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TNO report

TNO Early Research Program 2015-2018
Annual plan 2015

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Contents

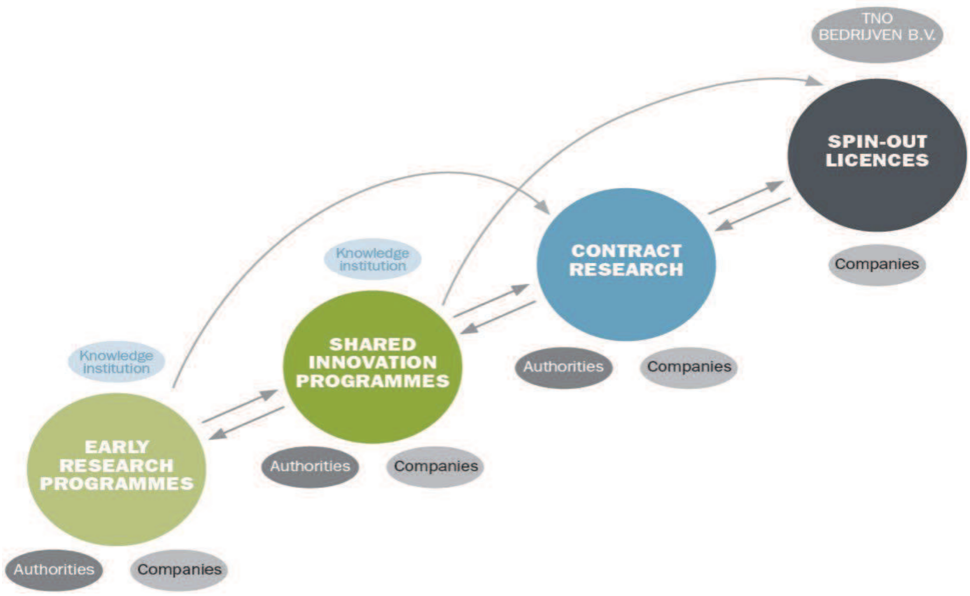
1 Introduction

From Enabling Technology to Early Research

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 is meant to build and renew TNO's knowledge assets (Kennis als Vermogen).

In the period 2011 – 2014 we labelled the corresponding program ETP = Enabling Technology Program. Five research areas were selected that largely covered the future knowledge needs of TNO's application domains: Materials Technology, Modelling, Adaptive Multi-Sensor Networks, Systems Biology, and Human Behaviour. For the coming years new topics and ambitions were defined, to be able to better respond to TNO's changing external environment. That is also why we have chosen a different name: ERP = Early Research Program, see diagram below.



The main changes are:

– Use case inspired instead of enabling research. The portfolio of research projects will still be focussed on generating cutting edge knowledge and technology as an asset providing the basis for Shared Innovation Programs and Contract Research. However, from the start there must be concrete ideas about leading applications were this knowledge is needed, and concerted action (in our theme organization) to develop these applications;
– A potential to enlarge the research effort by collaboration with knowledge partners and stakeholders. Leveraging can be reached by aligning TNO programs with, e.g. TKI, NWO and EU schemes (early examples are: quantum computing and complexity), and by attracting contributions from stakeholders and sponsors. Projects should become the nucleus of research ecosystems with the ambition to grow to a meaningful size like the TNO-Imec Holst Centre in the 2015-2018 TNO strategy period;
– A more flexible portfolio of projects. Instead of five programs for the next four years we now start with eight projects, and room for seed projects and supportive actions. Progress will be evaluated on scientific output, and on the realization of use cases. We expect changes in the portfolio on a yearly basis, because ERP projects will evolve into Shared Innovation programs or will fail to live

up to expectations. The need for flexibility will restrain sponsoring of PhD research. There will be a shift towards in kind cooperation with universities.

In line with the request of EZ we, together with our TO2 partners (the federation of applied research organizations in The Netherlands), will inform Top-sectors and Ministries of this approach of building our knowledge base, aiming at early involvement of companies and other stakeholders in public private cooperation.

Selected projects

The selection of ERP topics started in 2013 with a mapping of TNO's knowledge portfolio on available publications of grand challenges, (topsector) roadmaps and (EU) key enabling technologies by our principal scientists (see correlations below).

		TNO Transitions				
		Industry: from economic stagnation to growth in high-tech industries	Healthy Living: from illness and care to health and behavior	Defense and Security: from multifarious threats to manageable risks	Environment: from bottlenecks by urbanization to vital urban regions	Energy: from conventional sources to renewable energy
EC Societal challenges	Health, demographic change and wellbeing		■		■	
	Food security, sustainable agriculture and forestry, marine and maritime and inland water research, and the Bioeconomy	■	■			
	Secure, clean and efficient energy					■
	Smart, green and integrated transport	■			■	■
	Climate action, environment, resource efficiency and raw materials	■			■	■
	Europe in a changing world - inclusive, innovative and reflective societies		■			
	Secure societies - protecting freedom and security of Europe and its citizens			■		
	Competitive industries	■				

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TopSectors	Horticulture and propagation materials				■	
	Water	■		■	■	
	Agri & food		■			
	Life sciences and health	■	■			
	Chemistry	■	■			
	Energy				■	■
	High Tech Systems & Materials	■	■	■	■	
	Logistics & Mobility				■	
	Creative industry	■	■	■	■	■
Social Themes	Sustainable urban environment	■			■	■
	Social safety & security	■		■	■	
	Defence	■		■		
	Lifestyle & Health		■			
	Geological survey of the Netherlands (DINO)					■

Examples of highly relevant emerging issues are: quantum / nanotechnology, ICT Big Data (EU-KET), sustainable energy, affordable infrastructure, effective logistics, healthy food (grand challenges), predictable emergent and resilient behaviour in complex systems (by grip on complexity).

The resulting issues, and the societal and economic ambitions of TNO's five Themes (Industry, Healthy Living, Urbanisation, Energy, and Defence, Safety & Security) led to the following eight research topics:

– <u>Quantum Computer / Quantum Internet</u> (QuTech), an early example of a newly emerging research ecosystem centered around TU Delft and TNO, announced September 2013 by Minister Kamp and started in 2014, with the support of NWO, EZ, the Topsector HTSM and industry. The technical ambitions are to develop a quantum bit that will replace the transistor allowing the paradigm shift from a binary computer to a quantum computer, and to develop secure quantum internet, thus providing the ultimate encryption.

- Complexity, "the study of the phenomena which emerge from a collection of interacting objects”. Joining a 4 year NWO program, where the fundamentals and potential of this type of research were explored, NWO, TNO and stakeholders (Friesland Campina, ASML, NS are among the early adaptors) will embark on a new connecting 4 year program “Grip on Complexity” where explorative and applied research will be combined. TNO already selected a first set of promising topics for 2015 such as: autonomous driving, healthy food and induced seismicity.
- Personalized Food, to make good use of the recent insight that there is an enormous variation between individual humans, at the genome level, at the microbiome level and at the systems level, opening up the potential for developing more personalized approaches (food, medicines). Main challenge is to find approaches that will effectively reduce healthcare costs (from illness and care to fact based preventive behaviour). Although these aspects influence all parts of our lives there are two periods which deserve specific attention: Early Life which roughly comprises the period from conception until the second birthday in which the complete developmental plan for a healthy life has to be established, and Ageing which roughly comprises the last third of our lives in which existing systems are deteriorating. The research links to the Grand Design initiative of the Ministry EZ. It lays down the technological foundations for a joined programming in the Top-sector Agrifood theme Health between TNO, DLO and NWO. Furthermore this project falls within the framework of Top-sector LSH (roadmap Specialized Nutrition). Collaboration with WUR, RU, UM and with large medical centres (especially large cohort studies) will be actively pursued.
- Energy Storage & Conversion, a major enabler for the transition to the sustainable supply of energy, while at the same time keeping the system reliable and affordable. TNO will align its research with the R&D landscape that is being formed focusing on storage of energy in molecular bonds, including ECN, FOM DIFFER, TU/e Darcy center, TU Delft, Twente University, Leiden University and Utrecht University. Additionally, a range of companies located in the Netherlands are interested in solutions for energy storage in molecular bonds, including: chemical/fuel producers (*e.g.* DSM, Shell, SABIC, BASF), material/catalyst developers (*e.g.* Albemarle, Cabot, Kriya Materials, Johnson Matthey, Akzo Nobel, Dow, Nedmag, Sabic), component/system suppliers (*e.g.* Siemens, Proton Ventures, Inventum, NXP, Solesta, Vaillant Group) and energy companies (*e.g.* Alliander, Cogas, Tennet, E.on, Electrabel, RWE). We will focus on the conversions of electrons to chemicals, photons to chemicals, thermochemical storage and the dynamics of the energy system.
- 3D Nanomanufacturing, to enable future mass production of 3D nano-electronics devices. The Netherlands have a stronghold in the semicon industry (Eindhoven area) that is now unrivaled in Europe. This research will enable the transition from 2D to 3D nanostructures, that will support the need for ever more powerful devices. The focus is on the manufacturing and metrology of nanostructures at the very high speeds, accuracies and reliabilities required for industrial applications. Cross-over to photo-voltaic devices, (microwave) sensors and biomedical / healthcare instruments is foreseen. The research is aligned with Top-sector roadmaps: Semiconductor Equipment, Advanced instrumentations and Nanotechnology and is linked to research at AMOLF (metamaterials and nanophotonics), University of Twente (3D nanophotonics devices), TU/e (dynamic design rules and metamaterials modeling/design),TU Delft (precision and microsystem engineering).
- Structural Integrity addresses the challenge to maintain critical and massively expensive infrastructure and to prevent unpredicted failure at acceptable costs. The program will have wide application for maintenance of large structures, in particular in the *transportation infrastructure* and the *energy production infrastructure*. The technology focus is on advanced sensing and inspection, and on multi-scale, multi-physics, probabilistic modelling for predicting (future) structural performance, and will initially be directed at (rail)road supporting structures (steel

reinforced bridge) integrity, offshore wind structure integrity, and well integrity for sustainable energy supply. Top-sectors Water (TKI Delta-technology), Energy (TKI Wind on sea) and HTSM-ICT roadmap are linked, as well as Ministries EZ (wind energy), I&M (Rijkswaterstaat), ProRail, water boards, provinces and municipalities. Several partners from the research community will be involved, e.g. TU Delft (InfraQuest, DuWind, Delphi consortium); TU/e (materials and structures); ECN (monitoring); Deltares (structural health modelling) and foreign universities and institutes.

– Human Enhancement, the effective support of humans in demanding environments, is focused on two challenges: to enable the full and safe transition to the use of automated systems in e.g. the industrial (maritime and offshore) sector and in the mobility sector (automated driving), and to enhance the human ability to withstand work related stressors to improve individual health (prevent absenteeism) and mitigate organizational risks. The first challenge is connected to the roadmaps automotive and maritime & offshore, the Top-sectors HTSM, Logistics and Energy, and the societal theme mobility (Ministry I&M). The second challenge is relevant for the Top-sectors Life Sciences and Health (LSH), HTSM (Smart Industry and Social Innovation), and to the Ministry of Social Affairs. The TNO expertise for this research is to a large extent built up in the Defence domain, so both defence and civil domains will profit from dual use opportunities. The research is linked to that of several academic partners. In the maritime domain collaboration will be sought with Marin.
– Sense Making from Big Data, the rapidly growing challenge to benefit from any collection of data so large and complex that it becomes too difficult to process using on-hand data management tools or traditional data processing applications. The *ICT Roadmap for the Top-sectors (2012)* recognizes Big Data as one of the leading ICT Research and Innovation Themes, which is addressed in the Action Line *Data, Data, Data*. Although the topic is clearly general and relevant for a wide range of domains, the focus will be on two fields where we expect Big Data methods to be a game changer: Logistics, and *Personalized* health. Collaboration with academia is covered through TNO part-time professors and an envisioned TNO-NWO program on Big Data. Opportunities for collaboration with TO2 partners are at hand with DLO (in the field of agriculture and food security), ECN (for decision making for wind farms) and Deltares (the Digital Delta project).

The Tables below present the relations between the topics and Top-sectors / Ministries.

Top-sectors

ERP	HTSM	Agri-Food	LSH	Energy	Chemis-try	Logistics	Water
1. Quantum Computer / Internet							
2. Complexity							
3. Personalized Food							
4. Energy Storage & Conversion							
5. 3D Nanomanufacturing							
6. Structural Integrity							
7. Human Enhancement							
8. Sense Making from Big Data							

Ministries

ERP	EZ	VWS	IM	SZW	Def	V+J	OCW
1. Quantum Computer / Internet							
2. Complexity							
3. Personalized Food							
4. Energy Storage & Conversion							
5. 3D Nanomanufacturing							
6. Structural Integrity							
7. Human Enhancement							
8. Sense Making from Big Data							

In addition to these eight topics we will start several seed projects. One has already been selected: Organ-on-a-chip, an emerging technology that has the potential to substantially improve the efficiency of drug and food development by developing better predictive personalized *in vitro* screening models, and at the same time will contribute to reduction, replacement and refinement of animal studies.
Finally, we will conduct a project “Orchestrating Innovation”, adjacent to selected use-cases of the ERP, to boost the innovation process of these cases and at the same time develop new insights how to improve technology driven innovation management.

In the next chapters each of the eight projects will be described, explaining the drivers for their selection, the envisaged research and cooperation, and the intended results for 2015.

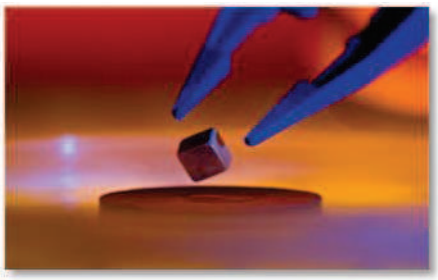
2 Quantum computing and Quantum internet

2.1 Introduction

Quantum mechanics is the theory to describe the (interaction between) elementary particles. Academic research has confirmed the validity of this intriguing theory as well as many of its counterintuitive aspects. But only due to recent breakthroughs is it possible to demonstrate important quantum mechanical concepts on systems large enough to be visible to humans. The concepts of ‘superposition’ and ‘entanglement’ could now be used in a controlled way, and thereby open the path to applications like the most powerful computer ever imagined, the Quantum Computer, and communication which is inherently safe for eavesdropping, called Secure Quantum Internet. Or as the Nobel Prize Committee formulated it in 2013: “Perhaps the quantum computer will change our everyday lives in this century in the same radical way as the classical computer did in the last century.”

The Netherlands is very well positioned to take a leading role in this currently ongoing international competition to develop and industrialize these applications. This shall have a huge impact in many fields:

- A Quantum Computer shall finally provide the society with the required computational power to work on some of the Grand Challenges: The development of room-temperature superconductivity will provide us with lossless energy transport and storage which in its turn solves our energy shortage. The development of new medicines will be done by rigorous calculations instead of trial and error, which reduces both costs and time. And more.



1. Superconductivity is now only possible at low temperatures.

- Secure Quantum Internet is the ultimate encryption: there will be no means to listen in to secured communication. The quantum computer on the other hand, will be able to crack most classical encryption schemes. It is therefore of vital importance for the Netherlands to be one of the first countries in the world to have access to the most advanced quantum technologies. Related (Grand) Challenges are Cyber Security, Digitalization, and Safe Society.

- The Netherlands could be a centre of excellence on quantum technologies. This will be a new impulse to the Dutch economy by generating thousands of high quality, sustainable jobs.
- This centre of excellence will lead to significant knowledge transfer to other sectors like nanotechnology, electronics, and semiconductor industry, and thereby improving the relative competitive position of our industry and safeguarding employment.
- Like the development of the transistor, the core component of the classical computer, the development of the quantum bit and quantum computer will lead to numerous spin-off.

For all those reasons, the Minister of Economic Affairs Mr Kamp announced in September 2013 the start of QuTech. This institute has been founded by the Technical University of Delft (TUD) and TNO to cope with the challenges in research, development, commercialization, and coordination & cooperation with industry and institutes still ahead of us. This ERP “Quantum Computer and Quantum Internet” forms within TNO the basis for QuTech.

2. The QuTech logo

During 2014 the TUD and TNO laid the foundations of QuTech. (Development of technical plans, contracts for cooperation, discussions with industry and closing contracts with first commercial partner.) In the years 2015-2018 QuTech will make the change from academic research at the university to mission oriented development of the quantum computer and secure quantum internet. As part of this ERP, TNO will develop a series of experimental process flows, proof-of-concept components and setups, to demonstrate the feasibility of several core technologies.

For further information on the ambition and people of QuTech and an introduction to quantum computing please visit **www.qutech.nl**.

2.2 ERP environment

2.2.1 International perspective

Some quotes from the “Quantum Computing Market Forecast 2015-2020” (2014) by consultancy agency Market Research Media Ltd illustrate the international focus on quantum computing:

- Quantum computing is a geopolitical game changer.
- Quantum computing opens new horizons almost in every aspect of human life, whether it’s new medicine or renewable energy.
- Quantum computing is an economy game changer, with a potential of disrupting entire industries and creating new ones.

This report also states that the quantum computing market is of significant size and growing fast: 3.3B$ in 2015 to 5.5B$ in 2020. Although for the coming years the vast majority of the budgets are related to investments, of course.
Companies like Google, Lockheed Martin, and IBM invest heavily in quantum technology. The latter is developing technology itself, the other two are mainly buying in knowledge from American universities. Also institutes like NASA and the NSA allocate huge budgets to it as could be read in The New York Times, The Washington Post, and MIT Technology Review over the last two years.

3. Quantum computing market forecast.

Also Microsoft invests in quantum computing. Microsoft works on the theory and architecture of quantum computers and has selected a few partners for the development of hardware. Microsoft has selected the TUD/QuTech as one of the main partners and is funding the current developments in Delft already.
Currently only D-Wave, a Canadian company, claims to manufacture commercial quantum computers. Whether this computer really is a quantum computer is subject to debate, however.

The best international institutes working on quantum technology are universities like Sante Barbara and Berkely, as well as Innsbruck, Munchen, and Zurich. Most universities focus on fundamental research and are therefore no direct competitors for QuTech. The initiatives in the German speaking region do have a technological focus, but their expertise is in the field of optical quantum technology, whereas Delft is more experienced in solid state quantum technology.
QuTech has the ambition to initiate a European Flagship on quantum technology. The joint European institutes have a leading position in fundamental research in quantum computing. The solid state technology in Delft, the optical technology of the German speaking region, and the more fundamental research in England, France, and Denmark are complementary and together ahead of any other region in the world. QuTech, with the highest ambition towards industrialization of quantum technology seems to be the natural leader for such initiative.

2.2.2 Dutch perspective

The TUD hosts a team of world class scientists in solid state quantum technology. Four out of the ten most-sited scientists of the Netherlands (all fields of expertise) work in Delft in this field (source: Volkskrant, October 2012). This team also had 10 papers in the Nature magazines in 2013. This is the scientific foundation of QuTech.

On the other hand the Netherlands has a large ecosystem of high-tech / high-precision equipment manufacturing companies including an extended supply chain. This sector has developed and successfully commercialized tube technology for radio and television, transistor and chip technology, lighting and medical equipment, and wafersteppers. Each wave of innovation has led to a new wave of employment. And like ASML and FEI started as spin-off companies from Philips, it is now time to create the new seed for high-tech business. This infrastructure of high-tech industry will accelerate the development of the quantum computer now. In the future the quantum technology will be a new unique selling point of this Dutch ecosystem. Mayor of Eindhoven Mr Rob van Gijzel confirmed already the importance of quantum technology, developed in Delft, for his city: "Ik ben zeer verheugd over de krachtige voorwaartse ontwikkeling van Quantum Computing in Nederland die door het QuTech centrum gerealiseerd wordt. Dit is een toekomstige technologie die van groot belang is voor de technologiesector in de regio Eindhoven." (private communication)

2.2.3 TNO perspective

TNO is experienced in multiple technologies which are critical for the development of the quantum computer, and complementary to the knowledge of the TUD. Secondly, TNO brings to QuTech its experience in prototyping, mission oriented project execution, and contacts to the industry.

