease progression, leading to increased understanding of co-morbid diseases (for type-2 diabetes: atherosclerosis and retinopathy). Knowledge on inflammatory mechanisms and robustness as well as co-morbid diseases will be transferred to WP2 as input for the PHAS. Currently, there is no prior art on these three innovations. TNO is world leading in the area of metabolic health and metabolism. Low grade chronic inflammation is the next pillar that needs to be tackled for chronic lifestyle related diseases. Personalized systems thinking and resilience is our core value. Understanding inflammatory resilience will broaden our biology basis enabling novel ways to intervene and improve health. TNO has the unique knowledge, experience, tools and technologies to tackle the challenges above. This gives us the right to play and the exclusive chance to meet the needs from society and industry. In 2019, WP1 will extend the work started in 2018 with the following intended results and deliverables: • Proof of concept for improved inflammatory robustness upon interventions using innovative biomarkers in human biobank plasma samples [input for PHAS in WP2]. • Novel mechanism-based interventions designed by Systems Biology Intelligence to be tested in human study • Proof of concept of reversal of organ inflammation through life-style interventions in mice [publication] • In-silico (systems intelligence) identification of 1-10 biomarkers that reflect organ inflammation in plasma [input for PHAS in WP2]. • 2-3 interventions using novel mycobiome screening platform for inflammatory disease as a POC to attract partners to continue in PPS projects **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 systems change, requires not only personalized strategies promoting behavioral maintenance of individuals (focus in 2018) but also a focus on (health) communities as a whole (2019). The central concept in both foci is empowerment through personal health data valorization, which enables individuals ánd community to take control over their own lives and

	communities. In addition, we will explore and exploit community driven health data marketplaces, which are key for personal health data valorization. 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 2019 we will incorporate in the system the knowledge on chronic low-grade inflammation and socio-psychology collected in 2018. In addition we develop ontology based reasoning and will consider different modeling techniques for a world-leading PHAS in collaboration with the ERP Artificial Intelligence (ERP AI). In 2018 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 will be implemented and further improved in the PPS 'T2D Health Data Community' that has started July 2018. The core of the systems is composed of a time-based predictive model for personalized health trajectories related to T2D and predicted required interventions to prevent these trajectories. In 2019 this system will be extended on several levels: First, we will test whether the integration of the knowledge on chronic low-grade inflammation and co-morbidities (outcome 2018) with personal data can lead to improvement of the personalized health advice. Moreover, we will incorporate learning capacities to improve the models based on collected knowledge / data. In order to structure the reasoning of the system and make it easier to update the system with new knowledge, we will incorporate ontology-based structured reasoning for knowledge on nutrition and behavior in the systems. This will be done in close collaboration with ERP AI (and external partners). ERP AI will develop the fundamental mechanisms of ontology modeling while this ERP develops the biological knowledge to fill these ontologies and models. To be able to use telephone and smartphone collected data in training of our system, federated learning capabilities will be included in the PHAS architecture (connect to ERP AI). The current modeling strategies followed in the PHAS system do not make use of the full strength of the links between data and knowledge; for the best and strongest predictions, hybrid models are needed for this type of modeling. These type of models will be developed in the ERP AI. This ERP and ERP AI will research together how hybrid models can lead to better predictive models for personalized advice. Deliverables: • Development of an ontology based reasoning framework for the PHAS (in collaboration with the ERP A.I.); document describing version 0.1 • A white paper on the development of hybrid A.I. solutions for advice support systems in HealthCare

- A demonstration to 2-4 customers showing the feasibility and improvement of the advice with the new modelling network and PHAS functionalities (ppt).

WP2b will focus on (health) communities as a whole: we will build a prototype community to investigate its value in empowering citizens and patients in their lifestyle changes. Also, we will include the ecosystem as a relevant factor in achieving sustained lifestyle changes.
As part of the research related innovation, we will gain understanding of the working mechanism of communities and their interrelations. Thereby we can understand how to organize and build communities. From this perspective we will identify community needs, and by supporting these we can promote collective action and influence existing (health and social, political) systems. We aim to develop a community framework (overview) to understand how social systems function and change, and how communities and organizations can be activated, and which working mechanisms underlie these approaches. The results of this package can be embedded in the building of the online health data communities and provide them with personalized health advices via the PHAS.
Deliverables :

- Proof of principle of a community building strategy in order to optimize community collaboration in existing social networks (use cases: NDC community & highly motivated community).



Complex interventions to promote and sustain behavior change can be defined as interventions with several interacting components. Complexity varies on various dimension (e.g., intervention components, variability in outcomes, differences in delivery modes, degree of flexibility or tailoring, application in different settings). To improve the efficient design and diffusion of evidence-based interventions, calls have been made in the scientific community of behavior change for disruptive innovation and standardization. We aim to respond to this call to develop a distillation and matching model (the figure shows an example of a modular build intervention scheme). In part we aim to distill common behavior change strategies, and to match these with the intervention change mechanisms. This will enable the modular built of evidence-based interventions. The distillation and matching model will be based on a decision tree, incorporating: (1) behavioral (goal) process, (2) behavioral mechanisms of change, (3) behavior change techniques and requirements of usage, and (4) practical applications.
Deliverables

- A distillation and matching model of behavior change engineering [input for PHAS].

The future of personal health data valorization will be via community driven health data marketplaces (https://www.futureofpatientdata.org/). Important questions will be in which way citizens and patients can be convinced to make use of such health data marketplaces; what are the ethical, economic and social obstacles? For this, two different health data communities use-cases will be organized. The first one will be localized around a group of patients that will make use of the MyConsent system (together with the HHDC (Holland Health Data Cooperative) to consent to the secondary use of their health data. The other will be centered around the “digital literate” highly motivated type 2 diabetes community that is created in 2018. In interdisciplinary workshops with various stakeholders the ethical, economic and social aspects leading towards sustainable patient communities and health data valorization will be explored.

Deliverables

- A white paper about the tools, approach, and future of community driven health data marketplaces (ethical, economic and community value). [output from the workshops]
- An implementation framework based on the PHAS combined with the community framework for health data communities.
- A scientific report on the (health) outcomes of the Highly Motivated T2D community.