By building prototypes and demonstrators based on the state-of-the-art scientific knowledge of the TUD, TNO/QuTech shall be positioned as a pioneer in quantum technology. Moreover, TNO/QuTech will invite industrial partners to participate in the development of the demonstrators to strengthen the relationships and have some of this work funded by industry and European projects.

On the other hand TNO has to develop some of its existing technologies further to meet the requirements of the quantum computer (e.g. RF-technology, nanofabrication, multiscale physics simulations). This will improve the competitive position of TNO in the existing (non-quantum technology) markets like nano-technology/semicon and RF-technology/Radar. These markets are already very important to TNO.

Finally, the further development of existing and new technologies generate possibilities for unforeseen spin-off.

The first 6 months of QuTech enabled TNO already to discuss potential cooperation with Agilent, ASM, ASML, ATOS, Dept. of Defense, FEI, Fox-IT, ID Quantique, NL-NCSA, and NLR. Potential cooperation is expected to lead to applications of quantum technologies on a timescale much shorter than the development of the quantum computer itself. Quantum computing requires, e.g., material quality, interface quality, material combinations, and material configurations (like nanowires) which are not yet known to the semiconductor industry. Cooperation with companies like ASM and FEI shall give those companies early insight in this *quantum* technology and enable them to use this knowledge to improve their products, while their (foreign) competitors only have access to *nano*technology.

2.3 Eco-system

2.3.1 TNO Themes and Programs

QuTech makes use of the expertise (and colleagues) of the Research Groups of Optics, Nano-Instrumentation, Radar Technologies, Optomechatronics, Intelligent Imaging, Instrument Manufacturing, Information Security, Material Solution, and Thin Film Technologies.

Technological developments in QuTech are directly connected to the following Themes and Programs:

- Industry – Semiconductor Equipment. The semiconductor industry will soon be fabricating devices with critical dimensions of 7 nm and below. At those scales quantummechanical effects cannot be ignored anymore. Experimental experience with quantummechanical effects as well as experience with the applications of new materials that will be applied in conventional CMOS is relevant for TNO and its industrial partners like ASM and FEI.
- Industry – Flexible & Free-form products. This roadmap is frequently inspired by the state-of-the-art knowledge from the semiconductor industry.
- Industry – Space & Scientific Instrumentation. Quantum technology enables the development of beyond-state-of-the-art detectors which can be applied in this domain. Single Quantum and SRON already work on the application of sensors based on those technologies.
- Defense & Security – Cyber Security & Resilience. Quantum technology will enable inherently interception-safe communication, as well as quantum computers able to break many conventional encryption schemes.
- Defense & Security – National Security & Crisis Management. See above.
- Other roadmaps will ultimately be affected by the availability of unprecedented computing power. But this impact is not expected to materialize before the end of this four-year plan.

2.3.2 National TopSectors and Themes / Stakeholders

The TopSector Nanotechnology has adopted QuTech already. The HTSM TKI-bestuur has allocated funding to QuTech/TNO for the years 2014-2016.

2.3.3 Academic partners / programs

The main partner in QuTech / for TNO is of course the TUD. The world-class scientific heritage of the TUD forms the foundation for QuTech. The TUD invests tens of millions of euros in QuTech: about 20 staff members (professors and supporting staff) and renovation of the building/laboratories is funded by the TUD. Moreover, the TUD has already about 70 scientists working in Qutech, funded by FOM/NWO- and European grants and industrial sponsoring.
Also the Technical University of Eindhoven participates in the work of QuTech by means of the group of professor Erik Bakkers, specialized in the growth of semiconducting nanowires.
The Leiden University participates in QuTech by means of the group of theoretical physics headed by professor Carlo Beenakker, specialized in mesoscopic physics.
The University of Twente may participate in the future as well, likely in the field of materials science. Discussion are ongoing but no concrete activities yet.

2.3.4 TO2 / RTP partners / programs

No remarks at this moment.

2.3.5 EC H2020 opportunities

QuTech has the ambition to initiate and lead an EU Flagship-like cooperation. Discussions with ‘Brussel’ are ongoing already, with support from ‘The Hague’.
In parallel QuTech will submit proposals to regular calls of H2020, STW, FOM, etc. Some upcoming calls in H2020 open opportunities for funding of research and development in the field of quantum computing, quantum communication, or quantum technology in general. Some technological developments may also find funding by calls related to, e.g., low temperature electronics, integration of new materials into the process flows of More Moore. TNO and TUD are currently studying which proposals will be submitted to which calls in the coming years.

2.4 Research & Technology lines 2015-2018

The envisioned developments cover many TRL's, multiple disciplines, and thereby about 15 years. This will result in a different approach during the subsequent phases of the development. The first phase (2014 – 2017; Proof of Principle) will be dominated by solving the current bottlenecks to accelerate the research, and by making the transition towards the mission-based way of working. The latter includes, amongst others, a better defined goal of the project, working out the project plan, system architectural considerations, and involving third parties.
The second phase (2018 – 2022; Proof of Concept) will be used to demonstrate progress on key technologies (critical milestones), benchmarking, defining the requirements and system architecture, and updating the project plan including contributions by third parties and potential spin-off. Also a relevant and mathematical challenge shall be selected for the demonstration. This challenge shall be mapped to the electronic hardware.
During the third phase of the project (2023 – 2029; working demonstrator) all technologies shall be developed to the level of a working demonstrator. A convincing demonstration shall be executed. Positioning the Dutch industry (by knowledge transfer) is critical during this phase.

QuTech works according to four Roadmaps, one for each type of qubit. The most critical enabling technologies that will be developed during the coming years are incorporated in the most relevant Roadmap. The State-of-the-art, knowledge gaps, and planned developments will be described per Roadmap. (Beyond 2018 Roadmaps will likely be organized according to components and modules of the quantum computer or setups for secure quantum internet.)

2.4.1 Roadmap A: Topologically protected qubits

So called zero state- or Majorana qubits have the potential of very long coherence times. The most convincing experiments on the demonstration of the appearance of Majorana quasi-particles have been performed by the TUD in 2012/2013. This was done on devices based on InSb nanowires in which superconductivity is induced by a connected superconductor. A qubit based on Majorana quasi-particles actually requires braiding of those Majorana particles which in turn requires the integration of a few nanowire crosses (instead of nanowires) in combination with a few Josephson Junctions.
The research in this Roadmap is focused first on improvements in materials, device technology, and measurement techniques. Improvements in materials are needed to reach higher electron mobility in the nanowires/nanocrosses. A new process flow shall lead to better control/prevention of contamination, and in-vacuum growth of superconductor and semiconductor material shall lead to ultimately well-defined interfaces. Several properties of the current superconductor material NbTiN, like the quasi-particle density of states within the superconducting gap, are unknown. This material will therefore be characterized better by means of tunneling studies.
The interface between the semiconductor and superconductor materials is the most critical and very sensitive to imperfections like oxidation, dangling bonds, chemical residues, or non-homogeneous coverage. To improve this interface we will investigate etch recipes which are more gentle than the current Ar sputtering (needed to remove native oxides that show up due to transport of the nanowires from the growth chamber at TU/e to the deposition chamber at TUD). High-resolution electron microscopy will be used to investigate the precise interface coverage. Deposition of the superconductor material by means of sputtering maybe replaced by other techniques or materials. A new deposition tool will be installed and a new process flow will be develop to ultimately execute all material growth and deposition steps in one system without breaking vacuum. The device is grown on top of an insulating Si substrate with gate pattern. This 'gate chip' will be improved by better planarization (even CMP seems to result in too rough surfaces), and selection of a dielectric material which is both high quality (no charge noise on timescales of days at low temperatures) and enables a non-reactive and hydrophobic surface to avoid reactivity in ambient conditions.

TNO will work on most of the challenges mentioned above: TNO's experience with nano-fabrication and contamination control will be required. Also the new deposition tool will be installed in the cleanroom of TNO and a specialist in this technology will be hired. Finally TNO will execute simulations on multiscale physics to understand, amongst others, the effects of stress induced in the nanowires by cooling down from room temperature to 15 mK on electron mobility.
Beyond these developments this Roadmap will focus more on the development of so called Majorana-Cooper pair Boxes (MCPB), superconducting-insulating-superconducting (SIS) junctions, integration into a circuit, and finally the actual braiding of Majorana's.

2.4.2 Roadmap B: Surface Code & transmon qubits

The transmon qubits are relatively speaking the most mature type of qubits. Circuits with 5 qubits with controlled interaction are currently being studied. The activities over the next few years will be dedicated to the development of a 17-qubit design. This is the smallest set of qubits required to demonstrate surface code protection. This protection against decoherence is based on a set of primary qubits plus ancillary qubits. The latter will be used to probe decoherence at the primary qubits (parity check), followed by repair of the states of the primary qubits.
Important technological developments on which TNO will work include the development of electronics architectures for circuits with more than 8 qubits, more compact resonator designs (to make devices with more than 17 qubits fit on one chip), and FPGA- and RF technology for fast electronic feedback control.

2.4.3 Roadmap C: Surface Code & spin qubits

Spin qubits may intrinsically have longer coherence times. Still surface code protection is required. Current research topics include scaling to circuits of 5 qubits, and integration on the devices of the superconducting transmon qubits.
Important technological developments on which TNO will work include investigation of potential 2D architectures (required for scaling beyond about 5 qubits), a PCB/interposer for connection of about 100 DC-, RF-, and microwave signals to/from the circuit, nano-lithography and contamination control for higher quality devices and miniaturized qubits (to reduce the number of imperfections in the device which limit the coherence times).

2.4.4 Roadmap D: encryption & N-V centers

The fourth type of qubit is based on the N-V color centers in diamond. One of the advantages of this type of qubit is the possibility to read the state of this qubit by means of visible photons. This makes this type of qubit attractive for applications in encryption and communication via glass fibers. Entanglement over 3 meters distance has been demonstrated by the TUD last year.
Challenges include the efficiency in coupling light to the fibers, wavelength conversion (from the intrinsic wavelength of N-V centers near 637nm to the wavelengths used for telecommunication, needed to make use of known technologies and reduce the transmission losses in fibers), generation of arrays of color centers in a controlled way.

2.4.5 Growing the eco-system 2015-2018

Discussions with industry are already aimed at participation of industry in the envisioned developments. Industrial partners could accelerate these developments on the one hand, and industry could use the experience with working with qubits in other markets. Some examples:
ASM could advise QuTech on challenges in material deposition and interface control, and could even execute some test for us. In return ASM could have early access to state-of-the-art nanowires and use this to develop new processes and equipment before the industry will incorporate nanowires in CMOS.

FEI could help QuTech with its state-of-the-art microscopes. In return QuTech could provide FEI with samples with unique combinations of materials which can be used to develop the microscopes further.
IDQuantique and Fox-IT have a strong interest in Quantum Key Distribution. Those companies could advise QuTech on the availability of current technologies and the specifications as set by (potential) end users. In return QuTech could give early access to the latest quantum communication demonstrators.
Similar cross-over may be possible with companies, large and small, working in the field of low-temperature electronics, cooling technology, multiscale physics simulations, fiber array technology, etc. QuTech will actively work on the development of such cooperations. In parallel QuTech is looking for partners who share the ambition of developing the first quantum computer, like Microsoft.

2.5 Activities and deliverables 2015

QuTech will work on more work packages and scientific questions than described here. This chapter describes only the activities TNO personnel is involved in.

2.5.1 Roadmap A

For the topological protected qubits it is most critical to get the new cluster tool up and running. This will enable for the first time the growth of nanowires and subsequent deposition of superconducting material without breaking vacuum. Calibration and testing of this complex setup and related process flows is expected to take significant time and effort in 2015.

Multiple colleagues will work on nano-fabrication of the devices. The contamination and surface conditions of the superconductor-semiconductor interface is currently being investigated. This shall result in new insights in optimal surface conditioning between process steps. In 2015 the preferred cleaning/conditioning/etching technique shall be validated on realistic devices and implemented in the process flow. In parallel we work on the development of extremely flat basis devices with embedded bottom gates.

Thirdly, simulations on nanowires and their environment will continue to develop better understanding of the relationship between stress and electrical performance.

2.5.2 Roadmap B

By the end of 2014 the first circuits with 8 transmon qubits shall be tested. While the colleagues from the TUD will investigate more fundamental questions, the colleagues of TNO will focus on implementation of feedback control based on FPGA's (the design thereof is ongoing since mid of 2014).

During 2014 TNO realized the first demonstrators for RF multiplexing for qubit control. In 2015 this technology shall be improved and extended to larger numbers of in- and outputs.

TNO will also improve the contamination control for the device manufacturing of these transmon qubit devices.

2.5.3 Roadmap C

The initiation of spin qubits is very cumbersome. When future circuits contain more than a few qubits the initiation will take weeks. TNO aims to develop a machine learning algorithm to automate this process. While saving a lot of time in the near future, this technology may open more options for control and feedback to the qubits.

The coherence time of the spin qubits is affected by defects in the substrate material. TNO will investigate the possibilities and limitations in nano-fabrication to reduce the impact by defects.
Finally, TNO will work on the connectivity for spin qubit circuits. Ideas exist to develop a multipurpose connectivity board ('interposer') to deal with this challenge independently from the configurations/generations of qubit circuits.

2.5.4 Roadmap D
When teleportation is demonstrated over more than one kilometer by the end of 2014, the following technical challenges have to be solved. First, conversion of 637nm light to wavelengths used for telecommunication is required to make use for 'standard' telecommunication technology for further development of the secure quantum internet. The theory of the required non-linear optical effects is studied and a test setup is built in 2014. During 2015 colleagues of TUD and TNO will work on a demonstration of such wavelength conversion with sufficient efficiency to meet the requirements for this application.

The collection efficiency of the currently used solid immersion lens for N-V centres in diamond is not sufficient to support further progress. In 2014 TNO developed a control algorithm to apply a deformable mirror to correct for the imperfections in the solid immersion lens (SIL) and misalignments of this SIL relative to the position of the N-V centre. Experiments in 2015 shall show the improvements due to this adaptive optics and may raise new challenges.

Future applications require the use of arrays of N-V centres which are optically coupled to arrays of optical fibers. This requires first the technology to generate well defined (positioned) arrays of N-V centres. TNO will work on the controlled positioning of arrays of N-V centers in 2014-2015. The lead time of this research is likely large compared to the effort.

The development of fiber arrays will be started in 2015. TNO will use its experience with this type of challenges from former projects. A very innovative alternative based on the technology of a Dutch SME may be considered as well.

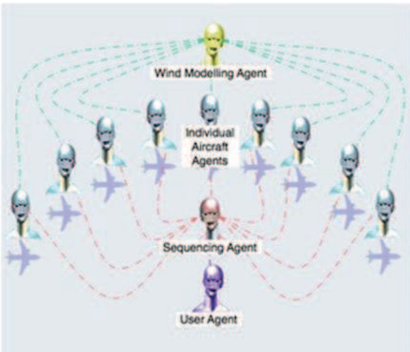
3 Complexity

3.1 Introduction

What is Complexity? There is no clear definition (similar to Device or Pain), but we can give a commonly adopted description as "the study of the phenomena which emerge from a collection of interacting objects"[1],[2] or a set of minimum criteria: the system is built of a set of many interacting agents (objects, components), the system is open and thus can/will (be) interact(ing) with its environment and the agent behaviour depends on their individual history, memory or feedback. As a result the complex system under investigation will have the next minimum characteristics: 1) the system behaviour is alive and thus develops in non-trivial and complicated directions, 2) the system shows (surprising, extreme) emergent behaviour and thus is not at equilibrium and 3) emergent phenomena arise by themselves and thus in the absence of a central controller cause the system to move between order and disorder.

A small list of examples where complexity plays a role: traffic jams, epidemics, internet overload, criminal and terrorist organisations, quantum entanglement, animals or robots swarms, industrial value chains, stock markets, cell biology, oncology, cardiology, internal medicine, psychiatry etc. etc. An industrial example of the use of complexity is e.g. found in airport traffic control[3], where airport congestion is resolved through the use of autonomous software agents, see Fig 2.1.

Complexity science or briefly complexity tries to give a generic scientific approach to study the above systems and sometimes is seen as the Mother of Sciences or the Science of All Sciences:



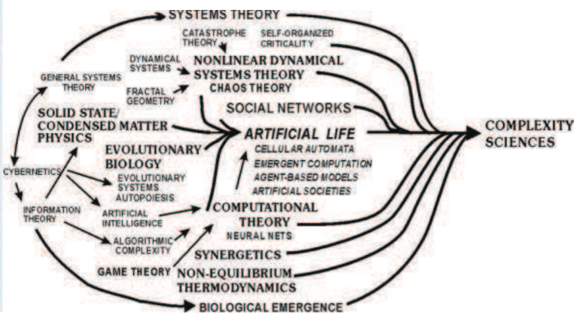


Fig 2.1 Complexity in use: autonomous software agents for air traffic control[3]

Fig 2.2 Complexity as the Mother of Sciences[4]

3.2 ERP environment

3.2.1 European perspective

Europe formally started in 2010 a transition period called “Europe 2020”[5]. Such vision and strategy is guided to a large extent by the notion of demand driven innovation under the rationale of providing solutions to the Grand Human Challenges while enabling industrial leadership. The Horizon 2020 program defines 8 societal challenges to be solved which are linked to the 5 TNO focus transitions as

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[1] http://en.wikipedia.org/wiki/Complexity
[2] http://www.nwo.nl/en/research-and-results/programmes/complexity
[3] http://aosgrp.com/autonomy_and_agents/technology/a_real-world_example_of_com/
[4] Jeffrey Goldstein et al., Social Entrepreneurship Has Complexity Science Written All Over It, International Social Innovation Research Conference, 2009
[5] Communication from the Commission of 3 March 2010 - Europe 2020 A strategy for smart, sustainable and inclusive growth [COM(2010) 2020 final, http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52010DC2020

given in the TNO Strategic Plan 2015-2018 as given in Figure 1.1. European policy documents and the Horizon 2020 program are littered with topics that require the advancement and application of complexity knowledge in practical approaches.

Secure, clean and efficient energy will benefit from complexity as outlined in the 2014 EC report “Smart Energy Grids and Complexity Science”[6] stating that “Complexity science can make valuable contributions in this area because of the multiplicity of interacting players operating as independent decision makers with autonomous behaviours, goals and attitudes. Furthermore technical power systems will operate under varying environmental conditions, exchanging transactions in the power markets. Research resting on a robust complexity science foundation will allow stakeholders to rapidly identify and interpret emergent phenomena”. Health, demographic change and wellbeing societal challenges of the H2020 program e.g. needs solutions for an ageing society and an increase in disease burden. Systems medicine approaches are proposed as good candidates to tackle the often complex pathophysiology of diseases through the integration of biological, socio-demographic, psychological, and other types of data. This integration requires novel mathematical and computational approaches which are able to deal with the complex and dynamic non-linear interactions between various processes.
Developments in this and other areas are supported by the EC, e.g. under the Future and Emerging Technologies Complexity program under the Digital Agenda for Europe[7]: “In complex systems, even if the local interactions among the various components may be simple, the overall behaviour is difficult and sometimes impossible to predict and novel properties may emerge. Understanding this kind of complexity is helping to study and understand many different phenomena, from financial crises, global epidemics, propagation of news, connectivity of the internet, animal behaviour, and even the growth and evolution of cities and companies. Mathematical and computer-based models and simulations, often utilizing various techniques from statistical physics are at the heart of this initiative”.

The relevance and use of complexity to solve societal challenges has been addressed[8], while an attempt to come to a European complexity research roadmap 2012-2020 was undertaken by the Complex Systems Society in the ASSYST EC project[9]. They propose applications based research into exemplar complex systems as complex matter, from molecules to organisms, physiological functions, ecosystem complexity, from individual cognition to social cognition etc. as well as fundamental research into complex systems science on formal epistemology, experimentation, machine learning, stochastic and multiscale dynamics, instabilities and robustness, collective behaviour in homogeneous and heterogeneous systems, from optimal control to multiscale governance etc.

3.2.2 Netherlands perspective

The NL innovation policy has been organized in 9 national Topsectors and 5 social themes. These have formulated short and long term research needs and are linked to the 5 TNO focus transitions as given in the TNO Strategic Plan 2015-2018 as given in Figure 1.2. Complexity will contribute to solving these challenges defined at the NL level, much in line with the situation at the EC level.

The TKI contract 2013 of the TopSector Agri&Food[10] states that a.o. the research theme “Duurzame ketens en robuuste systemen voor agro-horti-food” will require and benefit from a complexity science

[6] http://ses.jrc.ec.europa.eu/publications/reports/smart-energy-grids-and-complexity-science.
[7] http://ec.europa.eu/digital-agenda/en/complexity
[8] A. Carbone et al., Complexity aided design: the FuturICT technological innovation paradigm, European Physical Journal Special Topics, 2012, Vol. 214, pp. 435-459; http://iet.jrc.ec.europa.eu/ses/publications/journal-papers/complexity-aided-design-futurict-technological-innovation-paradigm
[9] http://www.complexssociety.eu/texts/roadmaps/CSS_Roadmap_2012-A.pdf, March 2012.
[10] http://www.tki-agrifood.nl/downloads/innovatiecontract/update-innovatiecontract-agrifood-2013.pdf

approach as in current international research at the New England Complexity Systems Institute, the Sante Fé Institute, the Complex Systems Institute in Paris and the Resilience Institute of Stockholm University. Similar during the Food Innovation Summit 2012[11] prof. P. Allen stresses “The science of complexity is, basically, telling us a story about evolution. Systems evolve qualitatively over time and interact with each other. For example, the human body has adapted to food and in turn food has been adapted to it. The food we consume is governed by culture and lifestyle, but also by climate, soil and energy issues. All these aspects are in a continuous state of flux.”

Other TopSectors roadmaps do not (yet) explicitly mention complexity as a relevant research topic but from their context it is clear that complexity science is meant as an important enabler, reflecting the EC situation. E.g. the Topsector Logistics[12],[13] has Synchromodality as a key issue, which enables transporters to operate more sustainably, at lower costs and at higher quality. This requires information systems, infrastructures, smart coordination mechanisms, policies, and legal possibilities to be able to use different transportation modes flexibly to deliver maximum value to the transporter or end customer. Such an approach is very well suited for a complexity approach. In the Topsector Life Science & Health there is strong focus on a better understanding of the complexity of human physiology in the transition from health to disease and vice versa resulting in research themes as healthy aging, medical devices, personalized nutrition, E-health, and personalized medicines[14]. The Topsector Chemistry[15] identifies self-assembly as a critical technology to come to new advanced materials, thus addressing the issue of self-organization in complexity. This is comparable to the use of self-assembly for (large area) processing of nanostructured and nanosized semiconductor materials in the Topsector HighTechSystems & Materials, e.g. for solar applications[16]. Also for the Topsector HighTechSystems & Materials, improved dynamic behaviour of instruments and production equipment is important[17]. At a system level non-linear behaviour and interactions of individual components in these applications leads to emergent behaviour as considered from a complexity perspective. Multi-scale modelling and simulation thus is seen as a critical technology to understand and remedy this. Similar trends are visible in societal themes like security and safety[18] and defense[19]. The description of the changing organization of jihadism in the Netherlands shows the basic elements of complexity[20], like self-organization, resilience and emergent behavior.

Within NWO the program Complexity is executed from 2008-2014 with a total budget of about 7 MEUR[21],[22] and with industrial participation from e.g. the Nederlandsche Bank, Equens and NS. The academic projects in this program are in a phase of completion and can also provide a starting point for TNO activities. A nice example of the outcome of this NWO program are the results obtained by prof. J. Meijer (LUMC) on biological clocks[23]: *The rotation of the earth around its axis causes 24-hour rhythms in many aspects of the physical environment. As an adaptation to the external cycles, we have developed internal clocks that can anticipate to these changes. The clocks should be robust on the one hand, but flexible enough to adapt to changes in conditions. Our research shows that the*

[11] http://ezines.tifn.nl/intouch/july2012/06-peter-allen.html, TI Food & Nutrition Innovation Summit 2012, Oosterbeek
[12] http://topsectoren.nl/documenten/logistiek/Brochure-Topsector-Logistiek_2014-05-26_131.pdf
[13] http://www.dinalog.nl/en/themes/synchromodal_transport/
[14] http://www.lifescienceshealth.com/home.html
[15] http://topsectoren.nl/documenten/chemie/Chemie-maakt-het-verschil_2014-06-02_137.pdf
[16] http://www.hollandhightech.nl/htsm/Roadmaps/High_Tech_Materials
[17] http://www.hollandhightech.nl/htsm/Roadmaps/Mechatronics_Manufacturing
[18] http://www.rijksbegroting.nl/2014/voorbereiding/begroting,kst186671_7.html
[19] http://www.defensie.nl/binaries/defensie/documenten/rapporten/2010/03/29/eindrapport-verkenningen-2010-houvast-voor-de-krijgsmacht-van-de-toekomst/eindrapport-verkenningen-2010-houvast-voor-de-krijgsmacht-van-de-toekomst.pdf
[20] https://www.aivd.nl/publish/pages/2632/transformatie_jihadisme_in_nederland_juni_2014.pdf
[21] http://www.nwo.nl/over-nwo/X+publicatie/ew/thema-complexiteit---complexity---uitwerking-2008.html
[22] http://www.nwo.nl/en/research-and-results/programmes/complexity
[23] http://www.grip-on-complexity.nl/content/Lectures/Meijer

properties of the clock emerge large at the level of the neuronal network. These networks can develop attributes that are opposite to the attributes of the individual neurons. The possibility to exert control over our 24 h rhythms is larger when the neurons of the clock are highly synchronized, and diminishes with less coordination among the individual cells". The related networks have created a vivid complexity community in the Netherlands with Complexity centers in Groningen, Utrecht, Wageningen etc. The recently awarded NWO "Zwaartekracht" program "Networks"[24] will help to create a strong mathematical basis for network-based complexity research.

In 2013-2014 contacts have been established between NWO and TNO to come to a close cooperation in this area. This has led to joint workshops and TNO input for the proposal to the board of NWO for a follow-up program 2015-2018 "Grip on Complexity" to be formally offered to the NWO Board on September 18 2014.

3.2.3 TNO perspective
For the TNO Strategic Plan 2015-2018 5 Transitions (Themes) have been defined to focus the TNO activities. The expected relevance for these 5 themes is

- Defence, Safety and Security: human resilience & enhancement; resilience & effectiveness of organisations;
- Energy: emergent behaviour in multi-scale energy supply; policy & decision making in the energy transition; understanding of time- and space multiscale multilevel phenomena for the mitigation of risks of seismicity due use of the deep subsurface for subsurface energy storage, geothermal energy production and the exploitation of shale gas resources
- Healthy Living: personalized food in relation to the human body and human brain; technology enabled health in self-learning organisations; patients treated with optimal diagnosis-intervention combinations that fully meet his or her individual biological needs.
- Industry: complex, highly distributed and intensively communicating (cyber-physical) systems; emergent behaviour in and resilience of products and production equipment based on quantum- and nanotechnology (multi-scale behaviour).
- Urbanisation: emergent behaviour in and resilience of smart cities, i.e. transport and logistics; emergent behaviour in and resilience of products based on multi-scale behaviour, i.e. safety of installations; dynamics of a circular economy as a complex system

3.2.4 Conclusions
Complexity is an internationally and nationally well-established scientific field of activity and is generally seen as a highly relevant technology to solve questions in systems with emergent behaviour and thus can be used to contribute to the solution of grand challenges posed by the EC, the Netherlands government and the TNO transitions.

3.3 Eco-system

3.3.1 Topsectors and Programs
ERP Complexity will develop connections to the NL Topsectors and Programs through participation with industry, academia and TO2 partners in joint projects in dedicated tenders organised by the various TKI or EC. Also joint projects with industrial partners are envisaged that will be part of the relevant TNO-TKI contract and thus are supported by TNO VP contributions (SMO). It is the ambition of this ERP to come to a situation in 2018 where 50% of the budget comes from outside TNO. Participation of SME in these projects is deemed a prerequisite.

[24] http://www.nwo.nl/actueel/nieuws/2013/153-miljoen-voor-zes-nederlandse-onderzoeksteams.html

3.3.2 TNO Themes and Programs
ERP Complexity will develop connections to the TNO Themes and Programs through mutual participation in and collaboration with TNO VP, as part of the innovation contracts TNO. The options for participation and collaboration will be evaluated on a regular basis, but formally at least once per year as part of the annual update of the ERP plan. The relation with the TNO VP will be organised through the relevant TNO Program Directors and the TNO CSO.

3.3.3 Academic Partners and Programs
ERP Complexity will organise intensive collaboration with academia through the expected 2nd NWO program on Complexity "Grip on Complexity". During 2014 the contents of this program was discussed in joint TNO-NWO workshops, which has resulted in a proposal for an academic research program[25] to be submitted formally to the NWO board on September 18, 2014. It is expected that this will result in a NWO program for the period 2015-2018 with an annual budget of about 2 MEUR. TNO and NWO have the explicit wish to come to a concerted program with academia and industry, where the TNO contribution will be from this ERP. The NWO program will be centred around 3 research challenges: Grip on transitions, Grip on resilience and Grip on emergence.

It is evident that the wish to come to such a close cooperation with NWO will impact the way of working in this ERP as well as the precise topics to be worked on. It is anticipated that this will become clear in Q4 2014 and that then an update of this multiannual plan will become available.

3.3.4 TO2 Partners and Programs
ERP Complexity will build connections to the other TO2 institutes where appropriate and useful. Especially in relation the anticipated NWO program collaboration is possible, but has to be elaborated in 2015.

3.3.5 EC H2020 opportunities
As mentioned in section 2.2 various opportunities exist to participate in Horizon 2020 programs and projects, to be reviewed on a case-by-case basis for fit. Especially 1) relations with European institutes focusing on complexity research and 2) foreign companies that see benefit in collaboration with Nl partners, can and will be built in this way over the next years.

3.3.6 Conclusions
It is the intention of this ERP to come to a strong collaboration with various partners outside TNO. Building blocks have already been laid as a start and which can be elaborated in the next years.

3.4 Research and technology lines 2015-2018

3.4.1 State-of-the-art, knowledge gaps, position
From the previous chapters, it is evident that ERP Complexity basically can support all 5 TNO transitions. As of today, complexity is not a well-defined activity in TNO with various local initiatives and approaches. A well-underpinned appreciation of the quality of development and use of complexity science is therefore hard to give. Thus also the true value of complexity science cannot be rightfully judged in a significant number of domains. E.g. the notion and use of complexity in high tech systems and materials development is lagging. Promising ideas exist for using complexity in a number of applications (energy grids, transport, logistics, health care etc) but are far from mature.

E.g., in the area of mobility, an agent Based Model for Upscaling Transitions and Innovations for Modelling Commuter Travel Behaviour is being developed. Swarming behaviour provides useful and innovative starting points of this. The safety and defence complexity research has started at TNO

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[25] Outline of the NWO future challenge "Grip on Complexity: How manageable are complex systems?, final draft 26-05-2014.

approximately 7 years ago. It first focused on modelling complex human behaviour and on how to improve war games by incorporating complexity principles like self-organisation and emergent behaviour. More recently, research has focused on developing methods to provide insight in complex organisations and their emergent behaviour (e.g. modelling and analysing piracy operations at the Somalia coastline). Similarly, the developed methodology and tooling has been applied in the Healthy living theme, to provide insight into diabetes development in the Dutch population and to determine social return policies to improve opportunities for low economic classes. A number of these activities were undertaken as part of the ETPs Modellen and Gedrag&Innovatie in the 2011-2014 TNO Strategy period and thus provide a basic starting point.

From the general vision on the TNO ERPs for the period 2015-2018, the true added value for external and internal stakeholders must emerge by realising new connections to external partners and initiatives with high quality fundamental and applied knowledge as the basis. Thus in alignment with the overall TNO Strategic Plan, the goals of this Early Research Program Complexity for the period 2015-2018 are:

- act as a nucleus for new research initiatives and partnerships with external partners (universities, industry, TO2), in particular through the cooperation with NWO.
- create a platform for Complexity Science as a valuable technology for the different Themes in TNO
- facilitate and promote cross-theme use of complexity tools

In the end this program will be a success when by 2018

- complexity will be recognized as a prerequisite for a significant number of TNO activities and roadmaps
- TNO will have an internationally recognized knowledge position in specific complexity domains, well embedded in an academic community
- External stakeholders value this position by significant cooperation, e.g. quantified by direct financial participation

3.4.2 Technology lines 2015-2018

It is clear that not all applications addressed in section 2.2.3 can be envisaged at once. In order to come to tangible results, focus will be brought in by selecting specific use cases as technology demonstrators to show industrial/societal relevance.

Initially in 2015 the focus will be on use cases in three Themes given in section 2.2.3:

- Healthy Living: personalized food and health;
- Energy: time- and space multi-scale phenomena in induced seismicity
- Urbanisation: cooperative driving and logistics; safety in the urban environment; system dynamics of a circular economy; development of smart city concepts

Social Innovation as relevant to Theme Healthy Living will be included as a generic research topic in the above.

From a content point of view, the focus will be on the development and validation of industrially/societally relevant, agent based models to analyse complex adaptive systems. Collaboration with the TNO Themes will be through joint projects and joint initiation of external collaboration with industry.

Research questions to be addressed include:

- Concepts from complexity science change our understanding of cities. Scaling, fractals, and simulation models explain and can be used to demonstrate how flows and networks shape cities and how they can be better predicted and managed for improving urban planning and design.

Today's explosion of measurements in the urban field—the so-called big data phenomenon—is opening up possibilities that were unthinkable just a few years ago. In order to understand cities we must view them not simply as places in space but as systems of networks and flows. Drawing on the complexity sciences, social physics, urban economics, transportation theory, regional science, and urban geography, we seek to introduce theories and methods that reveal the deep structure of how cities function[26] to answer questions as "What is the relation between data produced by urban operations (nodes, flows, networks) and data obtained from urban structures (qualities & quantities). In what ways are properties determined or emerging from this relationship?". In order to investigate this we foresee an information driven multi-agent based approach based on a real-life dataset, where collaboration with UU and VU is foreseen.

- Managing industrial safety in a good way, to maintain a certain safety level at company, sector and national level is getting more complex, e.g.:
  - companies are more and more interconnected (eg. by outsourcing) and dependent one each other (eg. feed stocks, sharing maintenance services)
  - various legislation and inspection regimes exist
  - different fields of expertise (technical integrity, organizational and psychological science) have to be combined
  - a strongly interrelated stakeholder arena: companies, government and society on national en international level

  Those determinants are interconnected and influence each other. Although a lot of effort has already been taken to improve industrial safety, it is yet not investigated how these determinants are interconnected and how they influence each other. The safety science field can be characterized by focusing on causal relationships for improving safety. Focusing on improving safety within a company only and denying the complex systems in which the company operates. Within the ERP Complexity we would like to explore a new perspective on industrial safety, in which a more holistic approach is taken. Nowadays from different scientific fields network or system approaches seem to yield promising results in not only gaining better understanding the interdependencies, but also in being able to forecast the future. Within the different stakeholders in the industrial safety field a lot of different data is produced. With current big data methods it should now be possible to investigate how determinants are interconnected, and being able to forecast the future industrial safety priority areas. *'In what way are data obtained from (different) companies (industrial safety) related to data obtained by inspection. What are emerging properties from this relation for improving industrial safety?* Collaboration with TU Delft is foreseen.

It is expected that these areas can, as a start, be further elaborated in the joint NWO-TNO program starting in 2015. Other relevant applications can then be addressed further in years thereafter, also a part of continuous renewal of this program.

3.4.3 Growing the eco-system 2015-2018

Growth of the eco-system in TNO can be achieved by building more and closer relationships to the various TNO VP. However, in view of limited (and further reducing) internal financial resources, prime attention will be placed on developing external relations with industry, TO2 and academia.

One priority will be to come to co-operation with innovative SME. Existing networks can be used for this, but a dedicated activity is likely needed. The co-operation with NWO can be fruitfully used for this, e.g. by joint formulation and development of a Complexity Platform in the Netherlands.

[26] http://mitpress.mit.edu/books/new-science-cities (Michel Batty, The New Science of Cities)

Relations with other TO2 institutes in this area have not yet been explored. However, examples of future collaboration could e.g. be found in Deltares (water management), ECN (energy systems), DLO (food) etc. Options for this will be evaluated in 2015.

3.5 Activities and deliverables 2015

The precise activities and deliverables 2015 will be available in the update of this proposal once the joint NWO-TNO program Grip on Complexity has been shaped. As agreed with MinEZ this update will be available before end 2014.

4 Personalized Food for Health

4.1 Introduction

4.1.1 Personalized foods

Food has always been an indispensable part of human life. The specific foods which were available differed over time periods and based on locations on earth. First humans lived as so-called hunters-gatherers, living from wildlife meat obtained from hunting and fruits and vegetables obtained from nature. Around 10.000 years ago this lifestyle changed with the advent of agriculture and the development of permanent residences. This led to a more stable food supply but also a reduced food variation. The industrial revolution in the 18th century led to a change in diet now based on industrially treated and refined foods. Again this led to a decrease in diet complexity. Finally in the 19th and 20th century processed and sanitized foods became the standard diet for most people. Furthermore, pleasure foods not necessary for compensating the body for energy consumption based on physical activity have become common goods. Together with a drastic change in life style, especially in the western world, from a daily large physical activity to a sessile and reduced activity life have changed human life and its health status dramatically.

The use of antibiotics and vaccines since the middle of the 20th century has resulted in a dramatic increase in life span and a reduced infectious pressure. At (about) the same time however a dramatic increase in new diseases is showing up: cardiovascular diseases, cancer, obesity, type 2 diabetes, allergies, asthma/COPD, autism, and dementia and so on. Nutrition and health research has made major progress, but its relation with the microbiome, inflammation and immune regulation is still in its infancy, especially in relation to early life programming and healthy ageing. We now realize that this is becoming a major area of health and thus societal impact, and consequently of commercial importance. Furthermore it recently has become clear there is an enormous variation between individual humans, at the genome level, at the microbiome level and at the systems level. This opens up the potential for developing more personalized approaches. Although these aspects influence all parts of our lives there are two periods which deserve specific attention and therefore have been selected as the first two use cases:

- Early Life which roughly comprises the period from conception until the second birthday in which the complete developmental plan for a healthy life has to be established
- Ageing which roughly comprises the last third of our lives in which existing systems are deteriorating

These use case are now discussed in more detail.

4.1.2 The use case Early Life

The early life phase strongly contributes to the health status during future life. It is characterized by developing all relevant parts of the human body but also by the less well visible regulatory circuits which determine the responses towards internal and external stimuli. It is becoming clear that so-called homeostasis, a healthy balance between all the sometimes contradictory biological processes is a major determinant of human health. An important part of this balance is the interaction between the immune system and micro-organisms and other external stimuli, which is developing to a large extent during the first months of life. This development is characterized by an inherent and essential temporal instability which constitutes the training of the system and which finally results in a stable situation. Health in general is characterized by the flexibility of all major processes and mechanisms within the borders of the healthy balance, whereas early life development is thought to be characterized by establishing the “set-points and amplitudes” of flexibility. This means that both the standard values and the variations around standard values which are considered to be within the normal healthy range will be determined. Disturbances in this development are thought to be involved in the sharp increase in allergic diseases (atopic syndrome comprising of eczema, food allergy, hay fever and asthma) and auto-immune diseases (the unwanted attack of human body components by its own immune system). However also the relation of a disturbed balance between microbiota, immune system and human body during early life with diseases as diverse as obesity, type 1 and type 2 diabetes, specific cancer types and autism is increasingly gaining attention.