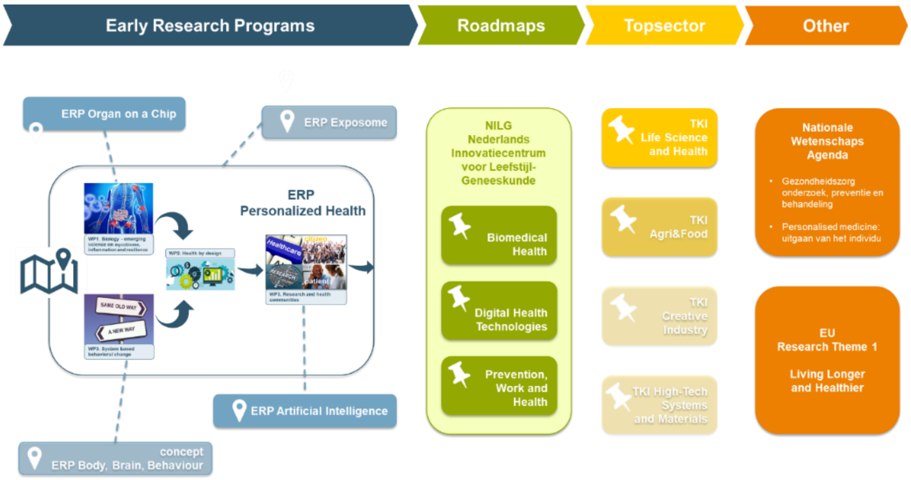


Figure - ERP PH interaction with other ERPs and VPs; connections to Topsector and NWA routes

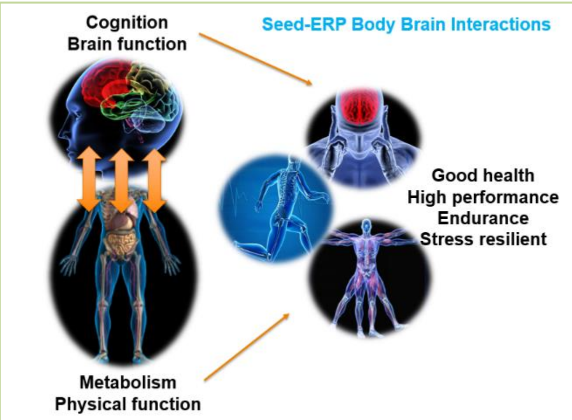
Network and external collaborations:

ERP PH interacts and collaborates with ERP Artificial Intelligence, ERP Exposome, ERP Organ-on-a-chip and ERP Body, Brain, Behaviour. Output of ERP PH is absorbed in VP Biomedical Health, Digital Health Technologies and Prevention Work and Health. Furthermore, this ERP is linked to the Netherlands Innovation Center for Lifestyle Medicine (NILG, a collaboration between TNO and LUMC). ERP Personalized Health connects very well with at least two routes of the NWA: “Gezondheidszorgonderzoek, preventie en behandeling” and “Personalised medicine: uitgaan van het individu”. This furthermore aligns nicely with the KIA of the various Topsectors.

	Other collaborations include: Collaboration with LUMC on Lifestyle as Medicine and on HAGK (HuisArtsen GeneesKunde) J&J: co-author on manuscript 2018, continued collaboration in 2019 Intensify collaboration on mycobiome with AUMC (AMC) and Radboud MC, A-star Singapore, LipidInflammaGenes consortium (Norway), AUMC (VUMC)
Dynamics	In the first year, ERP Personalized Health has incorporated the building blocks of the earlier programs (Early Life, Healthy Ageing) into its innovations in biology and research methodology. ERP PH has actively sought connections to TNO's other (early) research programs. The 2019 plan builds upon this by intensifying the collaborations and focusing on embedding its innovations in VPs and other programs or projects, which will provide opportunities for maximizing the impact. In 2018, the collaboration between TNO and LUMC in the area of Lifestyle as Medicine has reached an important milestone with the official launch of the Netherlands Innovation Center of Lifestyle Medicine (NILG, www.nilg.eu) at 3 July 2018. A range of new projects will develop under NILG providing opportunities for transfer of ERP PH technology and output towards PPP and implementation in other NILG projects. In the 2019 plan, we have combined WP2 and WP3 (in 2018 structure) into one WP, on research methodology innovation. This will stimulate interaction and alignment of the different activities related to research and methodology innovation. For example, the developments regarding the PHAS can be tailored towards the application in the research and healthy community. The grouping of these WPs will increase focus in activities and will be helpful in achieving the output as intended in the ERP program 2018-2021 within the assigned budget.

19 Body-Brain interaction

General information	
Title VP/ERP	Kiem-ERP: Body Brain Interactions
Contact person TNO (DM en VPM)	Dr. Paulien Bongers (Dir. Res.) Dr.Robert Kleemann/Dr.Jan v.Erp (Pr.Sc.) Dr. Annelies Dijk-Stroeve (PM)
Contact person(s) government or topsector	t.b.d.

Programme 2019	
Summary	There is a growing interest in the complex interactions between our body and our brain because this powerful connection could be used to optimize cognition and reduce stress, burnout and neurodegenerative diseases, as well as improve physical performance and decrease the burden of metabolic diseases and addictions. In 2019, this seed-ERP will pave the road to establish a full-ERP on ‘Body Brain Interactions’ which will enable TNO to become a world-leading player in body-brain innovation technologies and applied body-brain research in the years to come.  The project proposal is timely and meets the needs of a modern society which requires 1) high level of cognitive and physical performance throughout life (also under adverse conditions); 2) optimal protection against mental and physiological stress; 3) strategies to counteract cognitive decline and a plethora of associated metabolic diseases. Obviously, recent demographic and socio-economic changes propel these needs and urge the development of first tools and interventions to optimize body-brain interactions. This unmet need requires an <u>exact understanding</u> of how body and brain interact bidirectionally to define <u>causative</u> determinants that can be modulated to optimize body and brain functioning. Inherent to advancing into a new field, this requires development of dedicated technologies (e.g. sophisticated analytical tools, data integration and modelling systems for complex biological (β) and psychosocial (γ) datasets, and comprehensive experimental models to test new treatment concepts). **State-of-the-art and beyond:** The interactions between body and brain are hardly understood. Thus the current state of the art knowledge of body-brain biology is merely descriptive in nature and based on observational studies and associates that fully lack causal underpinning. For example,

	some studies find that a particular type of bacteria (e.g. bifidobacterial) are increased in obesity whereas other studies report the opposite. The same goes for metabolites that are produced in the gut such as short chain fatty acids: some studies report a positive association between these molecules measured in the feces and metabolic health and behavior whereas other studies find the opposite. Hence, there seems to be an interaction but it is not understood on the molecular level. This fairly trivial example of a not understood body-brain interaction holds also true for other interactions, e.g. where psychological or behavioral processes influence bodily processes and physical wellbeing. Further, we currently lack analytical and data analysis tools to determine the underlying mechanisms which are essential to modulate body-brain interaction. Without better understanding of the causalities between body and brain, it is impossible to develop strategies to optimize body-brain interactions. We aim for the improvement and enhancement of capabilities and whole-body strength (e.g. military, athletes, healthy citizens) as well as for a better management of disease and prevention of the disease burden that is expected to arise from the pandemic of obesity and the high incidence of cognitive disorders (e.g. cognitive decline, neurodegenerative diseases). TNO has expertise in the various relevant subdomains (e.g. microbiology, systems biology, medical biology/physiology, neurobiology, psychology, cognitive neuroscience, behavioral sciences and data science) and has a history of generating new knowledge and creating value by combining scientific insights across disciplines. As deep knowledge on the mechanisms that drive body-brain interactions is absent, determinants that influence these are largely unknown. This implies a need for well-designed experimental studies in which the effects of interventions (including treatments) are investigated to identify these determinants. Subsequent steps include the translation of effective interventions for practical implementation. **Objectives for 2022:** The ERP 'Body Brain Interactions' hence concentrates on a comprehensive in-depth understanding of the interactions between body and brain far beyond descriptive relationships (current state of the art) as these are insufficient to develop interventions for optimal body-brain functioning ('begrijpen in plaats van beschrijven'). The main objectives are therefore: 1) to identify key determinants of body-brain interaction on the physiological-biochemical level and the psychosocial level; and 2) to develop ground-breaking techniques that will allowing mechanism-guided interventions. True understanding and knowledge of body-brain interactions will provide new targets for interventions (of interest for nutrition and pharma stakeholders) and will stimulate the development of advanced decision-support technologies and stress-management technologies (of interest for e.g. governmental and eHealth stakeholders, defense, police etc.). In four years, significant progress can be made in this area as this is sufficient time to set up, conduct and analyze interventions studies. Where possible, collaboration with others (e.g. Donders Institute (Radboud), Oxford University, and Coronel Institute of Occupational Health