Food is an important factor in all these processes and one of the few external factors which easily can reach in principal every individual. Diet deficiency in folate during pregnancy increases the risk for spina bifida in new-borns but supplementation of folate significantly decreases this risk. Breast milk is known to be full of health-stimulating components for the new-born baby (and therefore the gold standard for synthetic infant formula products). Foods are not expected to cure but most likely will be able to influence (in a more or less subtle way) a healthy balance.

We now begin to realize that both the reduction in food complexity and the increased hygiene may hamper the development of a robust “defence programming” in early life, contribution to the above mentioned disorders. The working hypothesis for this use case is thus that specific food exposure regimes in early life will contribute to major health improvements and business opportunities.

4.1.3 The use case Healthy Ageing

Ageing is characterized by a loss of flexibility in a number of primary processes, leading to slow but progressive deterioration, manifesting in “old age diseases” (CVD, cancer, mental diseases). Current healthcare focuses on therapy, *i.e.* combatting symptoms once they appear which usually is at a relatively late stage. These treatments range from lowering cholesterol by statins to heart surgery, from hypertension medication to stroke-related therapy, from chemotherapy to cancer surgery and from cognitive decline pharmacology to Alzheimer clinics. Since therapies in nearly all cases target disease symptoms and not the origin of disease development current targets are not useful for preventive approaches. It is increasingly becoming clear that the onset of many “old age diseases” depends on disturbances in and deterioration of the healthy balance. At the same time it is clear that both timing of and the specific ways in which this system gets disturbed are highly variable between individuals. Therefore personalized approaches for diagnosing these changes in an early stages are essential and will also allow for targeted interventions based amongst others on specific foods and diets (in line with the TNO P4 Health vision). Real healthy ageing should thus include the personalized optimization of this system, which can and should be done by personalized diet and lifestyle. Health is characterized by the flexibility of all major processes and mechanisms and ageing and disease relate to loss of this flexibility, causing onset of disease. Shaping and maintenance of this flexibility thus is the goal of prevention. The general idea is the optimization of the microbiome, immune, metabolic health balance during ageing by optimizing intestinal inflammatory- immune flexibility. Recent scientific developments show the importance of these individual aspects for determining health, but also show that especially the interactions between these aspects are of uttermost importance in determining health outcome. Of course other aspects will also influence health but the aspects described here seem to play a central role and are at the basis of many different disease developments. Furthermore we already have a strongly developed knowledge and technology position for most of these aspects. Under healthy conditions, the metabolic-immune system is continuously triggered by a large variety of challenges, maintaining an immune alertness that transmits from local (intestinal) to systemic immune, inflammatory and metabolic balance. These challenges can be food-based, but also microbial (infections) and hormonal (neural stress). Depending on the individuals genotype, phenotype and exposure history, imbalances may develop into any immune-metabolic related disease, including vascular diseases, rheumatoid arthritis, COPD, allergies, and a range of neuronal disorders.

The program will focus on the early recognition of these imbalances and the development of *in vitro* and *in vivo* models to analyse the interactions between food components, microbiota and the intestinal-systemic immune-metabolic system. The development of tools to study and insight in mechanism underlying these interactions will be an important and essential part of this program. It will contain three interacting components, each with scientifically and commercially relevant aspects:

1) Understanding the mechanistic basis of optimal immune-metabolic health (together with the early life use case) leading to novel diagnostic targets and tools to screen for ingredients that promote human outcome.
2) Development of *in vitro* and *in vivo* models to analyse the interactions between food components, microbiota and the intestinal-systemic immune-metabolic system which predict the effects on human outcome, in relation to prevention of specific ageing disorders.
3) Development of specific dietary strategies based on personal health (including analytical methods to determine individual health status) and a database of compounds and their beneficial effects.

4.2 ERP environment

4.2.1 European perspective

TNO is optimally connected to, and partially leading, all major ongoing European personalized food initiatives. The major program is the FP6 Food4Me program, setting the stage for all aspects, including ethics, business models, analytics, and consumer acceptance. The TNO-coordinated FP7 project Qualify exploits business models for SME in this area. We coordinate the H2020 P4Health proposal, focusing on the introduction of personalized food strategies in health and type 2 diabetes, are involved in the H2020 “malnutrition for the elderly” proposal and coordinate the major European “big data in nutrition research” initiative. Furthermore, the FP7 project NU-AGE designs foods for ageing populations. Finally, the TNO co-initiated European Nutrigenomics Organisation is a recognized authority in this area. Importantly, European research programs now shift towards academic-business consortia and implementation activities. TNO is leading or involved in both.

4.2.2 Netherlands perspective

Health care costs in the Netherlands are high (2^{nd} highest in the world) and rising. If this rise continues, the societal costs will become prohibitively high. For this reason, cost reduction in health care is high on the political agenda. One way to prevent this catastrophic rise in healthcare cost is to invest more in prevention. For this reason, TNO’s transition in this field for the coming strategic period ranging from 2015 to 2018 is called: Healthy living, from illness and care to health and behaviour. Considering the approximately 90 billion EUR yearly budget for healthcare, even small initial gains in healthy behaviour can mean big savings in the long term. Gains preferably need to be found in adding health to life instead of adding years to life, meaning that the focus should be on perceivable health benefits that enhances quality of life. This program targets exactly that aspect, aiming at consumer empowerment with the aid of novel diagnostic and technological solutions to be able to quantify and visualize the effects of food on personal health.

4.2.3 TNO perspective

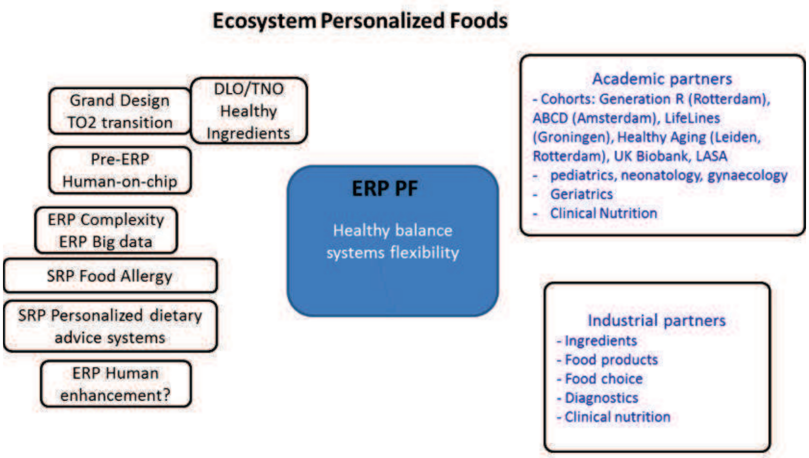
The Council for Public Health and Care in 2010 described the transition: “from disease and care to health and behaviour”. Our healthcare system is one of the best in the world but is suffering from increasingly rising costs. High quality care, prevention and cost control therefore are the major drivers for the nearby future. The strongly rising incidence of life style related and chronic diseases further necessitates changes in the current processes. The advent of smart monitoring and data analysis, but especially also effective health interventions stimulate maintenance of health and longer participation of elderly. Innovations in good and health foods play an essential role in this transition.

The above text is derived from the TNO strategic documents and shows a perfect alignment with the goals of the here described ERP Personalized food for health. The industrial perspective for this development is also significant. Based on well-designed studies and novel scientific insights the potential for developing foods with health maintaining and disease delaying or even preventing effects may come within reach. Taking stratification for specific target groups into account will further support this development. These developments are of in interest for food companies globally, both with global presence and with more local presence.

4.3 Eco-system

4.3.1 TNO Themes and Programs

This ERP has clear relevance for the new TNO transition Healthy Living: from illness and care to health and behaviour. The closest link within this TNO transition is with the roadmap for Food&Nutrition, which specifically addresses this topic. The roadmap for Biomedical Innovations is interconnected as far as diagnostics and complex (systems biology) models are concerned. Furthermore, the ERP 'Complexity' has expressed interest in the topic of personalized health and behaviour. This will lead to a co-funded 400-800K project investigating the possibilities to predict personal health behaviour (funded with VP budget). The ERP "Making sense of big data" has chosen Personalized Health as one of its use cases and collaboration with this ERP is currently under discussion. Also the ERP "Human enhancement" has clear interfaces with this ERP especially in the area of mental health. Also here collaborative efforts will be discussed. Finally the pre-ERP "organ-on-a-chip" can be a partner and enabler of this ERP by looking at possibilities to use life-like complex cell and tissue models as screening tools for healthy products.



4.3.2 Figure 1 National Top Sectors and Themes / Stakeholders

This ERP links to the Grand Design initiative (including SIPs and TO2 FLEX budgets) of the Dutch Ministry of Economic Affairs. It lays down the technological foundations for a joined programming in the agrifood sector between TNO, DLO and NWO. This ERP falls within the framework of the Top Sector AgriFood's theme 6, 'Health', which looks at the quantification of diet-health relationships. Within this theme, developing new methodology to measure health and study the effect of diet on health are the main innovation challenges, which aligns perfectly with this ERP. Furthermore, healthy ageing is a separate program line within theme 6. Finally, the latest incarnation of the 'Innovation Contract' (2014) describes the relevance of the interaction between nutrition and behaviour. This includes this ERP's aim to develop technologies to eventually empower consumers to make a healthy choice. Furthermore this ERP falls within the framework of the Top Sector Life Science & Health and more specifically its roadmap on Specialized Nutrition.

4.3.3 Academic partners / programs

This ERP takes a clear position within the Dutch knowledge infrastructure bridging the currently existing gap between food/nutrition/agriculture on the one hand and the health/preventive medicine field on the other hand. On the food/nutrition/agriculture side collaboration with DLO, which currently are already under discussion (*e.g.* FLEX-budget for which the goal is to improve personal health by employing do-it-yourself health measurement techniques to generate short term feedback on health status in order to empower consumers to choose and maintain an optimal personalized diet (& lifestyle) will be strengthened and potential collaboration with WUR, RU and UM in this field will be actively pursued. On the health/preventive medicine side current collaborations with large medical centres and especially large cohort studies that are running (Generation R, ABCD, LifeLines, LASA and so on) will be strengthened. Being able to bring these topics together with TNO as the integrating partner will be essential for building the desired ecosystem in this area.

4.3.4 EC H2020 opportunities

In the Horizon2020 work program 2014-2015 for the Challenge 'Health, demographic change and wellbeing', the following introduction is used to introduce 'Personalising health and care'.

"The development and preservation of good health, and the occurrence and evolution of common diseases and disabilities result from varying degrees of interaction between the genetic make-up of individual human beings and behavioural, environmental (including endocrine disruptors), occupational, nutritional and other modifiable lifestyle factors. *This applies from the earliest stages of development throughout life. Understanding these factors, their interactions and the extent to which they contribute to health preservation and/or to disease development is important for the development of preventive and therapeutic measures supporting good health, prolonged active independence and a productive working life, not least in the context of changing demographic patterns and the ageing of the European population. In particular, proposals should contribute to improving risk identification and validation, and will allow better diagnosis, risk-based prevention strategies and policies*." The H2020 program closely aligns with TNO's work, ideas and expertise in the field of (personalized) healthcare.

Amongst the topics which are proposed for the 2015, 2016 and 2017 call in the health area at least five have a strategic fit with this ERP:

- Nutrition for the elderly
- Ageing at large
- Personalized medicine
- Early development
- Sustainable health and care systems

4.4 Research & Technology lines 2015-2018

4.4.1 State-of-the-art, knowledge gaps

Food influences human life on a daily base but from a scientific point of view our knowledge is still rather limited. Historically information on how food influences human health is mainly derived from retrospective or observational studies, often based on epidemiological surveys in which diets of people with a specific disease were compared with diets of healthy control groups. Most of our current knowledge on healthy and unhealthy diets is based on such studies, which has proven to be useful for recommendations at a population level. Such analyses however suffer from multiple confounding factors (diet is not the only difference between the groups, also lifestyle, smoking, social background etcetera often are different) and do not take into account individual differences between humans. Furthermore they lack a more thorough scientific understanding of how a healthy diet actually achieves its effect.

To increase our scientific knowledge research was started in which individual ingredients are experimentally studied for their specific health effects. This approach resembles the pharmaceutical way of studying drug activities with the complicating factor that food ingredients often have more subtle effects than drugs and often also have multiple effects which cannot be covered all by experimental systems. Furthermore a diet is composed of hundreds to thousands of ingredients potentially influencing each other's activities and diets are changing on a daily base. This makes research on individual ingredients complex and outcomes difficult to translate to human health.

So what can we learn from this? It is clear there is an enormous gap between long term retrospective population based studies and (short term) experimental scientific research on individual ingredients, which both lack sufficient predictive value for human outcome. This could be solved by developing novel experimental systems which allow for generating scientific knowledge and understanding but at the same time take into account complexities in diet and human biology. With respect to the latter point we can take advantage of the enormous increase in understanding of human biology during the last two decades, driven by the genomics revolution and the development of many new technologies allowing for detailed analysis of human biology and development. For the first time in history it is now possible not only to think about a human system but also to develop an experimental version of such a system. In this system the homeostasis or healthy balance between microbiota, immune system and human biology plays a central role and its flexibility to a large extent determines human health. Furthermore this system should allow for bridging the gap between *in vitro* (outside the body) and *in vivo* (in a living organism) experiments by creating both *in vitro* and *in vivo* versions of this concept based on the same principles and leading to increased predictive value for human outcome.

The development of this system will be the major target for the research and technology lines 2015-2018. The basis for this development will be the current state-of-the-art, which is characterized by its monodisciplinary character. This means we do have methods available and can measure at the level of ingredients, microbiota, immune response, cell and tissue response, ingredient absorption, metabolic processes, animal models and human physiological response. However what is currently lacking are approaches which integrate multiple aspects and take into account the way they influence each other. This knowledge gap in the current situation can be translated into specific knowledge questions to be answered as well as technological developments which are indispensable for answering these knowledge questions. Figure 2 shows a schematic overview of the components of the envisioned system and the planned developments.

We choose to launch this ecosystem by exploiting our knowledge base in microbe host interactions, systems biology, metabolic health, immunology and food ingredients in two focus areas crucial in the human lifespan: early life and healthy ageing. Personalized foods for these two "phases of life" are of high impact and profit from a common technology basis. In both areas the combined immune, inflammatory, metabolic and microbiological aspects collaborate in determining health. In early life, these aspects collaborate in imprinting health, in healthy ageing; they connect in maintenance of health leading to prevention.

4.4.2 Technology lines 2015-2018

The major goal for the period 2015-2018 is to enable the identification, measurement and quantification of health effects in biologically relevant models. The relation between nutrition and health research with the microbiome, metabolism, inflammation and immune regulation, which from an industrial and applied perspective is still in its infancy, will play a central role. Especially the interactions between these aspects and the way in which they together establish a stable and healthy balance will be important. This development will be based on the combination of:

- *in silico* models based on known data
- the development of *in vitro* systems predictive for the *in vivo* situation by taking biological complexity into account
- *in vivo* models for validating *in vitro* models
- *in vivo* models targeting those aspects that cannot be covered by *in vitro* systems
- development of predictive diagnostics for stratification
- human cohort studies for identifying novel relationships and targets

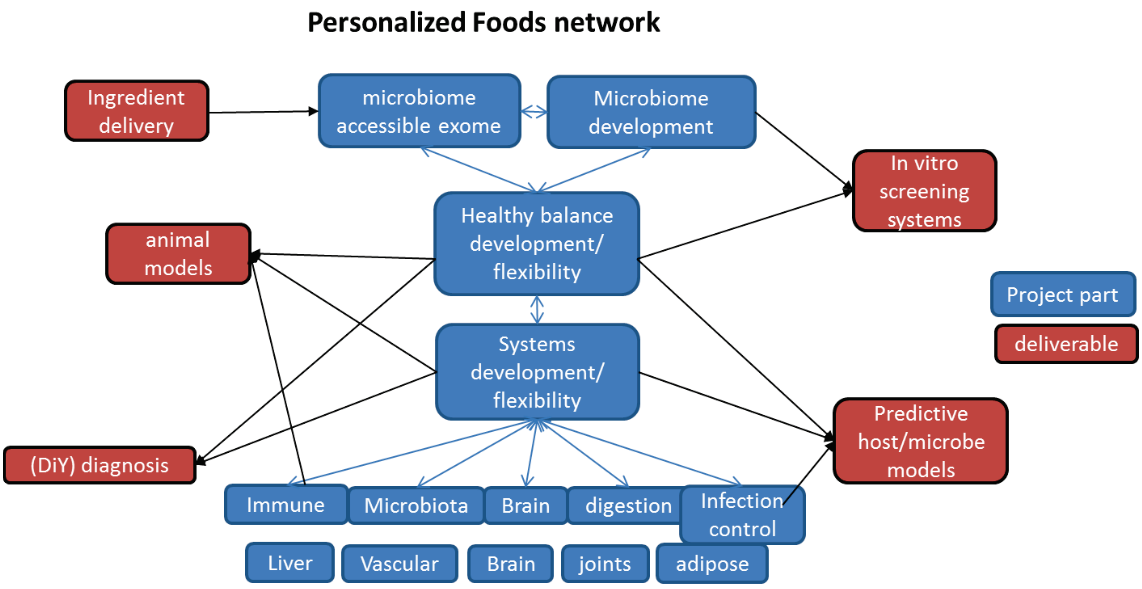


Figure 2 general outline technology network

This technology development will be discussed with industrial partners and be tuned to their needs and expectations. This will lead to novel ways of identifying effects of food products on human development in general and on specific target groups. This will allow for the identification and development of novel food products targeting human well-being in many different ways. At the same time these developments will ask for novel diagnostic tools to allow for determining who needs what product. Since these developments in the majority of cases will target human health and well-being they will also support the transformation of the healthcare system from a reactive disease based way of working towards a proactive preventive (stay healthy, keeping disease away) way of working. On the longer term this may even be of interest for pharmaceutical companies.

4.4.3 Growing the eco-system 2015-2018

The goal of the ecosystem Personalized Food for health will be to deliver science based tools that enable determination and quantification of health effects. This will allow the development of novel and stratified foods as well as the development of novel diagnostic approaches. The latter is essential to determine which individuals can profit from specific stratified foods and is a first step in the direction of consumers making personal choices concerning foods for a healthier life. TNO will develop the health determining and quantifying technologies together with academic partners and input from industrial partners. These technologies will support industrial partners with their development of novel and stratified foods and supporting diagnostics, which in a later stage can be translated into services for personalized and do-it-yourself approaches. A streamlining with NWO programs to support academic research of importance for this program will be part of growing the ecosystem.

4.5 Activities and deliverables 2015

Five work packages have been defined of which the first three focus on the technological developments described above. They consist of a first work package which has clear similarities for both use cases followed by two work packages each targeting a specific use case. A fourth work package aims at building the ecosystem and a fifth work package which targets managing and aligning all efforts.

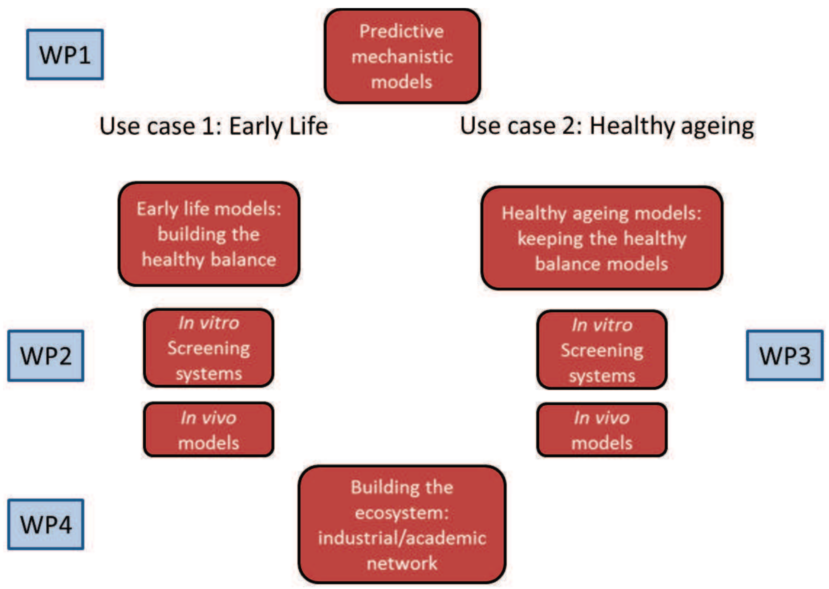


Figure 3 ERP work packages within technology network

WP1 Predictive mechanistic models

Development of a model that integrates all components of the microbiome, immune response and human biology. From this model predictions of the most relevant biomarkers and mechanisms for Early Life and Healthy Ageing will be derived. These biomarkers and mechanisms will be targeted in WP2 and 3.

- Ingredients influencing human health
- Ranking human biological pathways based on importance during early life and ageing
- Determining microbiome diversity during early life and ageing
- Immune responses during early life and ageing
- Integrated model of human biology/microbiome/immune response
- Selection of health relevant parameters for early life and healthy ageing
- Selection of health indicating parameters supported by the industry
- Novel diagnostics based on selected health parameters

WP2 Early Life models: building the healthy balance

- Development of *in vitro* models aiming at integration of:
    - Food/ingredient microbiome interaction
    - Infant host cell/tissue microbiota interaction

  - Microbiota immune interaction screen: immune programming
  - Integrated healthy balance development read-out
- Development of *in vivo* models aiming at:
  - Analysing food effects preconception and during pregnancy
  - Integrating microbiota/immune/host physiology data in relation to health
  - Longitudinal analysis of developmental processes
- Analysis of the most relevant parameters for early life selected in WP1Diagnostics for subgroups

WP3 Healthy Ageing: models: Maintaining the healthy balance
- Development of *in vitro* models aiming at integration of:
  - Ageing host cell/tissue microbiota interaction
  - Microbiota or immune inflammation interaction
  - Disturbed healthy balance/flexibility read-out
- Development of *in vivo* models aiming at:
  - Analysing food effects in ageing model
  - Integrating microbiota/immune/host physiology data in relation to health
  - Analysis of the most relevant parameters for ageing selected in WP1
- Diagnostics for subgroups

WP4 Building the ecosystem
This work package aims at identifying relevant partners for the ecosystem Personalized Nutrition, attracting them based on our current track record and plans to take part in the ecosystem. These partners will both be industrial and academic partners. For both types of partners it will be essential to attract partners which are competing for the same market or scientific goals in order to build an ecosystem of sufficient size and impact. This means the ecosystem has to be sufficiently precompetitive (avoiding commercial conflicts) on the one hand, but sufficiently attractive and appealing on the other hand to entice partners into investments in the program. As a start we aim at building a consortium in 2015 of partners who based on a limited admission fee may discuss and influence deliverables for the next years. The topic is of interest for international companies for all parts of the world, both globally active or more locally active, but also innovative SME s can be part of this ecosystem and special arrangements will be made to allow them to be part of this development as well. A big opportunity from the TNO perspective is the possibility to attract new partners in new markets.
The collaboration with DLO and other TO2 partners will be evaluated and targeted as well with a special emphasis on the following topics:
- DLO: determine if healthy lifestyle has been implemented
- TNO: measure health effects of lifestyle change

5 Energy Storage and Conversion

5.1 Introduction

One of the grand challenges for Europe in the coming decades will be to guarantee a sustainable supply of energy, while at the same time keep the system reliable and affordable. The renewable energy directive 2009/28/EC established a European framework for the promotion of renewable energy, setting mandatory national renewable energy targets for achieving a 20% share of renewable energy in the final energy consumption and a 10% share of energy from renewable sources in transport by 2020. Renewables include wind, solar, hydro-electric and tidal power as well as geothermal energy and biomass. To realize this “2020 target” and to promote a further growth in the share of renewable energy in the total energy market towards 2050, which is an absolute prerequisite for securing Europe’s future energy supply, the development of new breakthrough technologies is essential. Moreover, the future energy system will face a drastic shift from today’s centralized production from GWatt fossil-fueled plants towards more decentralized generation (*e.g.* local household photovoltaic systems), and generation by wind turbines in offshore wind parks.
Energy storage and conversion solutions facilitate the increase in flexibility of the energy system. This flexibility is needed to cope with the uncontrolled variability (‘intermittency’) of renewable energy sources and the fact that renewable energy production often takes place on a smaller, local and more decentralized level. Also the relation between different energy carriers will be of significant importance for the infrastructures (hybrid energy systems). Without additional measures, the reliability of energy supply will decrease. Storage and conversion is a promising part of the solution to the flexibility challenge, other options are also possible, such as increased flexibility in centralized production, international interconnections and demand response. In any case, the increase of sustainability of the system has negative impact on the reliability for which the solutions can be thought of that should keep the system reliable and affordable.
Heat storage has become an indispensable element in the energy revolution, smoothing out the fluctuations inherently connected to renewable energy sources. Locally implemented compact thermal storage services may introduce (partial) solutions for peak shaving and instabilities in smart electricity grids, and thus a substantial reduction potential in (societal) investments in upgrading the grid. Implementation in the existing infrastructures is essential, thus stressing the need for compact solutions.
The future energy system will inevitably include trans-sectoral exchange of energy flows, *e.g.* between industry, built environment and transport. As an example, the recuperation of waste heat in industrial applications offers a good perspective, considering that Dutch industrial production generates a substantial flow of waste heat between 90-150 °C.

5.2 ERP environment

Within this ERP, our mission is to provide solutions for large scale, central and small scale, decentral (local) energy conversion and storage to increase the necessary flexibility of the energy system. We aim to provide solutions for both industrial and domestic users.

Focus of the ERP Conversion and Storage
We will primarily focus on three different technology concepts for energy conversion and storage and on studies on energy systems dynamics to analyze the impact of these technologies on the energy transition as early as possible.
(1) Electrons-to-chemicals
(2) Photons-to-chemicals
(3) Thermochemical storage
(4) Energy system dynamics

Concepts (1) and (2) involve chemical conversions: in concept (1), electricity generated from renewable sources (*e.g.* wind, photovoltaics) is stored in form of chemical energy after an electrochemical conversion, in concept (2) sunlight is directly stored in form of chemical energy involving a photochemical and/or photothermal conversion. Concept (3) involves heat storage and release through dehydration/hydration of salts. Concepts (1) and (2) are most suited for large scale, central storage. Concept (3) is particularly suited for small scale, decentral storage, both in built environment and industrial batch application.
Recently, TNO has started to develop innovative and unique approaches for concepts (2) and (3) within the previous framework of the ETP Materials. For both concepts, joint development projects/programs with academic and industrial partners have been initiated (*vide infra*). Concept (1) complements concepts (2) and (3) as solution for energy storage and builds on TNO's track record in the field of electrochemistry. With these three concepts, we strongly belief to develop a robust and diverse portfolio offering energy storage solutions for both domestic and industrial users. Concepts (1) and (2) are currently on TRL level 2-3 and concept (3) on TRL level 2-4. *Ergo*, this portfolio enables TNO to serve the respective markets with technological solutions in the medium (3-5 years) and far future (> 5 years).
Energy Sytem Dynamics: To provide guidelines for the technology development in the above three lines and to facilitate the market introduction of the technologies to be developed in lines (1)-(3), a system study will be performed. This system study will focus on the impact of the storage and conversion solutions on the Dutch energy system. The impact is on a technological level (increasing reliability of the system) and financial aspects (affordability). Modeling, simulation and optimalisation of the hybrid energy infrastructures will allow a study of the impact before actual realization. Validation of models is ensured by input from the storage solutions under development by TNO and external developments.

<u>Use cases</u>
In relation to the ERP program lines, the next inspiring use cases have been defined:

Use case for electrons-to-chemicals
This program line is dedicated to the electrification of the chemical industry, *i.e.* the use of electricity for the transformation of chemical building blocks into value added chemicals and fuels. This line comprises two use cases: (1) the conversion of low cost CO_2 with (photo)electrochemically produced hydrogen to **dimethyl ether**, a diesel replacing fuel, and (2) the production of **ethylene oxide**. The envisaged research will take into account catalyst/electrode development and the integration of reaction and separation technology. Boundary conditions for this research line are that the developed technology should be relatively low in capital expenditures and should be able to accommodate the dynamic behavior of the electricity demand/supply.

Use case for photons-to-chemicals
The use case for 'photons-to-chemicals' is a chemical reaction leading to a fuel or value added chemical with a **conversion efficiency solar energy to chemical energy of at least 16%** (= efficiency photovoltaics x efficiency water electrolysis). The concept of choice is plasmon catalysis, in which nanoparticles of electrically conductive materials are used to collect sunlight and serve as catalyst for the conversion of choice.

Use case for thermochemical storage
A **heat battery** in an existing building, consisting of a compact thermal storage module that is connected to either a heat pump driven by renewable electricity or a solar thermal panel.
This use case envisages a development in subsequent steps:
(1) table top demonstrator; (2) prototype embedded in a virtual building ('emulator', Hardware In the Loop HIL); (3) Real-life demonstrator

Ambition
We aim to be an international frontrunner in storage of energy in molecular bonds, *i.e.* in form of chemical energy. We aim to embed the ERP program in a national ecosystem on energy storage in molecular bonds, *i.e.* a partnership with key academic and industrial players in the Netherlands, as to create a leading consortium, to leverage know how and R&D resources and to accelerate breakthroughs. Also we aim to lead the national discussion on the possible impact of these technologies during and after the energy transition by studying the system dynamics of energy and conversion technologies.

Interaction with other ERPs
In addition to the development of the three concepts for energy storage mentioned above, the impact of renewable energy solutions on the Dutch energy system in the coming years, in particular the dynamic behavior of the energy system on a regional and national scale, will also be a possible subject within the ERP Complexity. Latter research should provide answers to following questions: What does storage mean on local, regional, city or country wide application for the energy system? Also on an economical level: what is the value of storage in the entire system?
This analysis of the systems dynamics will involve the following:
TNO develops technologies, tools and methods for system analysis and integration aspects of storage and conversion (fit for purpose). Determine the value of storage or conversion for different applications in several time frames in the system, on different geographical levels, on centralized or decentralized level. The deliverables are used to assess technological and economic impact of storage and conversion in the transition.
TNO makes sure innovation is possible on storage and conversion with respect to the social and institutional aspects, especially on regulation and markets and subsequent potential blocking issues.

5.2.1 European perspective
Numerous reports (*e.g.* the EC Energy Roadmap 2050, 2011; IEA report Energy Technology Perspectives 2012 –Pathways to a Clean Energy System) describing possible future scenarios of the European energy landscape widely support the basic assumption that energy storage is one of the crucial flexibility sources in the future decarbonized energy system, apart from dispatchable power plants, demand-side response *via* a smart grid and interconnection with adjacent markets. Europe is frontrunner in terms of deployment of renewable energy, mainly driven by national support policies. The acceleration in massive deployment of zero/low carbon technologies in the next four decades will require an intensification of the investment efforts, as pointed out in a recent Communication of Deutsche Bank (2012), stressing that the energy storage market will (necessarily) be booming in the next decades.
The actual state-of-the-art energy storage technologies for which Europe holds strong competences can mainly be categorized into mechanical (pumped hydro, compressed air, flywheel), electrochemical, chemical, and thermal energy storage (and hybrid, like electromagnetic). Principally through hydrogen, chemical storage is an area that showed rapid development in recent years through considerable EU and MS funding. New developments in latent thermal storage materials and systems are rapidly emerging in laboratories all over Europe. The EU H2020 program clearly identified energy storage as one of the key priorities in its energy Challenge, amongst which compact thermal energy storage in the built environment (2013, Multiannual roadmap for the contractual PPP Energy Efficient Buildings under Horizon 2020) has been fully implemented in one of the leading public private partnerships.

5.2.2 Netherlands perspective
The renewable energy directive 2009/28/EC established a European framework for the promotion of renewable energy, setting mandatory national renewable energy targets for achieving a 20% share of

renewable energy in the final energy consumption and a 10% share of energy from renewable sources in transport by 2020. In view of this renewable energy directive and the increasing importance of efficient solutions for energy storage, an R&D landscape is forming focusing on storage of energy in molecular bonds, including TNO, ECN, FOM DIFFER (headed by Prof. Van De Sanden), TU/e (*e.g.* Prof. Janssen, Prof. Hensen, Prof. Adan), TU Delft (*e.g.* Prof. Zeman, Dr. Smets, Prof. Dam), Twente University (*e.g.* Prof. Mul, Prof. Lohse), Leiden University (Prof. Koper) and Utrecht University (Prof. Weckhuysen). Additionally, a range of companies located in the Netherlands are interested in solutions for energy storage in molecular bonds, including: chemical/fuel producers (*e.g.* DSM, Shell, SABIC, BASF), material/catalyst developers (*e.g.* Albemarle, Cabot, Kriya Materials, Johnson Matthey, Akzo Nobel, Dow, Nedmag, Sabic), component/system suppliers (*e.g.* Siemens, Proton Ventures, Inventum, NXP, Solesta, Vaillant Group) and energy companies (*e.g.* Alliander, Cogas, Tennet, E.on, Electrabel, RWE).

5.2.3 TNO perspective

The TNO transitions ‘Industry’, ‘Energy’ and ‘Urbanization’ have identified energy conversion and storage as an important subject for TNO for the upcoming strategy period. TNO will focus on energy storage in form of chemical bonds/chemical energy, and aim at forming a national consortium on this subject matter to realize the ambition of becoming a European frontrunner on this subject. The key expertise required to work on energy storage in form of chemical bonds is present at TNO and distributed over a range of research groups (*vide infra*).

5.3 Eco-system

For the Netherlands perspective and the TNO perspective see under 5.2.2 and 5.2.3.

5.3.1 National Top Sectors and Themes / Stakeholders

Energy storage is being addressed in different Top consortia for Knowledge and Innovation (TKIs) in the Topsector Energy:

- TKI EnerGO, wherein compact thermal energy storage and conversion forms a key priority. This is being implemented through a medium term research and innovation program, focusing on bringing first and second generation solutions in compact energy storage systems in the built environment to the market that optimally benefit from new solutions in thermal storage materials. The TKI launched a first program oriented call (3.5 M€) in June 2014.
- TKI ISPT, working on the reduction of energy consumption and energy efficiency in process technology in early adopters, large pilot projects and joint industry programs of applied research. One of the interests concerns the storage of industrial waste heat, as to introduce transportability and tradability and create opportunities for transsectoral energy exchange.
- TKI Gas (Power-to-Gas), working on innovations in the entire energy mix. The program lines within this TKI are focused on gas production, sustainable gas from biogas and gasification and in the application of LNG. The TKI strongly support the transition towards a sustainable energy.
- TKI Solar Energy. This TKI is focused on improving the Dutch photovoltaics sector and accelerate large scale implementation of photovoltaics.
- TKI Systems Integration. This TKI is focused on the integration aspects of different infrastructures (Gas, Heat, Electricity) and the relation between them. Storage/Conversion is one of the main program lines.
- TKI Switch2SmartGrids. In the search for flexibility options, storage is one part of the solutions. This TKI aims to define the optimal mix of demand response, flexibility in production, interconnection and storage/conversion functions in the system.

The ERP is well linked with the TKI programs, considering the involvement of TNO in TKI boards and program councils and alignment of TNO programs.

5.3.2 Academic partners/programs

(1) Electrons-to-chemicals:

No partnerships yet. Discussion on joint projects/program with potential national and international partners ongoing.

(2) Photons-to-chemicals:

- NWO project 'Unravelling the Mystery of Solar Steam Nanobubbles; 1.1 Mio € budget; TNO coordinator.
    - Partners: Prof. Weckhuysen / University Utrecht, Prof. Lohse / University Twente, Albemarle, BASF
- Metal and hybrid nanoparticles; 2 PhDs. Dr. Buskens, Prof. Möller / RWTH Aachen University, Prof. Urbach / Delft University of Technology (metal and hybrid nanoparticles; 2 PhDs).
- Discussions ongoing on national solar fuels program.

(3) Thermochemical storage:

- M2i, "Thermochemical storage of the future", Prof.Adan, TU/e-Applied Physics
- NWO/STW Perspectief program "The heat battery: MATerials for THERmal Storage and conversion "(MATTHERS), focused on breakthroughs in thermal storage material (12 PhDs, 1PD, 4.2 M€, presently under review, 2015), partners:
    - Eindhoven University of Technology (Prof Adan,Transport in Permeable Media, Prof Smeulders, Energy Technology, Prof Harting, Mesoscopic Transport Physics),
    - Radboud University (Prof Vlieg, Solid State Chemistry (SSC), Prof Kentgens, Solid State NMR, dr. Cuppen, Theoretical Chemistry),
    - University of Twente (Prof vd Meer, Thermal Engineering, Prof Lefferts, Catalytic Processes and Materials)
    - Delft University of Technology (Prof vd Akker, Transport Phenomena)
    - DIFFER (Prof vd Sanden)
      MATTHERS is fully aligned and interwoven with the TS Energy TKI EnerGO program on Compact Storage and Conversion (see National Topsectors).
    - TU/e Impuls 2 Program, 2PhDs on Thermochemical materials, (prof Adan, Applied Physics, prof Smeulders Mechanical Engineering)

(4) Energy Systems Dynamics

- TU/e, dr. Rene Kamphuis, dr W. Kling
- RuG, dr. G. Huitema
- Partnership discussion with ECN

5.3.3 TO2 / RTP partners / programs

For the fields of 'photons-to-chemicals' and 'electrons-to-chemicals', discussions are ongoing between ECN and TNO to ensure complementarity between the activities at ECN and TNO and evaluate potential cooperation in this field (TNO contact: Arij van Berkel).

With respect to latent heat storage, ECN is focusing on phase change materials (PCMs) and thermochemical materials in the higher temperature range (*i.e.* > 200^{o}C), both in industrial applications primarily. The areas of activity have been mutually agreed upon. We aim to undertake a joint action to explore the full complementarity in assets in thermochemical storage in the context of the joint TO2 funds 2015.

5.3.4 EC H2020 opportunities

(1) Electrons-to-chemicals

- CyclicCO2R (running FP 7 project, TNO is coordinator)
- Horizon 2020 call LCE 10: DIMENSIONS demonstration power to x (under review)
- Discussions ongoing on national solar fuels program.

(2) Photons-to-chemicals

Under evaluation. TNO's roadmap for this research line is actively discussed in Brussels (TNO contacts: Egbert-Jan Sol, Arun Junai).

(3) Thermochemical storage

Both Pillar 2 (Industrial Leadership, the ppp "Energy Efficient Buildings" in particular) and Pillar 3 (Societal Challenges, Energy in particular "providing the energy system with flexibility through enhanced energy storage technologies") H2020 program have identified energy storage as a key priority, which is illustrate by many of first calls 2014-2015 (e.g. LCE 8 (local small storage), LCE 9 (2015, Large scale storage) LCE 10 (next generation technologies for energy storage), EeB 06 (2015, Integrated solutions of thermal energy storage for building application). Apart from the calls in 2015, new and repetitive calls will be launched addressing the priority of compact thermal storage in the built environment (primarily in view of energy renovation of the existing stock). Prof Adan is a member of the EC Partnership Board on the ppp Energy Efficiency that is defining the respective program calls.