	(AMC/UvA)) and connections to existing research initiatives will be sought. Because body-brain interactions play a pivotal role in all stages of life and are a key determinant of good health and performance, the third objective is to validate the developed tools & technologies in proof-of-concept studies which can (due to the broad application possibilities) range from improving human performance to treatment of addictions and combating metabolic diseases.
Short Description	
Results 2019	From a list of possible but still poorly understood body-brain interactions defined in 2018 (‘explorative ERP’), this seed-ERP will focus on two important topics of body-brain interactions, that have the potential to grow out into two ecosystems, each with multiple use cases (in full-ERP phase). Topic 1: Interactions and mechanisms that determine cognitive decline in obesity and dysmetabolism. Topic 2: Interactions and mechanisms that determine recovery from mental and physical overload in stressful situations. Importantly, both topics involve a biochemical-molecular and a psychosocial component and both contribute to solving the above societal challenges.
Dynamics	

20 Exposense

<table>
<tr><td colspan="2">General information</td></tr>
<tr><td>Title VP/ERP</td><td>ERP ExpoSense</td></tr>
<tr><td>Contact person TNO (DM en VPM)</td><td>Stefan Bäumer (Principal Scientist-), Anjoeka Pronk (Senior scientist – Exposoom), Ingeborg Kooter (PL), Ardi Dortmans (SD CEE), Paulien Bongers (SD HL)</td></tr>
<tr><td>Contact person(s) government or topsector</td><td>LSH, HTSM , Chemie</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">Programme 2019</td></tr>
<tr><td>Summary</td><td>Our health is impacted by the environment we live in, combination of exposures (e.g. lifestyle factors, chemical exposures, social interactions and stress) may constitute a major risk factor for disease. 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 lifetime – will help to close this gap in knowledge. Moreover better understanding 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%)[18]. The long term goal (4years +) of this ERP is to develop a personal ‘early warning system’ (e.g. integrated in a smart watch) consisting of new sensor technology and new interpretation of the data. Both are tuned to each other for best performance. 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 able to assess, interpret and 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, with emphasis on child health.
The following results are foreseen for 2019:
Laboratory demonstrator of technology for the identification of the chemical composition of PM. Current state of the art PM detectors can discriminate the size of PM. However size is only one indicator for health risks. Chemical composition also determines health risks. The virtual impactor (sizing) will be optimized for separation of PM (<2.5um / 5um / >10um diameter) with added chemical identification, showing the concept of in-line chemical identification of PM at < 0.1 mg/m3 air starting with crystalline silica particles
Integrating sensor data with exposure models and big data will lead to new methods for assessing and interpreting (individual) external exposure PM profiles in the occupational and general environment. Ultimately, this will enable insights in personal exposure patterns over a (work) day of an individual or a group of individuals (based on a chemical sensor or contextual sensor worn) providing understanding of which exposures occur when, where</td></tr>
</table>

18 * https://www.gezondheidsraad.nl/documenten/adviezen/2018/01/23/gezondheidswinst-door-schonere-lucht

	and why, providing the opportunity to intervene. The developed methodology will consist of a set of (chemical and contextual) sensors and associated models and a data infrastructure for interpretation that can be applied to individuals or groups of individuals. • Methods and models will be developed to determine the *internal* exposure resulting from exposure to PM. This will be done by (1) estimating the internal exposure, (2) linking internal exposure to health effects. Based on this information early markers of effect can be identified (e.g. for health surveillance) or effects of new exposures with unknown risks can be predicted before the ultimate effects develop (e.g. for nano particles, indoor air pollution etc).
Short Description	The aim of the program is to deliver comprehensive equipment and models for the prediction of the impact of particulate matter (PM) exposure on air pollution-related human health, especially in the work environment. To this aim two important aspects are foreseen. First development of portable sensors (< 25 mm^3) and second an integrated model for the assessment, interpretation and feedback 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 very hazardous substances. 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 two 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 health, it is important to know the chemical composition of the particles. The technology breakthrough is to not only discriminate the size of the particles (i.e. 2.5um /5 um / >10um diameter) in a low cost and small solution - but also chemically identify PM with respect to both organic and inorganic components. Concentrations of PM which have to be measured are in the range of down to 25ug/m^3 to be in agreement with the European Air Quality standard[19]. 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 often annual averages for environmental exposure) and the predictive power for personal exposure levels is limited. Therefore exposure assessment can be done at group level only. 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. Technology breakthroughs include creating a dynamic data infrastructure that can manage (sensor) data flows in real time, methodology for data fusion of high resolution (in time and space) sensor data and

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

	(currently) low resolution exposure models and in dealing with uncertainty of the sensor data. *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 and models (e.g. biomarkers) can assist in bridging external exposure data towards health status. Secondly, to address the effects of any exposure in the past, in absence of the possibility to collect external exposure data retrospectively, employing markers of internal exposure is the only way to document past exposures. Thus, the development of approaches is needed that enable the quantitative linkage between external exposure to internal exposure to internal early markers of health effects. Specifically, methodology and data infrastructures for (semi-) automatic integration of personalized internal PM exposure data with external PM exposure data, internal exposure and effect models, mechanistic insights and PM-mediated health effect data will be developed.
Results 2019	**WP 1 Governing the Exposense trajectory** The ERP Exposense includes the development of sensors as well as exposome technologies. Having both capabilities in one organization is regarded as a strength and should be exploited to maximize benefits for all partners involved. This sort of vertical integration of technology across domains and units within TNO needs to be coordinated into a coherent program. Activities include: - Refine the overall roadmap of the ERP: from sensor development for measuring external exposures, chemical identity characterisation of the exposures, application of sensor data in combination with predictive models in the environmental (outdoor, indoor) and occupational domains, non-invasive monitoring of early markers of exposure up to health effects and individual feedback. Next to the units Healthy Living, Industry, Circular Economy and Environment and Defence, relevant partners to team up with will be defined. - Steer the overall as well as sub elements of the plan with regard to valorisation. Which sensor – model integration strategy will result in the best connection to the markets? In addition, definition of market outlets for sub-technologies that may be attractive for application during the course of the ERP. - Definition of demonstrators that connect sensors and models. Preparation of a pilot study in 2020 / 2021 in which external and internal exposure measurements will be combined with health measurements: study design, study setting and partners. The PM sensor developed in WP2 will be field validated in this study. Existing sensors will also be used. - Grow the eco-system of national and international cooperation in the field of Exposense, <u>Deliverables:</u> Updates roadmap and sub-technologies for market application (market plan) including a valorisation strategy, MoU with noninvasive monitoring partner(s), Study design for first pilot study combining external and internal exposure measurements, including partners.

WP2: Sensor development

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 and poor reproducibility amongst different sensors of the same type (resulting in current variability between and within sensors). Priority in the sensor development will be set on improving TNO's PM sensor by adding chemical identification to the sensor, a feature that is lacking for current sensors. Figure 2 shows schematically how PM can be classified.

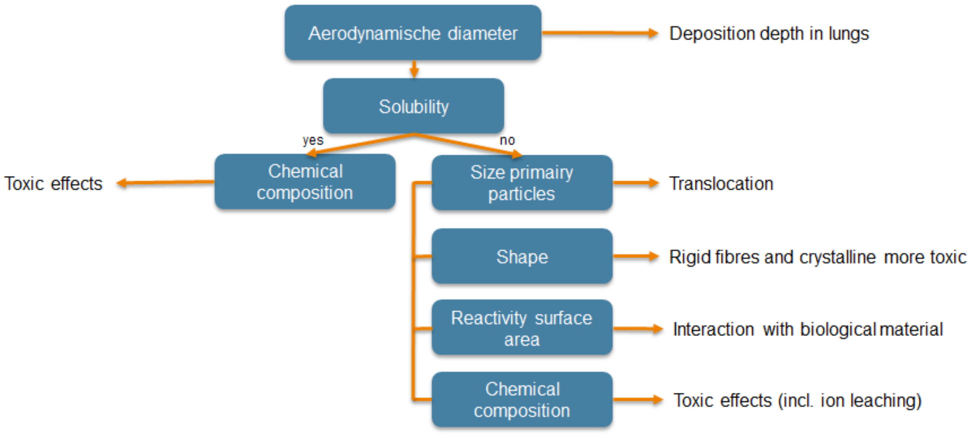


Figure 2: schematic classification of PM

Particles deposit in the respiratory tract depending on their aerodynamic diameter (figure 3). 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 true for soluble and also for non-soluble PM. In the latter case the surface reactivity is more important. However surface reactivity can be predicted from chemical composition.

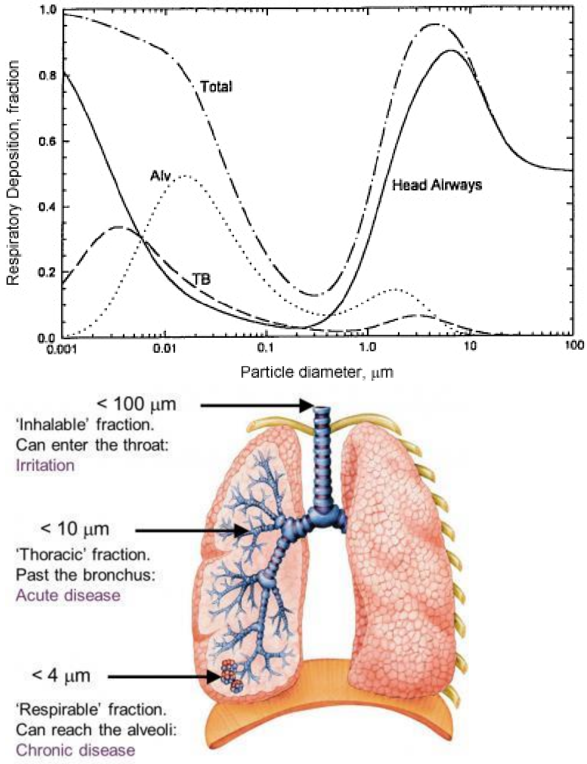


Figure 3: Deposition of particles upon inhalation in relation to their size.

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 biomarker selection and modelling of the internal exposome and health effects.

WP 2.1: PM detection and chemical identification
Chemical identification of particles have been assessed before in some papers, using FTIR analysis of collected particles (not an in-line solution), or a modified laser induced breakdown spectroscopy (LIBS) approach, in which the particles are targeted, vaporized using a laser, and the fragments are identified. Both solutions do not seem suitable as a wearable/portable in-line sensor for personal exposure monitoring. The approach that will be pursuit in 2019 is a combination of particle sizing using a virtual impactor, and infrared identification of the sized particles in a hollow waveguide channel. First the virtual impactor of the present sensor has to be reoptimized to allow for the integration with chemical identification. Next the (hollow) waveguide approach using IR spectroscopy for chemical fingerprinting will be further developed toward PM identification. Both, virtual impactor and waveguide principle will be combined in one demonstrator.

Deliverables:
Demonstrator optimized virtual impactor with added chemical identification, showing the concept of in-line chemical identification of PM at < 0.1 mg/m3 air starting with crystalline silica particles.

WP 2.2: VOC detection
Current European requirements for the occupational concentrations of e.g. benzene, formaldehyde, acrylonitrile are well below 100 ppb. On the other hand, detectors that can detect low ppb levels, are not selective to any VOC[20]. So, the use of many low-cost sensors in combination with optimized data mining and modelling is not a feasible option with these non-specific sensors, and a major improvement in the combined sensitivity-selectivity is still required.
In 2018 first steps towards sensitive and selective VOC detection were made by showing the technology principles of IR spectroscopy in conjunction with concentrator coatings and signal amplification through nano-antennas. In 2019 these technology building blocks will be optimized with respect to required coating thicknesses and antenna dimensions that are suitable for integration, and will be combined into a portable sensor showing feasibility and form factor. The FTIR read-out hardware will be obtained from a commercial or technological partner, like Fraunhofer.
Deliverables: Demonstrator portable VOC sensor (~1 dm^3 volume), showing the integration of the amplification solutions integrated with portable FTIR readout hardware and a sensitivity of <20ppb for benzene.

WP3: Exposome modelling

The concept for integrating exposure models and enriching these models with sensor and other data (Figure 4) was adapted in 2017 based on the Military Exposure Assessment Tool (MEAT). In line with this concept, in 2018 air quality models have been adapted to make them suitable for exposome purposes (increased resolution in time) and implemented in Urban Strategy (US) technology. In parallel, conventional occupational models for time weighted average (TWA) estimates have been implemented in the DIAMONDS platform.