The current TNO portfolio of EU projects contains several on energy storage and conversion in the built environment: e.g. Merrits, EINSTEIN

5.4 Research & Technology lines 2015-2018

5.4.1 State-of-the-art, knowledge gaps

(1) Electrons-to-chemicals

The use of electricity to produce chemicals is in principle well known. An example is the production of chlorine from salt. However, the large scale implementation of electricity as a driving force for conversion is hampered by relatively high energy demands, leading to high operational costs. Using electrocatalysis and moving away from the standard operating envelope a paradigm shift can be created. The knowledge gaps needed to further support the electrification of the chemical industry are centered around electrocatalysis, non-conventional feeds (*e.g.* CO_2) and operating windows (*e.g.* plasma), improved hydrogen production. Within the ERP, the focus will be on the first two gaps. The gap dealing with improving hydrogen production is currently addressed in many international projects. It is of importance to note that to demonstrate the potential for electrification, a technical system approach (*e.g.* integrated reaction/separation systems) have to steer the more fundamental research questions. Skillsets from mechanical engineering, chemical engineering and chemistry are needed. Due to TNO's multidisciplinary facets, TNO is well placed to develop the needed showcases.

(2) Photons-to-chemicals

This technology is not yet in commercial use because of low conversion efficiencies from solar energy to chemical energy. From the early 1970s to date, most research groups active in the field of solar fuels focus on the investigation of the photochemical reduction of carbon dioxide, photochemical water splitting into hydrogen and oxygen and direct conversion of carbon dioxide and water vapour into hydrocarbon fuels using sunlight as energy source and semiconductor materials as photocatalyst. Of critical importance in these processes is the efficiency of the photocatalytic materials in their use of sunlight for these conversions.

In the majority of work on reduction of CO_2 performed to date, the reduction is achieved in an electrochemical cell requiring an electric bias and using a photocatalyst sensitive to UV light. Typical efficiencies are at 1% or below and only the UV part of the solar spectrum is used for the reaction. Additionally, the energy associated with the electrical bias clearly offsets any advantage inherent to CO_2 conversion.

Water splitting into H_2 and O_2 is a multi-electron process promoted by a photocatalyst and light. For efficient water splitting, it is essential to use visible light, since the maximum solar conversion efficiency would be 2% when only UV light up to 400 nm is used (assuming 100% quantum efficiency). When one single semiconductor material is used as photocatalyst for water splitting, the bottom of the conduction band must be more negative than the reduction potential of water to produce hydrogen. Additionally, the top of the valence band must be more positive than the oxidation potential of water to produce oxygen. It is, however, intrinsically difficult to develop an oxide semiconductor catalyst that has both a sufficiently negative conduction band for H_2 production and a sufficiently narrow bandgap (less than 3 eV) for visible light absorption because of the highly positive valence band formed by the O 2p orbital. Although some non-oxide materials have appropriate band levels for water splitting under visible light, they are generally unstable and become deactivated through photocorrosion or self-oxidation. A prototypical example of such a catalyst is CdS. The main approach chosen to overcome these limitations is to apply two different photocatalytic materials: one for the reduction of water to hydrogen, and one for the oxidation of water to oxygen. The resulting process is then typically carried out in form of a Z-scheme, in which the water splitting reaction is broken up into two stages: one for H_2 and the other for O_2 evolution.; these are combined using a shuttle redox couple. Although the introduction of Z-scheme water –splitting systems has significantly extended the available wavelengths (about 660 nm for H_2 and 600 nm for O_2 evolution), the quantum efficiency is still too low to reach energy conversion efficiencies of 5% or higher.

In conclusion, despite the efforts of excellent research groups in the past four decades, photochemical water splitting, CO_2 reduction and co-splitting of water and CO_2 using semiconductor catalyst materials still proceed with an energy efficiency below 5%. This urged us to search for a new concept for chemical conversions using sunlight as energy source which has the potential to realize significantly higher efficiencies for the conversion of solar to chemical energy.

The concept of choice is plasmon mediated catalysis, in which metal nanoparticles are used to collect sunlight and as catalysts for the conversion of choice. Seminal work on this concept has recently been reported in literature (e.g. S. Mukherjee, F. Libisch, N. Large, O. Neumann, L. V. Brown, J. Cheng, J. B. Lassiter, E. A. Carter, P. Nordlander, N. J. Halas, Hot electrons do the impossible: plasmon induced dissociation of H_2 on Au, Nano Lett. 2013, 13, 240-247; P. Christopher, H. Xin, S. Linic, Visible-light-enhanced catalytic oxidation reactions on plasmonic silver nanostructures, Nat. Chem. 2011, 3, 467-472). We will focus on demonstrating a chemical reaction leading to a fuel or value added chemical with a conversion efficiency solar energy to chemical energy of at least 16% (= efficiency photovoltaics x efficiency water electrolysis).

(3) Thermochemical storage

Both in the built environment and in the area of low temperature industrial waste heat, there is need for compact storage technologies with long term stability. Neither sensible heat technologies nor PCMs can offer this. The main advantages of thermochemical storage, either by physisorption (binding to solid surfaces, e.g. zeolites and silica gels), chemisorption (chemical structure change, e.g. salt hydrates) or chemical reactions (transitions of metal hydroxides to -oxides) are the (2 to10 times) higher energy density compared to sensible or latent heat storage, and long term loss-free storage. The first and last are expensive, and the latter generally take place at (too) high temperatures (300-500 C).

At present, only a few first generation applications of thermochemical storage are on the market, which are all based on physisorption by rather expensive zeolites: a dishwasher by Bosch/Siemens, a self-cooling beer keg and a Zeotherm gas-fired adsorption heat pump from Vaillant.

Knowledge gaps particularly address the atomistic and molecular understanding of energy density and phase diagrams, and cyclic behaviour and the principles that govern hydration kinetics on different length scales (particle-reactor), all hampering the targeted engineering of these materials.

TNO has a good right to play. No (foreign) programs exist yet that exclusively aim at thermochemical storage breakthroughs. The European Technology Platform on Renewable Heating and Cooling (2013) identified such program approach as priority in the strategic research and innovation plan. Moreover, no initiatives exists that link fundamental research with upfront initiatives to bring such new technology to the market.

5.4.2 Technology lines 2015-2018

(1) Electrons-to-chemicals: Within this concept, the focus is on developing methodologies for using electricity for the production of chemicals and fuels. We propose to focus on following subjects:

- Electricity to fuel
- Electrocatalysis

For ‘Electricity to fuel’, technology will be developed allowing the conversion of for example low cost CO_2 (*e.g.* from biogas upgrading or from industrial processes) with (photo-)electrochemically produced hydrogen towards dimethyl ether (DME). DME can be used directly as a diesel replacing fuel. We will focus on developing a reaction concept that works at moderate pressure and temperature.

For ‘Electrocatalysis’, the focus is on the direct use of electricity to convert chemicals directly into products. An example could be the production of ethylene oxide or the conversion of low value biomass to platform chemicals/fuels. The envisaged research will take into account catalyst/electrode development and the integration of reaction and separation technology. Boundary conditions for this research line are that the developed technology should be relatively low in capital expenditures and should be able to accommodate the dynamic behavior of the electricity demand/supply.

To support ‘Electricity to fuel’ and ‘Electrocatalysis’, a system approach will be used to guide the development. This approach will address the position of ‘Electrons-to-chemicals’ within the overall energy grid and chemical industry.

For ‘Electrons-to-chemicals’, the expertise and competence of following TNO expertise groups is required:

- Process and Instrumentation Development (TS) (separation and conversion technology)
- Water Technology (ELSS) (electrochemistry)
- Thin Film Technology (TS) (electrocatalysis)
- Heat Transfer and Fluid Dynamics (TS) (fluid dynamics)
- Materials Solutions (TS) (catalyst/electrode development)
- Service Enabling & Management (ELSS) (system integration)

Expected deliverables:
- Breakthroughs in lowering the cost for energy storage into chemicals
- Reaction concept for conversion of hydrogen and carbon dioxide to fuel at moderate temperature and pressure
- Electrocatalytical conversion with high energy conversion efficiency

(2) Photons-to-chemicals: Within this concept, the focus is on developing methodologies for using sunlight for the production of chemicals and fuels in a photochemical and/or photothermal conversion. Biological/biochemical approaches are excluded. The aim is to develop technologies that convert solar energy into chemical energy with an efficiency of at least 16% (= efficiency PV x efficiency electrolysis). Unlike conventional solar fuels technologies, the focus is not on water splitting or CO_2 reduction. An example of a chemical conversion aimed for is the direct hydrogenation of CO_2 to methanol. The concept of choice is plasmon catalysis, in which nanoparticles of electrically conductive materials are used to collect sunlight and serve as catalyst for the conversion of choice.

For 'Photons-to-chemicals', the expertise and competence of following TNO expertise groups is required:
- Materials Solutions (TS) (nanoparticle catalyst development and characterization; chemical conversions)
- Process and Instrumentation Development (TS) (reactor concepts)
- Optics (TS) (reactor concepts, light incoupling, optical simulations)

Expected technology line deliverables:
- Nanoparticles for efficient harvesting of sunlight
- A reactor concept for chemical conversions using sunlight
- A reaction concept: photocatalytic/photothermal chemical conversion using sunlight as energy source with an energy conversion efficiency of at least 16%
- A number of technology spin offs

(3) Thermochemical storage
On the larger scale of thermochemistry, energy can be stored in the form of heat in thermochemical materials (TCMs) and Phase Change materials (PCMs). We will not focus on PCMs, being more mature technology, which is within the focus of ECN, addressing industrial applications primarily. TCMs are salt hydrates, where heat is stored through solid-solid transitions involving hydration and dehydration, being a reversible process. Thermo-chemical materials TCMs, are most promising for stable and compact thermal storage in the medium term.

The key challenges in order to develop viable material solutions in thermal storage using TCMs are:
- energy density, i.e. decreasing volume by manipulating energy density
- stability, stabilizing TCM particles and TCM/metal interfaces
- power, speeding up (dis)charging through understanding the solid-solid transitions
- operation window, i.e. TCMs that match with process conditions (p – T window)

The targeted technology deliverables:
- The engineering principles of thermal storage hybrids/composites based on thermochemical material, creating high energy density, multicyclic performance stability, high power in charging and discharging, and tunable application window.
- The design principles for devices, components (heat exchangers in particular) and systems that optimally interact with such breakthrough materials

Targeted deliverables of the ERP technology line Thermochemical storage 2015-2018
These four main challenges and technology deliverables are to be addressed within the full eco-system that is sketched in this ERP program. Our ERP technology line primarily focuses on *salt composites* and aims to deliver an understanding on how the energy density and operational conditions of salt hydrates are influenced by confinement, i.e due to composite structures through encapsulation, hybrid salts and impurities. This is in line with core strengths within TNO in encapsulation technology, printing and spray drying technology,
energy systems in the built environment, fluid dynamics and nano fluids.

Note: Program lines 1 and 2 are most suited for large scale, central storage, whereas program line 3 is particularly suited for small scale, decentralized storage, as well as for trans-sectoral exchange of heat flows.

(4) Energy System Dynamics:
The technology of enabling a smart energy system with flexible demand management, adaptable supply and dynamic conversion and storage is still in a pilot phase (TRL3-4). In particular network operators on a regional (Alliander, Stedin, Enexis) and national scale (Gasunie, Tennet) are interested in the development of these grids, since investments in infrastructure are performed for the next 30 years. A simple question ‘’do we still need a gas grid on a regional and local level?” cannot be answered yet with certainty. TNO’s offering will include the means to answer reliability and affordability questions when implementing specific storage solutions in the system, including advice on hybrid infrastructure development. Secondly the impact of control algorithms on the integration of storage and conversion in the system needs to be determined. Combination of system simulation and optimization with control algorithms is one of the key challenges.

For system dynamics the following expertise groups and competences are involved
- DSS, PONS (dynamic modeling and control, optimalisation)
- SEM, BIS (energy system expertise, demand response technologies, simulation, software engineering)
- SBA (financial modeling)

Expected deliverables systems study:
- Technologies, tools and methods for system analysis and integration aspects of storage and conversion. With these tools we can determine the value of storage or conversion for different applications in the system, for several timeframes in the system, on different geographical levels, on centralized or decentralized level, with different control algorithms. The deliverables are used to assess technologic and potential economic impact of the storage and conversion solutions in this ERP.

5.4.3 Growing the eco-system 2015-2018
We aim to embed the ERP program in a national ecosystem on energy storage in molecular bonds, *i.e.* a partnership with TNO, TU/e Darcy Center (including the Departments of Applied Physics, Mechanical Engineering, Chemical Engineering) and FOM DIFFER as the founding partners. The first steps in setting up such an ecosystem have been undertaken in 2014, resulting in a joint understanding to explore the options to realize such ambition. The main goal is to become an international frontrunner in storage of renewable energy in molecular bonds, *i.e.* in chemical energy, leveraging know-how, and Research and Development budgets, creating an ecosystem that grows to 30 M€ annual turnover in 2020. We aim to create an inspiring environment where academic pioneers and industry leaders meet to accelerate breakthroughs in energy storage, reducing time to market of innovations. Activities will cover the range from basic concept (TRL 1) to system prototype (TRL 7).

Industry leaders from the entire value chain will be involved in an early stage. Potential multipliers and accelerators for both fundamental and applied research as well as deployment are in the exploration of the links with the relevant Topsector TKIs (see before) and joint initiatives in NWO/STW and H2020 calls.

5.5 Activities and deliverables 2015

5.5.1 Technology line Electrons-to-chemicals

The foreseen activities for 2015 are:

- Developing fundamental insights in electrocatalysis for non-standard, non-equilibrium conditions aimed at reducing activation barriers for C-C coupling
- Process design and validation for power to dimethyl ether. Work should lead to a technical and economic showcase.

Deliverables 2015:

- National overarching program on electrification
- Showcase power to dimethyl ether

5.5.2 Technology line Photons-to-chemicals

Expected technology line deliverables 2015:

- Nanoparticles for efficient harvesting of sunlight
- A reactor concept for chemical conversions using sunlight
- A reaction concept: photocatalytic/photothermal chemical conversion using sunlight as energy source to demonstrate the concept (optimization of energy conversion efficiency and towards chemicals/fuels of choice will follow on this deliverable in 2016 onwards)

5.5.3 Technology line Thermochemical storage

The foreseen activities 2015 will focus on:

- fundamental modelling of equilibrium properties of a composite thermochemical storage material. As a follow up to the initial research activity in the preceding ETP Materials Technology, this should address the thermodynamic modelling of the energy density, phase diagram and hydration phase properties of (a) selected potential salthydrate(s) under confinement (i.e. encapsulation). This focusses on delivering an experimentally verified model describing the relation between composition/structure and energy density and operational window. Theoretical and computational thermodynamics will be used, potentially supported by MD for the nanoscale. The deliverables aim to lay the foundation for tuning the operational window to process conditions, using confinement.
- exploring the options to boost the heat conductivity of confined salt hydrates composites, e.g. through expanded graphite or carbon nanofibers. Starting point will be the experimental exploration of potential candidate salt hydrates and common polymers. This activity will be alligned and interwoven with parallel PhD activities in the Mathhers program.

5.5.4 Energy Systems Dynamics

- In 2015, ESD will focus on the further development of toolkits, simulation and optimalisation of energy systems including storage solutions. A key challenge is to model the storage functions in terms of capabilities and component characteristics and include control algorithms for smart grids.

6 3D Nanomanufacturing Instruments

6.1 Introduction

The market growth of semiconductor industry has a great impact on Dutch and European economy, but also on TNO as it includes the largest non-public account of TNO. Using strategic innovation, the Netherlands has been able to keep a competitive advantage in the development of equipment and instruments for nanometer-sized patterning, manufacturing and measurement. Examples include UV-light assisted patterning (ASML) and electron beam imaging (FEI).
In order to sustain a competitive edge for the semiconductor industry, enhancing yields and reducing the cost and the time-to-market are essential. This has to be done while simultaneously maintaining reliable (nano-) manufacturing. The process geometries and device dimensions are shrinking to the level that conventional technologies currently used for production and quality control are approaching physical boundaries and will appear neither technologically nor economically feasible. Besides shrinking the critical dimensions even further, 3D scaling is anticipated to introduce new functionalities and to make optimum use of the available space, as shown by ASML in figure 1.

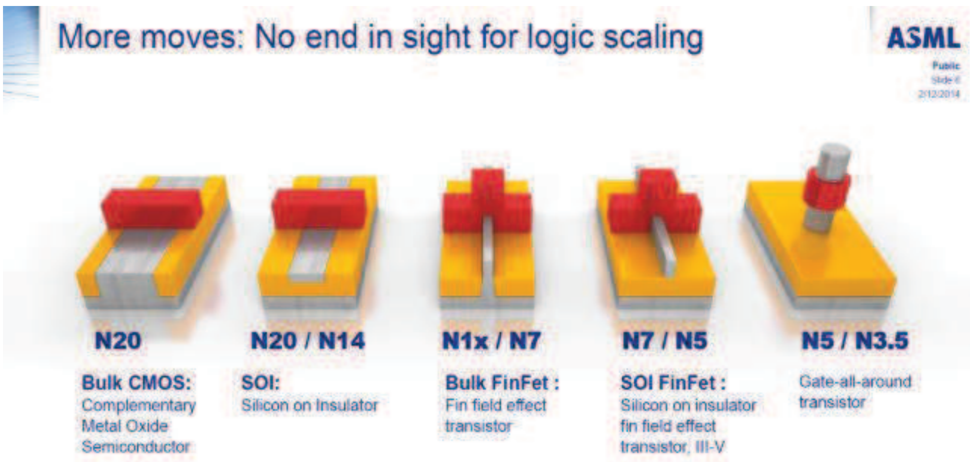


Figure 1: Transition of semiconductor devices from 2D towards 3D architectures (Courtesy of ASML).

Moreover, introduction of 3D architectures requires a breakthrough in the manufacturing process potentially based on a hybrid 3D nano-manufacturing. Only using optical/electron subtractive technologies are not sufficient to manufacture the 3D nanoarchitectures at the required scale.

Classical optical equipment do not provide a resolution at the required feature size (less than half a wavelength), while electron microscopy (e-beam Litho and inspection) faces challenges of beam size, depth of field, feature resolution, throughput and true 3D information (both for manufacturing and inspection).

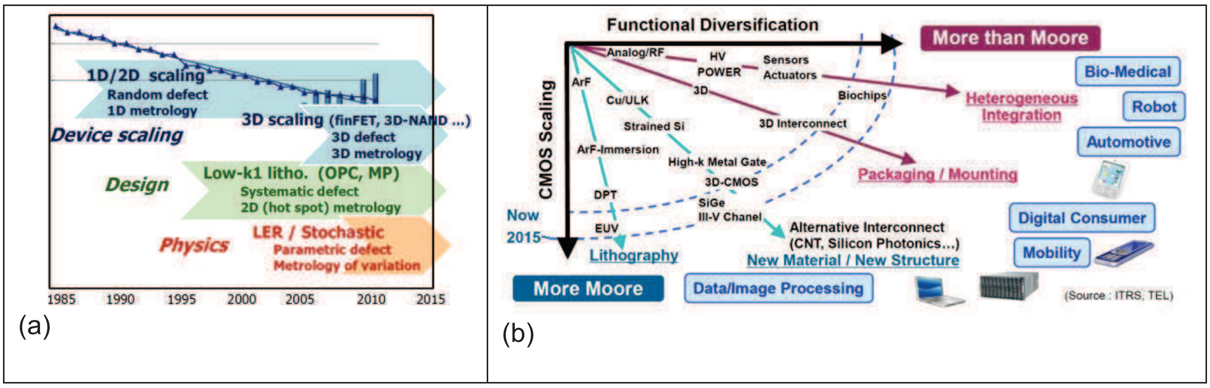


Figure 2: (a) Triple difficulties in nanomanufacturing and metrology for semiconductor industry [SPIE 2014 9050-1]. (b) roadmap of more than Moore for functional diversification (courtesy of TEL).