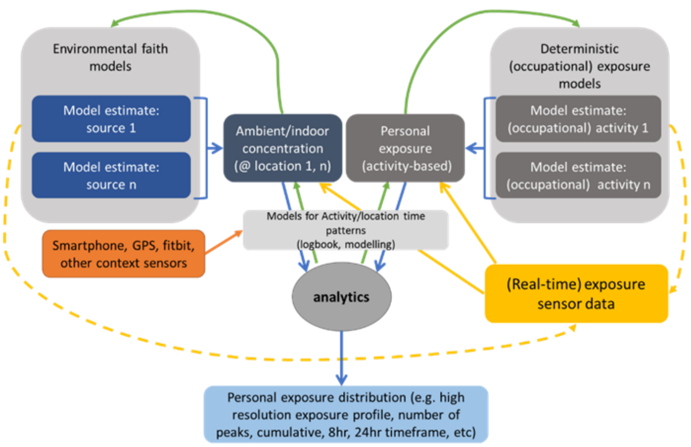


Figure 4: A dynamic (sensor) data enriched modelling concept for estimating personal external exposures, based in Military Exposure Assessment Tool (MEAT).

WP 3.1: Integration of the environmental (outdoor and indoor) and occupational modelling into complete exposure profiles based on a person's activity pattern.
PM exposure occurs through the environment, but also form work. Exposure to diesel exhaust for example comes from the general environment (traffic),but can be complemented through work if a person works at a garage or is driver by profession. Another example is exposure to silica that may be caused by the general environment but also when one is working in the construction industry.

[20] L. Spinelle, et al. Review of Portable and Low-Cost Sensors for the Ambient Air Monitoring of Benzene and Other Volatile Organic Compounds, *Sensors*, **17**, 1520, **2017**

	Currently PM exposure is explored either in the environment or in occupational settings. For exposome research the combination of both is required. Compilation of model based personal exposure profiles is, to a certain extent, already possible for environmental exposures and needs to be completed by the introduction of occupational exposure. In 2019: • infrastructures (US and Diamonds) will be further integrated and expanded with occupational exposure methodology to compose model based real time personal exposure profiles that can be stored and be used for further analysis off line. • In addition, a demonstrator will be developed in collaboration with the UK HSL and TNO Defence showing PM related model based exposure profiles generated from both the general and work environment. Deliverable: Demonstrator integrating occupational and general environment models providing exposure profiles based on both sources. *WP3.2 Domain-wise integration of modelling estimates with sensor data* In 2018 comparisons have been made between model estimations and sensor data both in the general environment and occupational domains. In 2019 methods will be developed for enhanced personal model predictions making use of wearable sensors or sensors in (close) proximity. Hereto the, data infrastructure needs to be expanded with a module to deal with sensor data. Development of a module for the data infrastructure for storing and cleaning of sensor data making use of big data technologies 3.2.1 Occupational domain For the occupational domain developments have been made in 2018 in the VP Sustainable work (SW, HL). From this work it has been concluded that new models are needed for sensor integration. Two types of models have been proposed, one based on determinants comparable to current occupational models but based on sensor data (further developed in VP 2019), and the other making use of dispersion models, similar to the environmental approach. In collaboration with NIOSH and HSL (outside TNO) and CBRN and ICT (inside TNO) the following will be developed: - Assessment method of personal exposures by application of environmental dispersion models in combination with sensor data - In addition the added value of context sensors (video imaging, beacons, activity measuring devices, etc) to collect the required contextual information for these models will be explored Deliverables: Memo on how dispersion models and context sensors can contribute to the composition of occupational personal exposure profiles. This knowledge will be directly applied in the exposure campaign VP SW. Activities in VP sustainable work (SW) 2019 related to the ERP include a measurement campaign using sensors (in which the context sensors can be piloted and which will provide data for environmental dispersion modelling), user centred research: privacy requirements, human factor research. 3.2.2 Environmental domain (outdoor and indoor) Comparisons between yearly and hourly based averages estimated by modelling and sensor measurements are being made for Black Carbon (collaboration UU exposome hub), results available November 2018, peer reviewed publication in 2019. The conclusions of these comparisons will guide further improvement of the modelling. Activities in 2019 most likely include (collaboration UU exposome hub (outside TNO) and TNO Mobility & TNO Defense):

	- Further improvement of air quality models according to findings from comparisons - Additional comparison of PM 2.5 data. This less reliable sensor is more realistic as a surrogate for other low cost sensors. Methodology development for gaining insight in dealing with uncertainty - Further improvement of indoor estimates since people spend 70-90% of their time indoors. In 2019 a plan for improving indoor personal exposure assessment will be made based on analysis of existing data (ZeroEnergy and Be Aware projects) and an expert workshop. - Development of technology to report personal environmental exposure estimations to individuals <u>Deliverables:</u> Report on the strategy dealing with less reliable sensor data comparing the BC and PM2.5 results for sensors versus modelled data. A draft scientific paper will be prepared and the results will be presented at a scientific conference (ISEE 2019, Utrecht), Report describing how the indoor exposure assessment can be improved within the context of the ERP, module for personal feedback of exposure profiles (to be implemented in a VP, possibly Child Health). Activities in VP CEE: further improvement of environmental dispersion models, tbd. Activities SUMS include making US estimations real time Further coordination between ERP and VPs will be done during detailing of the plans for 2019 *WP3.3 Internal exposome* WP 3.3.1 Development and demonstration of big data analytics tooling for internal exposome data In 2018 in the seed ERP, a start was made to integrate data/model components to retrieve, annotate, store, analyze and model internal exposome (describing the level of chemicals in blood, organs and the effects chemicals have) data to ultimately link exposure to health effects. Based on the DIAMONDS data infrastructure, a prototype infrastructure capable of analyzing internal exposome data and populating data models with own and public data will be build. This will be done along two lines of modelling: bottom up, relying on very detailed specific molecular data on one specific stressor within the exposome and top down, relying on the (semi-automated) integration of multiple public data sources to propose exposure health relationships. In 2018, a start was made with these approaches for benzene (but not for PM yet), primarily in qualitative sense. In 2019 (and beyond) the developments of 2018 will be continued towards an integral data infrastructure aiming at the of *quantitative* estimations of personalized internal exposures and health effects of PM related exposures. In collaboration with TNO ICT, TNO Defense, Imperial College, Aarhus, UU exposome hub the following activities are foreseen: - Improvement of the data infrastructure for integration of external exposure data with internal exposome data. Focus on making the approach more quantitative. Big data concepts will be incorporated (PHT, distributed computing, data locality, FAIR data concepts, data privacy). - Demonstrating the data infrastructure with an air pollution, black carbon, PM use case - Using bottom up and top down data modelling approaches <u>Deliverables:</u> Data infrastructure; Report demonstrating air pollution/and or black carbon internal modelling with the data infrastructure; Draft scientific publication on internal exposure and effect modelling of air pollution

	WP 3.3.2. Interaction with microbiome and metabolic health Inter individual differences in health responses to external stressors are possibly related to metabolic activity, immune health and microbiome (the populations of microorganisms within humans). Within this sub WP, the role of metabolic constitution and microbiome and immune health will be objectively evaluated, with the ultimate aim to determine how to incorporate these domains in exposome research, here in particular for PM. - Making an inventory of the role of metabolic constitution and microbiome in responses to PM related exposures and respiratory and immune health - In particular for individualized health. Deliverable: Report on the relevance of microbiome, immune and metabolic constitution in relation to the exposome of (primarily) PM related exposures. WP 3.3.3 Requirements for technology partners for noninvasive monitoring As internal exposome monitoring technology will not be developed at TNO, external technology for (noninvasive) assessment of internal exposure and effect markers is crucial for the long term goal and integration into the data models. Secondly this is needed for inclusion in the overarching pilot study foreseen in 2020. <u>Deliverable:</u> memo with critical needs for noninvasive technology for assessing internal exposure, in particular for PM **WP 4 dissemination** Th results achieved in the ERP but also projects adjacent to the ERP will be shown in a colloquium on the topic of Exposense. Internal and external speakers will be invited to discuss the different topics of the program and stimulate exchange and cooperation. The Colloquium should be held in Q4 2019. In addition, the results will be disseminated at conferences in specific domains. Next to the colloquium several publications and patents will be prepared during 2019. With these publications and IP the right to play for TNO will be further established and communicated. The EU project Exposogas, in which TNO participates, will most likely organize a dissemination event as well. Exposense will contribute to that event.
Dynamics	Technological developments in the seed-ERP started in 2018 focussed on the external exposome: sensors and models for external exposure assessment. With respect to the activities in 2018 some changes in scope for 2019 (and on) have been made. Sensor development for external exposures focussed on PM and VOC sensor development. Given new insights in a primary market focussed on respiratory health and work related safety PM sensing including chemical identification will have priority in the ERP sensor development.. Also for making the sensor technology suitable for applications in the field of personalized health advise, the technology needs to be made portable / wearable. TNO has plenty of experience in this field residing in the Holst Center. Involving Holst Center will speed up the transition to a wearable device, including wireless data transmission and low power solutions. In doing so the business cases could be made more attractive for a larger

	group of customers. Sensors for internal exposome (biomarkers) will not be part of the technological development within TNO in 2019. Modelling external exposome has mainly focussed on integrating existing exposure models in different domains and on comparison of these models with sensor data. In 2019, there will be a stronger focus on sensor-model integration for enriching existing models or development of new exposure models based on sensor data. Making use of big data concepts for sensor data storage and analysis will be included in 2019. Focus will be on PM related exposures. For reaching the Exposense 4 year goal assessment and interpretation of internal biomarkers is needed as well. Activities in 2018 included very limited exploratory work on this topic. The transition to a full scale ERP enables inclusion of these much needed developments. A new sub work package on internal exposure modelling for interpretation of internal data, is added to the ERP. This will also make use of big data concepts for sensor data storage and analysis. Since the development of methods for non-invasive collection of internal exposome data will not be part of this ERP, partnerships will be found to assure the long term goal of a technology for assessing and interpreting internal exposure data. <u>Development of collaborations:</u> - Within TNO: In 2018 there was a close collaboration with VPs within Industry, HL and CEE. In 2019 this will be expanded to VPs within Defence. In addition, expertise from the units Mobility (urban strategy technology) and ICT (big data concepts) will be incorporated. A direct link with the ERP Big data will be explored. In the 'Results 2019' section, collaboration outside the core units involved in the ERP (Industry, HL, CEE) are specifically mentioned. The VP on Integrated Photonics has explicitly in its work program investigations regarding spectrometer on chip. This is one important building block for the Exposense sensors as well. - - Photonics will Outside TNO: In 2018 the main collaborator was the UU Exposome hub. In 2019 new *international* collaborations will be with Imperial College, HSE, NIOSH, and potentially Aarhus. - Participation of TNO in EU initiatives HBM4EU, EU Exposogas - Collaborations on sensor development with University of Caen and Fraunhofer, that were started in 2018 will be intensified. - TNO is well connected to the NWA route and startimpuls "Meten & Detecteren". A proposal will be submitted strengthening the connections to the community and expanding the research towards lower TRL.

21 Wise policy making

<table>
<tr><td colspan="2">General information</td></tr>
<tr><td>Title VP/ERP</td><td>Wise Policy Making</td></tr>
<tr><td>Contact person TNO (DM en VPM)</td><td>H. van Veen / P. Werkhoven</td></tr>
<tr><td>Contact person(s) government or topsector</td><td></td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">Programme 2019</td></tr>
<tr><td>Summary</td><td>Decisions today are made in a volatile, uncertain, complex and ambiguous world stage where technological advances provide us with many opportunities, but equally as many threats. The goal of this ERP is to support governments, businesses and citizens in both their routine daily choices, as well as in the the pivotal and crucially defining choices they must make by enhancing their capacity to make wise decisions.

The current state of affairs is that, in the field of complex decision making (and how to do so more smartly), a great deal of CD&E-based knowledge has been accumulated at TNO about topics such as sense making, perspective taking, critical thinking and expertise. At the same time, little attention has been paid to the goals we aim to reach, and the ingrained limits to human capacity, such as cognitive biases and other inherent (hard-wired) limitations of our neural intelligence (brains). Therefore, the current proposal focuses on technological-human support focused on, for example, better modelling of complexity for an increasingly complex world, in combination with (long-term) ethical goal functions by means of artificial intelligence.

To reach a “wise” decision, we recognise three basic elements from the systems theory: the context, the goal and the decision itself.
1. Context: The decision maker (a person, machine or system) must grasp the complexity of the context in which the decision is made. He must develop an understanding of the array of possible choices and of the possible effects, side-effects and interrelated effects of those choices (see purple part of illustration 1).
2. Goal: The decision maker must know and understand what the most desirable outcome of the decision is. This means being able to define what the “correct” goals are that society as a whole should wish to achieve. Based on the goal, the decisionmaker should be able to weigh up the perspectives for taking action and determine the value of their effects (see green part of illustration 1).
3. Decision: A decision must be made both understandable ánd explainable on the basis of the above mentioned context and goal. This supports the decision makers accountability for the decision. The use of ever-more complex models to support decision making, demands an experimental approach to decision making (“trial balloons” in the illustration below). Experiments allow learning as they can lead to ongoing insights: they make it possible to identify less “correct” outcomes and will thus – if necessary – make it easier to adjust course.</td></tr>
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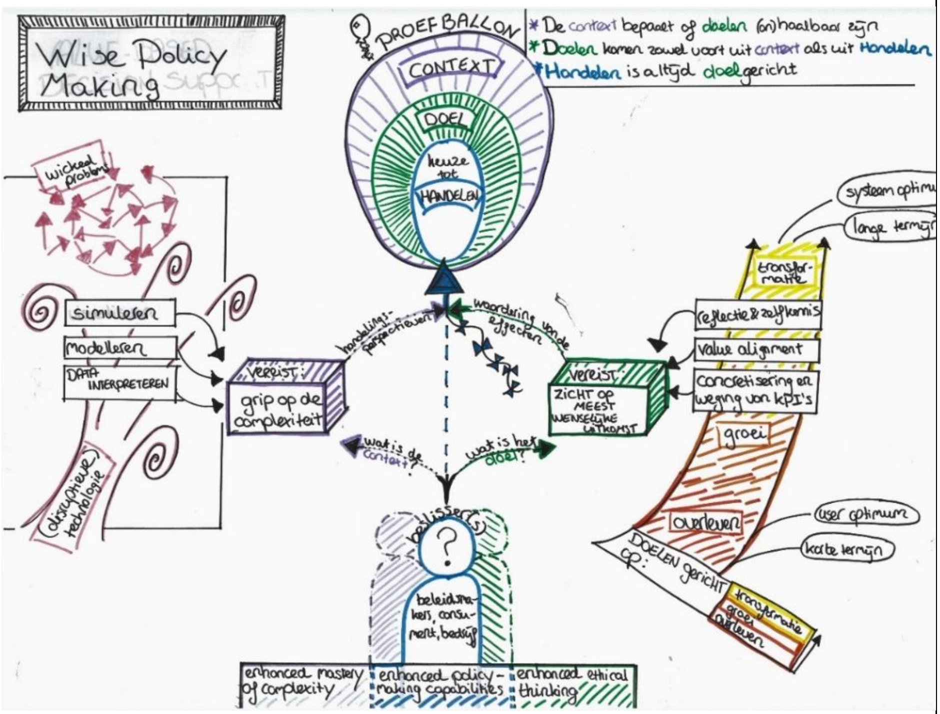