The growth of the nano-electronics market has been from 29 B$ in 1985 to 315 B$ in 2014 and the equipment spending will reach more than 10 B$ in 2015 (Figure 2).

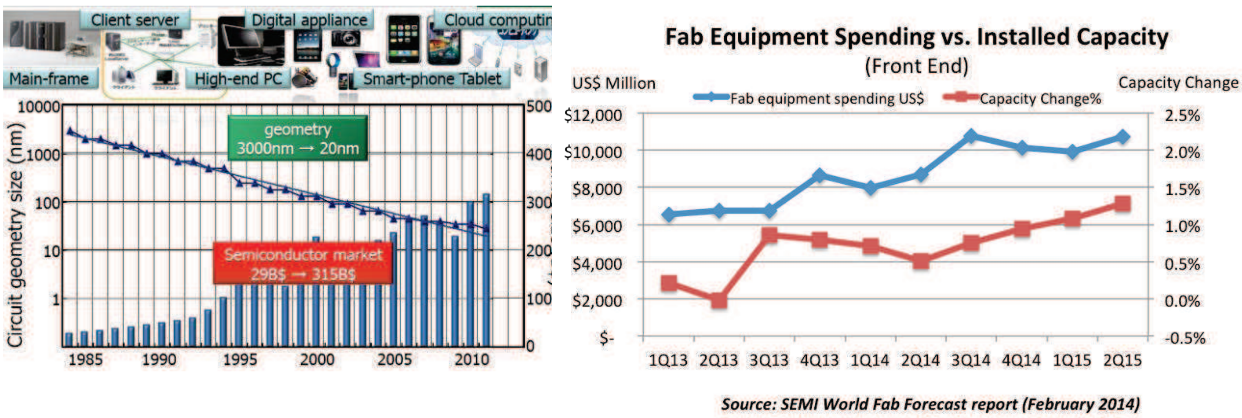


Figure 3: Semiconductor scaling and growth.

<u>Primary Use case:</u>
The primary application focus of this ERP will be on equipment and instruments for 3D "nanomanufacturing" and "nanometrology" of future 3D nano-electronics devices. The major requirements are (from ITRS):

- Very high resolution and sensitivity to be able to detect 3D structures down to ~10 nm and high aspect ratio (20).
- Very high speed of measurement on large area such as 100 cm^2 / hour.
- The ability to flexibly manufacture and resolve 3D features below 10 nm with high aspect ratio.
- Low cost per device or surface area.

<u>Cross-over use cases:</u>
To achieve focus, a single primary use case has been selected that will guide the decisions during the research. However, the technologies developed for this primary application (3D nanomanufacturing for future 3D nanoelectronics architectures) are also very relevant for the application domains below:

- 3D nano-manufacturing and nanometrology of printed large-area electronics and of photonics and photovoltaics devices. This is an important cross-over use case, as nanostructures are expected to strongly enhance light incoupling in solar cells and light outcoupling in lighting

devices such as OLEDs. Manufacturing of novel batteries with enhanced performance thanks to 3D structuring at nanoscale.
- Microwave frequency devices for Defense and Space applications to improve the performances of complex antenna systems. The fabrication and the performance of metamaterials, as an enabling technology for radar applications, is also to a large extent related to the technologies which will be developed in this ERP. Free-form 3D manufacturing of metamaterials and inspecting the shape and performance in 3D is the key challenge for this cross-over application.
- Instruments for bio-medical and health-care

4-year Target:
Proof-of-concept of technologies for 3D nanomanufacturing and nanometrology in experimental setups/hardware/built devices for the main applications mentioned above.

6.2 ERP environment

6.2.1. EU and NL perspective
The market growth of semiconductor industry has a great impact on Dutch and European economy.
In Europe, there have been extensive investments in semiconductor and nanoelectronics industries to create a competitive advantage in this market. The growth of nanoelectronics market in Europe has an important impact on the GDP and it has a high priority in the EC agenda.
Several investments by Intel in Ireland for state of the art high volume manufacturing fabs to produce leading edge nanoelectronics, with a workforce of about 4000 engineers, technicians and specialists. Global Foundries has invested about US$7 billion till today in Dresden, in Germany, with a workforce of about 3000 people. STMicroelectronics in Crolles, Infineon in Dresden and NXP in the Netherlands are other examples of successful and important Semiconductor industries. Using strategic innovation, the Netherlands has been able to keep a competitive advantage in the development of equipment and instruments for nanometer-sized patterning, manufacturing and measurement. Examples include UV-light assisted patterning (ASML) and electron beam imaging (FEI). Supply chain of ASML and FEI includes many companies in the Netherlands such as VDL, NTS, Hittech, Demcon and many other module suppliers. Obviously the growth of this market will directly impact these supply chains.

6.2.2 TNO perspective
The market growth of Semiconductor industry has a great impact also on TNO as it includes the largest non-public account of TNO. TNO aims to further expanding the business to nanometrology and inspection. TNO's ambitions are to continue helping its existing clients in this industry and further broaden and expand activities to more clients and be less dependent on only few customers. At TNO the Semiconductor Equipment program's goal is to develop solutions for nanometrology and nanomanufacturing in semiconductor market.

6.3 Eco-system

6.3.1 TNO Themes and Programs
The ERP 3D nanomanufacturing instruments is highly linked to several programs at TNO. The primary use-case of this ERP is very much aligned and matches the roadmap of Semiconductor Equipment program. The challenges of 3D nanomanufacturing and 3D nanometrology is addressed in this program and its sub-program (Yield improvement and Semiconductor Manufacturing Equipment). The cross-over use-case of printed large-area electronics and of photonics and photovoltaics devices is also highly related and linked to the program of flexible and free-form products. The technologies developed in this ERP will be highly relevant to this program. Moreover, Instruments for bio-medical and health-care, as the last but not least cross-over use case is to some extent related to the medical program at TNO. Finally the cross over Microwave frequency devices for Defense and Space applications to improve the performances of complex antenna systems is

related to the roadmaps of defence and space programs. For defence radar program, some developed technologies can be used to improve the angular scanning performances of active array antennas for radar. In the roadmap of defence it is explicitly mentioned that "We need to create disruptive technologies and applications. A potentially very promising new area is the combination of modern material science (Nano, meta-materials, graphene, etc.) into the military sensing". Space program includes developments of new concepts of polarizers and antennas at micro/millimeter wave frequencies. Some of the technologies developed in this ERP such as metamaterials and their manufacturing can be related to this development.

TNO Program	ERP link to the program
Semiconductor Equipment	The challenges of 3D nanometrology and nanomanufacturing for nanoelectronics
Flexible and free-form products	Equipment for high throughput manufacturing and metrology of 3D nanophotonics structures
Defence radar program	Improve the angular scanning performances of active array antennas for radar.
Space program	Developments of new concepts of polarizers and antennas at micro/millimeter wave frequencies. Miniature sensors and actuators for space equipment. Next generation of high performance optics.

6.3.2 National Top-Sectors

This ERP is very much aligned with several Top-Sectors roadmaps, including "Roadmap Semiconductor Equipment". All priorities in this ERP can be found back in top-sector roadmap "Semiconductor Equipment". The challenges of 3D nanometrology and nanomanufacturing has been explicitly mentioned in the roadmap as a result of "more Moore", metrology and characterization of semiconductor products become more critical since the features to be observed are becoming so small that imaging requires new technology. Moreover, regarding the nanomanufacturing, it has been mentioned that "New principles in manufacturing equipment necessary for further miniaturization (new equipment for "more Moore"), Equipment for devices with new functionality (new equipment for "more than Moore") and New principles in inspection equipment are required". This ERP is also aligned with the roadmap "Advanced Instrumentations". In this roadmap the challenge of metrology is also highlighted. The priorities of this roadmap are enabling optics and optomechatronics, which is the core of this ERP, Sensor system technology, including detector development and microwave technology, which is one of the cross-over use case in this ERP, precision technology including mechatronics and customized micro-electronics and nano-photonics, which is highly related to the primary use-case and the cross-over nanophotnics in this ERP.
The top sector roadmap "Nanotechnology" states the following application and technology challenges: Nanoelectronics and 'beyond Moore' (the primary use case of this ERP), Bionanotechnology (the cross-over use case of bio-medical and health care) and nanomaterials.

Topsector roadmap	ERP link to the program
Roadmap Semiconductor Equipment	Challenges of 3D nanometrology and nanomanufacturing has been explicitly mentioned in the roadmap
Advanced Instrumentations	Enabling optics and optomechatronics, which is the core of this ERP, Sensor system technology, including detector development and microwave technology,
Nanotechnology	Nanoelectronics and 'beyond Moore' (the primary use case of this ERP), Bionanotechnology (the cross-over use case of bio-medical and health care) and nanomaterials.

6.3.3 TO2/RTP partners
To be explored.

6.3.4 Academic partners
There are several academic partners, which their activities are linked and to some extent complementary to existing knowledge at TNO. Below are the detail description of these academic partner and their relation to TNO.

- AMOLF: AMOLF has an established position on development of metamaterials fundamentals and nanophotonics. Together with TNO a collaboration on development of nanophotonics and metamaterials for beyond conventional instrument and Photovoltaic devices has been established. A two PhD program on metainstrument has been initiated between AMOLF and TNO. AMOLF has knowledge in the field of nanophotonics. Their research program for the coming years focuses on spatio-temporal control of light at extreme limits. The role of AMOLF will be to develop fundamental knowledge regarding optical metamaterials and read-out techniques and TNO will develop ultimate instrument from this knowledge. collaborators: Albert Polman, Kobus Kuipers, Ewold Verhagen
- University of Twente: Group of Willem Vos researches on 3D nanophotonics devices. Discussion with Willem Vos and his group has been initiated for a collaboration on 3D nanophotonics structures and their nanomanufacturing processes.
- TU/e: Collaboration on development of knowledge for dynamic design rules (via PhD research) has been started since two years ago and will continue (Maarten Steinbuch) . The collaboration will result in developing design rules based on the dynamic insights to improve the effective bandwidth of the systems wile high accuracy is guaranteed. Moreover, several collaborations on metamaterials modeling/design (Giampiero Gerini) are ongoing (1 PhD funcded by TNO, 1 PhD proposal supported by TU/e impulse program).
- TU Delft: Collaborations on several topics with TU Delft, department of Precision and Microsystem Engineering (PME) and DIMES have been established. Hamed Sadeghian is part-time academic staff at PME. Fred van Keulen is the collaborator. Two PhD projects in collaboration with TNO are ongoing. Several MSc students are persuading their project as a collaboration between TUD and TNO. A new PhD project on meta-instrument via shared cost between TNO and TU Delft has been started. With DIMES a collaboration on integrated optomechanics devices is going on.
- High Tech Institute (TU/e): An informal discussion on possible collaborations has been done. Further discussions and agreement need to be followed.

6.3.5 EC H2020 opportunities
In H2020 program there are several areas which directly or indirectly target the nanomanufacturing and nanometrology. Nanotechnology including nanometrology and nanomanufacturing and focus on nanoinstruments have been identified as key enabling technologies (KET). Moreover, industrial leadership is recognized as one of the highest priorities and 22% of the total budget is allocated to this priority for nanotechnology, material and manufacturing processes. Another area which is linked to this ERP is integrating and opening research infrastructures of European interest (Advanced frontier research in nanoelectronics). Funding will be provided to support, in particular, the trans-national and virtual access activities provided to European researchers, the cooperation between research infrastructures, scientific communities, industries and other stakeholders, the improvement of the services the infrastructures provide, the harmonisation, optimisation and improvement of access procedures and interfaces.

There are several EU proposals that have been or in the process of being prepared:

- Proposal for the EU FET Proactive Call: Nanoarchitectronics. The main objective of the nanoarchitectronics paradigm is to overarch future researches in Electromagnetism from Microwaves to Optics through a visionary and synergic approach which is grounded on the extraordinary light-matter interactions at nanoscale.
- Seven Nanometer Technology (SeNaTe): The main objective of the SeNaTe project will be the demonstration of the first 7nm IC technology integration on real devices in the Advanced Patterning Center at imec using innovative device architecture.
- E450LMDAP: has already been granted, TNO will develop a nanometrology demonstrator for EUV masks and develop a demonstrator for hybrid metrology.

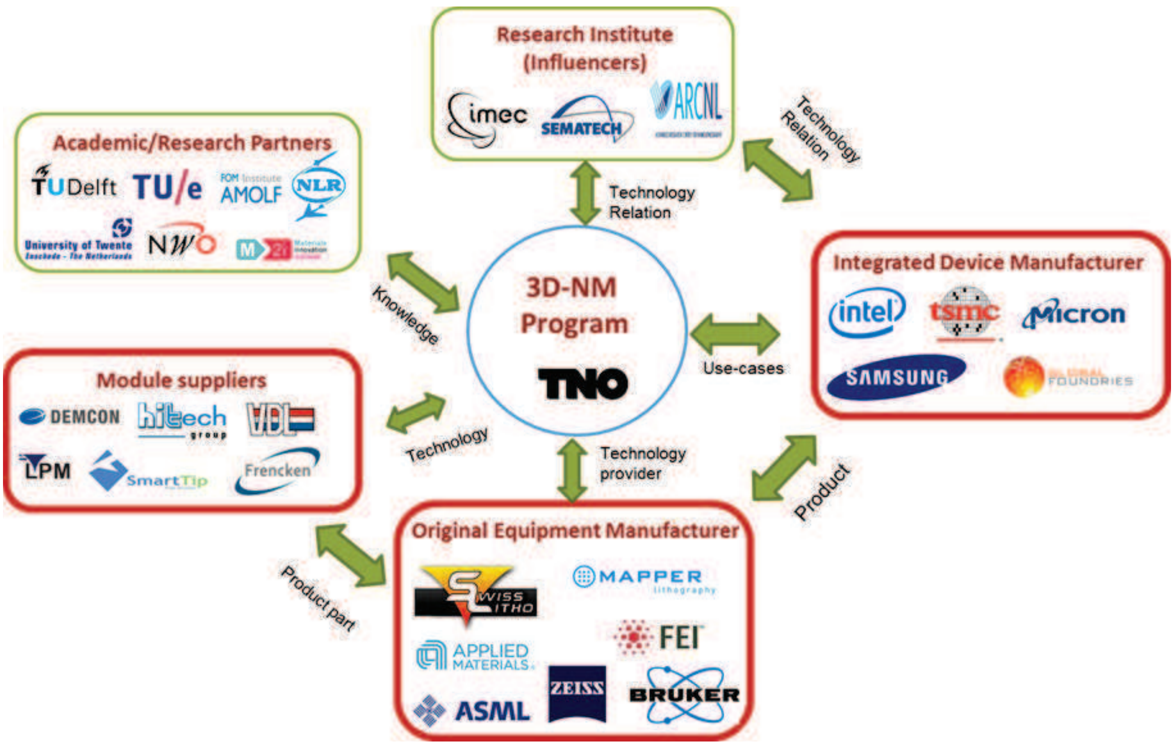


Figure 3: Envisioned Knowledge and Business Eco-system of the ERP 3D nanomanufacturing.

6.4 Research and Technology lines 2015-2018

This ERP aims to realize novel type of instrumentation concepts for highly sensitive, fast, nanoscale-resolution 3D manufacturing and inspection/imaging (3D-Microscope). The prospect of this technology is high-throughput / low-cost manufacturing and metrology of 3D nanofeatures (Primarily for Nano-electronics) on wafers or any large substrate. The work packages of the program and the flow of the activities is shown in figure 4.

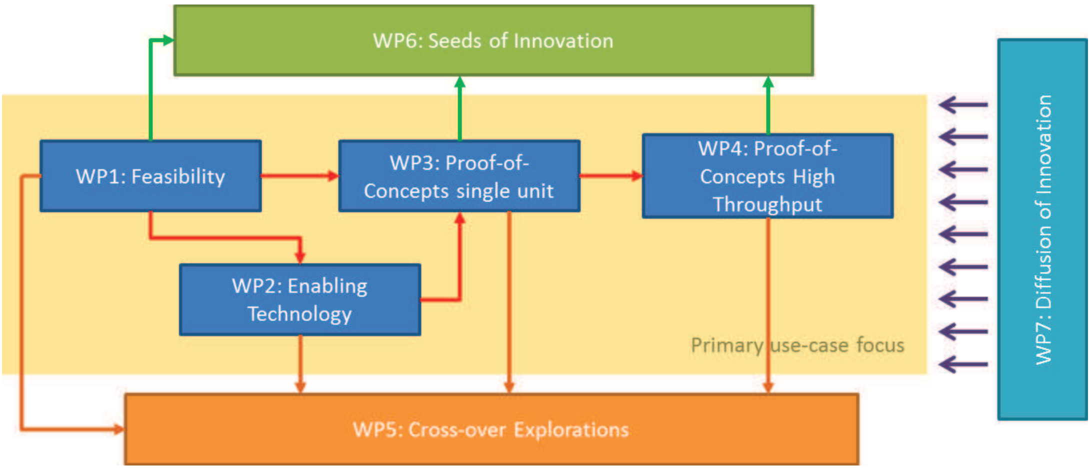


Figure 4: Work flow of the program.

Work Package1: **Technology assessment and feasibility** (State-of-the-art and knowledge gaps)
In the first phase, we will critically assess several potential technologies (most of them have been developed in the ETPs and other knowledge development programs) which are suitable for the aforementioned use-cases.
Technologies which will be considered in this WP:

- Scanning probe instruments (including High throughput atomic force microscopy, scanning capacitance microscopy, scanning nano-ultrasonic microscopy and near field heat radiation microscopy), Optical metamaterials (coupled plasmonic scatterers and plasmonic waveguides), and solid immersions.
- *Towards 3D-nanomanufacturing (bottom-up, hybrid nano patterning):* Photon and electron assisted nanoprinting, scanning probe nanomanufacturing and patterning (Dip-pen Litho, probe based resist activation and atomic manipulation). The role of TNO here is to take fundamental knowledge from partners, further research on their feasibility for 3D-nanomanufacturing and translate it to what is required by the use-cases.

<u>State-of-the-art and knowledge gaps:</u>
Scanning probe instruments: This technology has shown to be capable of nanometrology with sub-nanometer resolution as well as capabilities for nanomanufacturing and nanopatterning. Moreover, this family of instruments are already used in semiconductor industry at the research and ramp-up laboratories. However, the speed and thus the throughput of the measurement is very low to be used in in-line applications. TNO has developed several technologies in order to enhance the throughput to the level of acceptance by industry. The current SPMs are not yet capable of real 3D measurement (2.5 D). Further development is needed to develop SPM for real 3D measurement for negative-slope features (undercut) and high aspect ratio measurement. Due to finite size of the tip, very small trenches (< 14 nm) cannot be measured currently. TNO has started the developments on special tip manufacturing process for sub-20 nm teach measurement.
Optical metamaterials: Optical metamaterials, made from sub-wavelength metallodielectric building blocks exhibit unusual optical properties, to allow nanoscale resolution through sub-wavelength confinement of light fields. Moreover, metamaterials can be nanomechanically compliant, such that their optical response can be actively and rapidly tuned through electrically or optically actuated nanomechanical displacements. This could allow the simultaneous and fast scanning of many sub-wavelength sensing volumes in a massively parallel fashion. Hence, our primary goal is to develop the technology to realize an instrument based on nanomechanically reconfigurable metamaterials for fast, sensitive, and massively parallel optical inspection with nanoscale resolution. Moreover, the very same systems allow – in a reciprocal fashion – also efficient transduction of nanomechanical motion to optical signals.