Illustration 1: Schematic diagram of improved capacities to make policy and administrative choices (blue).
The purple shadow of the decision-making “entity” (e.g. a government) represents the required grasp of the complexity. This may involve modelling and carrying out simulations on the basis of this, as well as improving the cognitive capacities of the decision maker(s). This occurs against a backdrop of continuous new disruptions, which fundamentally alter the context each time.
The green shadow represents the required grasp of the most desirable outcome. This also occurs against a background of the various stages into which goals may be divided. The most fundamental goal is to survive (red hatched). These goals generally focus on self-interest (user optimum) and the short term. As a society becomes increasingly prosperous, it becomes possible to evolve towards goals based around growth (orange) and transformation (yellow). The long term and the interests of the whole (system optimum) now take centre stage.
In the “trial balloon”, the interaction between context, the goal and the decision come together. This illustration of the interaction between behaviour, goal and context comes from system theory, and thus covers how these develop in practice. In this balloon, how a decision maker can best be supported is tested in practice.
See Appendix A for a more extensive explanation of this system
</td></tr>
<tr><td>Short Description</td><td>Goals for 2022
Improved quality of decision making capacities for policy making is essential to secure a future in which the technological advances of this era are being put to use to maximally benefit human wellbeing. In 2022 this ERP aims to have developed methods and tools that significantly improve decision making capabilities. This encompasses the following 3 deliverables:</td></tr>
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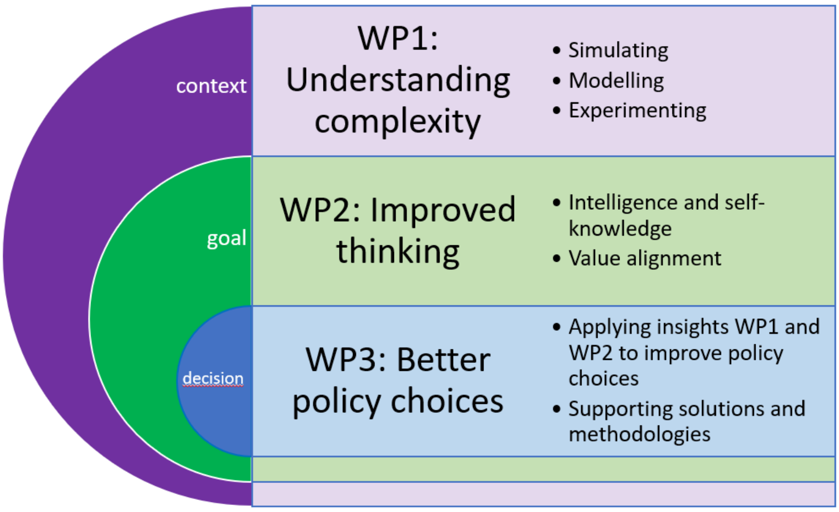
	1. A multidisciplinary vision for enhancing wisdom in developing and implementing policy. In this vision, current and future disruptive technological innovations and developments in society are linked to the potential to develop human behaviour in the direction of "wisdom". Wisdom is defined as the understanding of great complexity and reaching long-term solutions that work towards ethically-justifiable goals, aimed at the well-being (in a broad sense) of as many people as possible. 2. Supporting tools and methods that enable both the realisation ánd the justification of wise and unbiased decisions in accordance to above mentioned vision. These tools aim at improved and well-balanced, cognitive, emotional and ethical capacities (human and machine), focused on maximum human well-being in the long term. Governments will have access to grips and tools ("value-driven policy making") that can help them govern in concrete terms, and companies can provide accountability for their products and services. 3. Knowledge to predict and control human decision-making and the impact of new technology and linked policy. Practical pilots and experiments in "Policy Labs" that can facilitate understanding wise decision processes and the effects of choices. These allow the above-mentioned support to be tested in practice and steadily adjusted and improved through CD&E (Concept Development and Experimentation). Cases may be chosen around topics such as "smart grids", "transport", or "cognitive cities". Experiments provide insight into human decision making and its potential consequences (so that – if necessary – adjustments can be made) and can lead to the up-scaling of models and support tools.
Results 2019	At the end of 2019, this research team intends to have taken concrete steps towards positioning TNO as an international "thought leader" on the topic of wise decision making. The following actions are defined to achieve this: • Initiate structural and strategic partnerships with governments, business, knowledge institutes (incl. IAS) and universities around this topic. • Combining the topic of wise policy making with our knowledge and current research on Artificial Intelligence and autonomous control, and our research on ethics. • Executing the research program, aimed at the following three main results for 2019 (with below the steps to obtain these results): **1. <u>Understanding complexity</u>: The methodological and technical basis for grasping the complexity of a changing society and new technologies by:** ▪ Analysis, selection, and specification of qualitative and quantitative methods (tools) for modelling decision-making in relation to complex datasets for different (at least two) critical domains (e.g. energy transition, transport, safety and terrorism, environment and sustainability, etc… ▪ Designing (and if possible execution of) experimental trials (lab and field) aimed at the refinement of these methods by including knowledge on human (ir)rationality and cognitive biases in decision-making (e.g.,

	including hyperbolic discounting over time, neglect of probability or bandwagon effects) ▪ Developing first versions of algorithms for wise policy making that can be included in the abovementioned models and simulations handling complex data sets **2. <u>Improved thinking</u>: The most promising solutions for improved thinking (wisdom, i.e. the combination of increased intelligence and better ethical choices) in the aforementioned domains by:** ▪ Inventory and specification (of underlying processes and mechanisms) of human cognitive and ethical capacities and capacity limitations ▪ Analysis and selection of possibilities (biological, digital, psycho-social) to augment or enhance these capacities and to circumvent or neutralize these capacity limitations in order to increase wisdom (the combination of intelligence and ethics). This includes: • Inventory, evaluation and selection of (existing) methods and tools for value determination, judgement and alignment • Specification of improvement possibilities for current utility elicitation method(s) aiming at the formulation of *unbiased* goal functions • Combining these into leading principles to be used for value-driven policy making and value-driven codes of conduct taking into account the evolutionary limits human rationality (see main bullet 2.1) **3. <u>Better policy choices</u>: Providing practical tools and experimental facilities for supporting governments (and businesses) to improve their policy decisions by:** ▪ Inventory of possible solutions to improve policy decisions, by bringing together knowledge from previous research (WP1, WP2 and ERP AI, V1723, V1522, V1719, ERP Robotics, ERP Neuro) ▪ Defining the *practical* main rules (headlines) and boundary conditions to improve policy making, taking into account all kinds of human, societal and technological possibilities and limitations ▪ Selection and preparation of the most promising use cases, at least two (e.g. energy transition, smart mobility, safety etc..) ▪ The design and development of Policy Labs as a multi-disciplinary environment for targeted policy pilots and experiments. This includes the design and preparation of experiments focused on up-scaling and/or potential course adjustments



Parties (to be) involved and links to roadmaps and knowledge agendas

This proposal fills an important gap in TNO thought-leadership regarding AI and meaningful control of autonomous systems. In many research programs (such as: ERP AI, VP AI, MCAS, RVO Autonomy, MMT and several defense programs), the issue how to maintain meaningful control of intelligent autonomous systems is of key importance. However, none of these researches addresses the new role of humans who need the understanding and insights in how to strive for and achieve long-term goals based on ethical values for themselves and for society. Enhancing humans how to understand and cooperate with artificial intelligence (AI-Aware humans) and how to formulate and agree on the (ethical) goal functions is therefore urgently needed.

This topic provides TNO with the opportunity to excel in its transdisciplinary potential. A topic that unifies our internal disciplines and catalyzes our ability to work together.

- TNO nationally has the unique capability to bring together essential disciplines such as psychology, cognitive neuroscience, neurobiology, artificial intelligence, robotics, philosophy, nano- bio- and gene technology and (underpinned by its system engineering approach) knows how to invest in building a common language for shared situational awareness and bridging the gap between the various disciplines. We are not confined to monodisciplinary approaches ánd are not primarily driven by market forces like the entrepreneurs, SMEs, multinationals or consultants in these fields. This gives TNO the unique position from which we can build powerful solutions that combine state-of-the-art science and groundbreaking technological (commercial) initiatives.

Collaboration with Dutch institutes and universities:

- TNO closely collaborates with the UvA Institute for Advanced Study (IAS). IAS focuses on interdisciplinary research and brings together academic

	excellence to generate ideas, broaden knowledge and develop new interdisciplinary research frameworks and methodologies. - ECP (https://ecp.nl/) is an independent platform in which universities, government and industries exchange ideas on responsible use of new technologies in Dutch society (TNO is on the ECP board). One working group is currently working on a document called "AI impact assessment" and the most important recommendation is that both government and industries must incorporate an ethical framework by which to justify their actions. - We have good relations with Prof dr Peter Paul Verbeek (universiteit Twente) who works on the ethics of man and technology "ethiek van mens en technologie". - TNO already has (or has the connections to reach out to) international connections with key players in the field of o AI (Ben Goertzel, Joscha Bach, Stuart Russell), o ethics (Anders Sandberg, Sam Harris), o neurology (Sapolsky, Metzinger), o philosophy (Ken Wilber), o human enhancement (Kevin Warwick)
Dynamics	The exploratory phase, during which this proposal will be developed and defined in detail, will run from September to December 2018. This delayed exploratory phase means that the research proposal is now sketched in general terms, and will be defined in detail during Q3 and Q4.

22 SEED Project Innovation Outlook

General information	
Title VP/ERP	SEED Project Innovation Outlook
Contact person TNO (DM en VPM)	Jasper Lindenberg, Arjen Goetheer
Contact person(s) government or topsector	
Programme 2019	
Summary	Technology and innovation has an increasingly high impact on the economy and society at large. Anticipating correctly on future innovations makes the difference between success and failure. Due to technological complexity even large companies and governments are struggling with their future strategy. This complexity is even higher, as the political, social and economic factors for future trends are unclear, but have enormous impact on the actual innovation adopted in our society. Traditionally, foresight and other future thinking approaches focus on the process to create a common view among expert on future trends. However, present technologies like sophisticated data mining technologies can create more evidence based insights in future trends. Combined with advanced computer power and artificial intelligence (AI) approaches we can enhance the use of information to create a solid foundation for future anticipation. Classical foresight methods can be enriched, supported (and in the long run perhaps even replaced) by AI supported foresight methods. This has enormous benefits for the industry, research, as well as governments. Research will be able to identify new information quickly and feed it into their R&D, where companies can include more evidence in the decision making process on strategic investments. Governments will have more information to set innovation priorities for policies and also bring it in its societal context. This research will provide TNO with the knowledge, methodologies and tools to enable this new type of data-driven foresighting which will provide insight in future innovation developments, their potential impact on the Dutch economy and societal challenges on both the macro and micro level. The SEED ERP Innovation Outlook will explore, renew and test the possible process and technological approaches to this innovation outlook. It combines TNO expertise from different units and expertise groups on foresight analysis, scenario analysis, system dynamics, AI and big data analysis techniques and strategy development. It develops a data driven AI-supported future looking framework and methodology, building upon data-driven tools to map current and emerging trends in technology development and innovation, to determine their societal impact logic and design actionable strategies – and to provide scope to assess the future from a strategic perspective. The SEED ERP Innovation Outlook is linked to the NWA big data route, VW Big data impulse programme, KIA ICT (big data), Commit2Data, FWCs for DG RTD and is pursuing research collaboration with relevant (academic)

	partners, such as Fraunhofer ISI, the Taiwanese Institute for Economic Research (TIER), Rijksuniversiteit Groningen and stakeholders, such as ministries, regional governments, economic development boards, and other applied research institutes (e.g. the TO2 institutes). Building upon the findings gained with the explorative study in 2018 the following results are foreseen for 2019: 1) design of the first iteration of an AI-supported foresight framework and methodology to identify trends and assess economic and societal impact 2) a first iteration of methods to translate the insights into actionable strategies at both the micro and macro level 3) two use cases that test and validate the first iteration framework and used AI and big data analytics techniques 4) development of a knowledge eco-system with key partners and stakeholders/community 5) external profiling by means of workshops and whitepapers 6) detailed program of work for the envisaged ERP Innovation Outlook starting 2020. This includes the research questions that will be raised by (i) the evaluation in 2019 of our first iteration of both the frameworks and the applied AI technology and (ii) the requirements for upscaling and refining. The intended end result of the full ERP will be a world-class Innovation Outlook framework with supporting AI technology that will be able to (i) handle and predict global technology portfolio developments (ii) show the effect on societal challenges and economy on both the macro and micro level (iii) provide an overview of drivers and barriers to accelerate or delay these effects. This will require fundamental steps in (innovation) policy, impact assessment, modelling and (transparent) AI-technology.
Short Description	
Results 2019	
Dynamics	

23 Signature

The Hague, <datum>	TNO
<naam afdelingshoofd> Head of department	Prof.dr. P.J. Werkhoven Author