Deliverables: Assessment of different 3D nanomanufacturing and nanometrology technologies with experimentally proof of principles which verify the suitability of the technologies for each of the use-cases. The developed technologies will be secured by IP.

Work Package 2: Enabling technologies 2015-2018
Enabling technologies that need to be developed (depending on the results of WP 1):

1. Advance Motion Control and Dynamics Principles
   i. Dynamic design rules
   ii. High performance, robust control of nonlinearity
   iii. High performance, robust control of instability

The classical ways of design based on statically determined design rules are running against their limits, in the sense that these higher system performance requirements can hardly (or not) be met. The developments on dynamic design rules for faster and more accurate designs, which started in ETP Optomechatronics has to be further developed to achieve the requirements on speed and accuracy.

2. Nano-Opto-Mechanical systems
   i. Optical metamaterials, manufacturing and read-out
   ii. Near-field Physics
      a. Near-field Acoustics
      b. Near-field Thermal
      c. Near-field Optics
   iii. NanoMechanics
      a. Advance SPMs (read/write)
      b. Nano-mechanical systems

Functional integration, with the use of functional materials is considered as an enabling technology for this ERP. Examples are the use of optical metamaterials for beyond wavelength imaging and acoustic/mechanical functional materials for enhancing the dynamic and mechanical response (achieving higher stiffness and tuning the damping and quality factor of the instrument).

3. Free-form Physics and manufacturing
   i. Topology optimizations & Additive Manufacturing
      a. Eigen frequency (mass/stiffness)
      b. Thermal management
   ii. Acoustic/mechanical Metamaterials & Manufacturing

Topology optimization techniques for free-form mechanics design and addressing the system integration at an early stage in combination with additive manufacturing might be sued for multi-scale manufacturing of the components.

4. System Architecture

The final target of this ERP is to demonstrate the proof of principles of instruments. Therefore the role of system architecture activities is crucial to take into account the system approach, and sufficient attention to reliability, repeatability of demonstrators, ultimate accuracy and speed.
The system architecture activity makes sure that the enabling technologies will be developed with sufficient focus on instrument and not as an isolated activity.
Each technology line, besides the deliverables in terms of hardware/demonstrator/documents, articles and patents have to be published and filed.
A budget for the professorships which are directly linked to one or more technology lines and can clearly contribute to will be allocated.

Work Package 3: Proof of concept by a single fabrication or metrology unit
Based on the results of WP 1 and 2, and taking into account the actual demands in the semicon market, a decision will be taken on the type of unit of which the proof of concept will be built in WP3.

Work Package 4: Proof of concept high throughput demonstrator
After delivering proof of concept for the required technology, scalability will be demonstrated (substantiating that required throughput can be achieved.

Work Package 5: Exploration of cross-overs to other use-cases
As indicated above, the technologies developed in this ERP can be applied or developed further to several cross-over domains. During the course of this program, we will actively bridge the developed technologies to cross-over use cases.

Work Package 6: Seeds for innovation
During the technology developments in this ERP, definitely many new promising side-ideas will be generated which may not be essential for the primary goal of this ERP, but which can lead to new adjacent research domains and applications.

Work Package 7: Diffusion of innovation
In this work package, the business ecosystem and the valuation of the innovation for other cross-over use-cases will be worked out. This work package is also considered as a bridge to the project "Orchestrating Innovation" within TNO.

Growing the eco-systems 2015-2018:
The economic target of this ERP is to generate ShIPs around the primary use case together with several international players, Dutch players and academic partners. Each of the ShIPs will have several adjacent B2Bs. Obviously for the use-cases that there is no existing ShIP, the effort will be to develop one, and for the cross-over use cases which there is already a ShIP, the technologies developed in this ERP will be transferred and embedded in the related ShIPs. For 3D nano-manufacturing and nanometrology of printed large-area electronics and of photonics and photovoltaics devices the developed technologies will be transferred to Solliance and Holst programs as existing ShIPs. For the cross-over use case Instruments for bio-medical and health-care the developed technologies will be transferred to van 't Hoff program, as the existing ShIP.

6.5 Activities and deliverables 2015

The plan, activities and the deliverables during 2015 are discussed below.

***Work Package1:* Technology assessment and feasibility** (State-of-the-art and knowledge gaps)
In 2015 several technologies will be critically assessed to judge the feasibility of them for the target of this ERP. This includes:

1. Critical assessment of different Optical metamaterials for compact light control (focusing/steering): towards high resolution imaging and writing:
   - Flat lenses based on coupled scatterers;
   - Super-oscillatory lenses;
   - Hyper-lenses;

An important parallel activity to optical metamaterials is to study the optical systems (coupling light and readout) that will be required for the different metamaterial lens concepts.
Moreover, material physics modelling will be carried out to support the assessment and the feasibility of the metamaterial based optical components.

The overall assessment study will identify two most promising concepts to be further studied in WP2.

2. Critical assessment of other near field effects, especially nano-ultrasonics microscopy for 3D microscope: The use of high frequency, near field ultrasound/ultrasonics probe microscopy for sub-surface microscopy has been shown in academia. We will critically assess this technology towards a practical instrument. The technical challenges are ultimate resolution in lateral and depth, signal to noise ratio and the loss of signal, applicability for the primary use case and the crossover use cases, short and long term applications.
3. The use of acoustic/mechanical metamaterials for high performance mechanical systems, such as tunable damping, higher stiffness and lower mass. The manufacturing of these materials, which most probably will be based on 3D printing will be assessed.

Work Package 2: Enabling technologies

1. Dedicated design of the most promising concepts identified in WP1, aiming at design towards the final instrument. The design will take into account material characteristics, manufacturing tolerances, Integration challenges dictated by the system.
2. The most promising design will be verified experimentally:
   - manufacturing
   - testing of hardware demonstrators. The experimental verification will include first a characterization of the concept and then the use in a simple feasibility system.
3. An accurate analysis of the experimental results will be used to identify correction actions both from the design, manufacturing and testing point of view. This will used to define the development plan for 2016.
4. In order to achieve high performance instrument (accuracy x speed) the dynamic principles will be assessed within each instrument use case. Via system architecture activities, several ultimate type of instrument wish will be identified, then for each case, the dynamic design principles will be developed to maximize the performance of these architectures.
5. The Physical methods explained above such as near field acoustic microscopy, scanning prove microscopy or meta-instruments have the characteristics of nonlinear and suspect to instability. High performance, robust control methods will be developed for these methods.
6. Free form mechanics based on topology optimizations and additive manufacturing will be essential components of these instruments. Because one of the target is functional integration, miniaturized sub-systems, one enabling method is the use of topology optimization and consequently manufacturing with additive mthods.

Work Package 3: Proof of concept by a single fabrication or metrology unit

No activity will be done yet for this work package

Work Package 4: Proof of concept high throughput demonstrator

No activity will be done yet for this work package

Work Package 5: Exploration of cross-overs to other use-cases

An eye will be kept open for the applicability of the enabling technologies for the aforementioned cross-over use cases.

Work Package 6: Seeds for innovation

Some time will be reserved to explore new promising side-ideas which will pop up.

Work Package 7: Diffusion of innovation

Some time will be reserved for the work-package diffusion of innovation. In this work package, the business ecosystem and the valuation of the innovation for other cross-over use-cases will be worked out. This work package is also considered as a bridge to the project "Orchestrating Innovation" within TNO. There are several critical questions that need to be answered:

1. What is the most optimum business model/path for this ERP?
2. The ecosystem of this ERP is highly a global ecosystem (although there are several strong Dutch players) and at the same time our goal is to create impact on Dutch economy. Therefore a very clear policy is needed. The situation is to a large extend comparable to the Holst ecosystem.

7 Structural Integrity

7.1 Introduction

Our modern society is depending on the existence and availability of complex infrastructure. Important critical infrastructure is indispensable in the supply chain of energy, in transportation and in protection against water flooding. Massive investments in critical infrastructures have been made to reach the current level of economic and social development.
The integrity of this infrastructure is becoming a serious issue. Most of our transportation (infra)structure has been built in the years 60-70 (water management structures on the average 30 years earlier) and approaches the end of design life time. Moreover, loads are increasing (varying from heavier traffic to more extreme climate events). Offshore structures and wells are regularly exposed to extreme conditions. Other infrastructures like gas production wells, are going to be used for a different purpose as originally designed for, such as CO2 storage. In all these cases, structural integrity can no longer be taken for granted.
Premature and unpredictable failure of structures , with undesirable and unacceptable consequences can be disastrous for industry and society. However, in many cases inspection is difficult or even impossible today because defects are embedded deep in the material or structure. And our ability to forecast a structure's integrity is limited because our understanding of the process of degradation and its impact on the structure is still limited. With this state-of-the art, maintenance costs are sharply increasing, and proper levels of maintenance are under threat of becoming unaffordable. Condition-Based Maintenance (CBM) based on monitoring and forecasting the integrity of structures, is the most effective way to safeguard structural integrity while reducing maintenance costs, maximizing the "up-time" of the structures and allowing utilisation in a different way than a structure was originally designed for. The required knowledge can also be used at the design stage to minimize the total life cycle costs of assets.

The successful development of a CBM capability will require the further development and integration of many technology areas including non-destructive measurement, sensing/data processing/telemetry, and a variety of deterministic and probabilistic predictive modelling capabilities with the ability to quantify the uncertainty in the predictions. The multi-disciplinary and challenging nature of the problem, its current embryonic state of development, and its tremendous potential for safety and economic benefits qualify CBM as a 'grand challenge' problem in the twenty-first century. This ERP Structural Integrity aims at breakthroughs with respect to this grand CBM challenge which enable:
"detection and monitoring of (precursors of) degradation inside steel/cement/concrete structures"
and use this information for
"diagnosis of their structural health and forecast the service life for various intervention options"

The program will have wide application for maintenance of large structures, in particular in the *transportation infrastructure* and the *energy production infrastructure*. The technology developed will initially be directed at the following three use cases (for each test of the technology will be organized with stakeholders in the field concerned- see sections 6.3.3 and 6.4.3):

1. Concrete (rail)road supporting structure (steel reinforced bridge) integrity
2. Offshore wind structure integrity
3. Well integrity for sustainable energy supply.

7.2 ERP environment

As discussed in the introduction, maintaining structural integrity is a major societal issue for which technological breakthroughs are needed. The societal issue is further illustrated in section 2.1, while TNO's capabilities to contribute important solutions are described in section 2.2.

7.2.1 From the Netherlands and the worldwide perspective
Affordable high quality maintenance is needed for the asset management of our transportation and water infrastructure, and a precondition for the introduction of substantial offshore wind energy and large scale underground storage as part of a sustainable energy system.
The transportation and water infrastructure in the Netherlands only has a value of several 100-s billion euro and the yearly expenses for maintenance and repair is estimated to be 6 billion euro/year. The issue in countries such as Germany and the USA is of a similar type, partly more severe and concerns a much larger number of objects so that the budgets involved are orders of magnitudes bigger. For the USA the annual cost of corrosion of reinforced concrete bridges only has been estimated to be over $8 billion, and the indirect cost to the user resulting from traffic delays and lost productivity can be more than 10 times this direct cost.
Several countries (UK, Germany, Netherlands) heavily invest in offshore wind energy. The EU target is to have 43 GW in operation by 2020 (2014: 7 GW). About 10% of the operational costs relate to maintenance of the structures. A crucial condition for realizing the targets is that the costs of offshore wind energy, among which the maintenance costs, must be reduced with 40% (TKI Wind op Zee).
Gas production will decline in the decennia's to come. The cost of safe abandonment of the wells will be very high. However re-use of the current wells for geothermal energy, energy storage or CO2 storage are emerging options of growing interest. New hybrid large scale energy storage can contribute to the goal of generating 16% renewable energy by 2023 as stated in the "Energieakkoord" and developing the NL as the Gas Hub of NW Europe. Reliable integrity information and predictive lifetime modelling is essential for safe operations of these wells for their new usage and prevention of environmental risks.

7.2.2 From a TNO perspective
TNO has high a level of expertise in the fields of **advanced sensing and inspection technology** (intelligent imaging; ultrasonic -guided wave- systems; acoustics (sonar) and radar; fiber optic sensors; distributed sensor systems; data management platforms connecting sensor data to models) and **(multi-scale, multi-physics, probabilistic) modelling for predicting (future) structural performance** (material -concrete, steel- models and degradation mechanisms; transport in porous media -concrete, coatings-; structural response and failure models; connecting large scale -time, space- to small scale; combining various –physical and chemical- causal factors, incorporating stochastic nature of variables; user interface of models for end users). In the period 2011-2014 work in this field was done in the Enabling Technology Programs Adaptive Multi-Sensor Networks (ETP AMSN) and Models (ETP Modellen). On the one hand, results from these programs are now being put into practice with stakeholders, while on the other hand they provide a general basis to build on for this program and specific results with respect to monitoring and modelling of cracks in steel structures are useful staring points for specific developments in this program. TNO has relevant experimental facilities (Bouwlab, Structural Mechanics lab, acoustic sensor lab, fiber optic instrumentation lab), has experience with a living lab on the Van Brienenoordbrug, Koninginnebrug and IJkdijk, and has its IT platforms Anysense and Urban Strategy. Apart from having a high ranked position in several of the above specialisms, the combination of the specialisms and facilities plus the connection with the stakeholders in the relevant sectors is worldwide rather scarce so that TNO has a very good position for realizing the breakthroughs needed.

7.3 Ecosystem

7.3.1 TNO Themes and Programs

This ERP develops important technology for the TNO theme Urbanisation (roadmap Buildings and infrastructure) and the theme Energy (roadmap Maritime & Offshore and roadmap Geo Energy). Methods and techniques that will be developed are also relevant for protective structures so that there is an important relation with TNO Defense, Safety and Security (Roadmap Force Protection). The focus in the ERP is on the structural integrity of large scale structures. However, some of the expertise that will be developed is also relevant for small scale structural integrity issues of electronic devices and components dealt with in TNO Industry.

7.3.2 National policy including TopSectors

EZ, Rijkswaterstaat, ProRail, provinces, water boards and municipalities. This ERP's activities concerning civil infrastructure are directly linked to the innovation needs that Rijkswaterstaat identified for the period 2015-2025 (Innovatiebehoefte in beeld. Innovatieopgave Rijkswaterstaat 2015-2025; 27 September 2013) and similar needs that exist with ProRail, provinces, water boards and municipalities. Offshore wind and energy storage are important in EZ's energy policy and included in 'Energie akkoord voor duurzame groei'.

TopSectors. Water infrastructure and safety is an important issue in Topsector Water- TKI Deltatechnologie. It is the ambition of the Topsector Energy to have 14% energy produced by sustainable sources by 2020 at the lowest possible costs. Offshore wind energy will play an important role in that ambition. Therefore the focus of Topsector Energie - TKI Wind op Zee is reduction of the cost of offshore wind projects by 40% in 2020, compared to 2010. Topsector HTSM-roadmap ICT identifies monitoring and control systems as an area for development of high tech systems – an area that this ERP addresses by developing monitoring systems for structural integrity.

7.3.3 Ecosystem with Industry, Academia and RTOs

This section describes the relevant partners for an ecosystem on structural integrity. The development of the ecosystem is described in section 4.3.

CBM is attracting the attention of a variety of stakeholders. Frontrunners from the complete chain will be involved in the ecosystem: steel/concrete industry, sensor industry, monitoring/inspection companies, engineering companies, contractors, owners/operators, covering the spectrum from hardware developers to end users and asset managers.

An important aspect of creating the ecosystem is bringing together this value chain from industry with academia and RTOs. From the following network partners the most important peers will be involved: University of Cambridge, CSIC (UK)- sensor, monitoring, visualization; TU Delft (NL)- IS2C program, materials, sensors, modelling (already existing cooperations with i.a. TU Delft are InfraQuest, DuWind, Delphi consortium); TU/e (NL)- materials and structures; ECN (NL)- monitoring; Deltares (NL) – structural health modelling; Bundesanstalt für Materialforschung und -prüfung (D) - materials, sensors; BASt /Univitat Lübeck (D)- data analysis, decision support; MIT (USA)- modeling, materials, fiber optics; ETH Zurich, University Kiel: monitoring with AE; Universities Toulouse, Chalmers, Stuttgart, Milano, Trondheim - structural modelling and validation; University Gent, Polytechnic University Torino - probabilistic modelling; Aalborg University (DK)- probabilistic approaches in offshore wind; Fraunhofer (D)- material models; ultrasonic sensor arrays and structural health monitoring.

7.3.4 EC Horizon 2020

Transportation and water infrastructure and the transition towards a sustainable energy system are important issues motivating research calls in Horizon 2020. At present TNO is partner in many European Framework projects in these areas, and this will have follow up in Horizon 2020 because the issues have been identified to be important by stakeholders and the EC.
The European technology platforms are consulted by the EC on the issues for Horizon 2020.The

European Construction Technology Platform (ECTP), the organization of industry and research in the construction sector chain (among others TNO), has put forward transportation infrastructure maintenance as an important issue. ECTP has presented its view in this area in the ReFine roadmap. CEDR, the European organization of road authorities, also advocates maintenance as an important issue. The European Wind Energy Technology Platform (TPWind), the organization of industry and research in the wind energy sector, identifies maintenance of offshore wind structures as an important issue in its strategic research agenda. Furthermore, the European Strategic Energy Technology Plan (SET-Plan) considers offshore wind energy and energy storage to be important components in the future sustainable energy system.

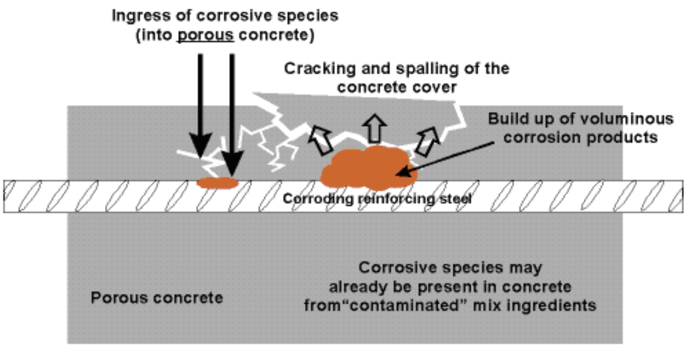
7.4 Research and Technology lines 2015-2018

This program will have wide application for maintenance of large structures. The technology developed will initially be directed at the three use cases mentioned in the Introduction. These uses cases will be described in section 7.4.1 before the description of state-of-the-art of the relevant technology in section 7.4.2. A field test of the technology will be organized with stakeholders for each use case, which will be the core around which an ecosystem is grown, as described in section 7.4.3.

<u>Use cases</u>

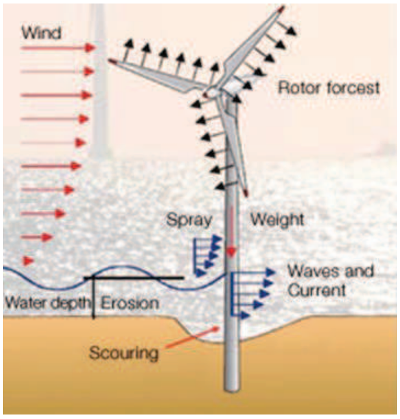
Steel reinforced concrete bridge integrity
Steel reinforcement corrosion is the most important degradation mechanism for reinforced concrete (rail)road supporting structures such as a bridge, viaduct or overpass. Due to corrosion, an affected bridge component gradually deteriorates and, as a consequence, the structural integrity of the bridge declines so that the remaining service life decreases with the progress of degradation. Corrosion of reinforcement in concrete comprises the following two stages (see figure):

- a first stage involves the transfers of aggressive agents (mainly carbon dioxide and chloride), water and oxygen, inducing the corrosion initiation;
- a second stage of corrosion growth starts when depassivation of the reinforcing steel has been achieved due to the contents of aggressive agents close to the reinforcing steel and leads to concrete damage (cracking, spalling) and steel-to-concrete interface degradation (de-bonding) .



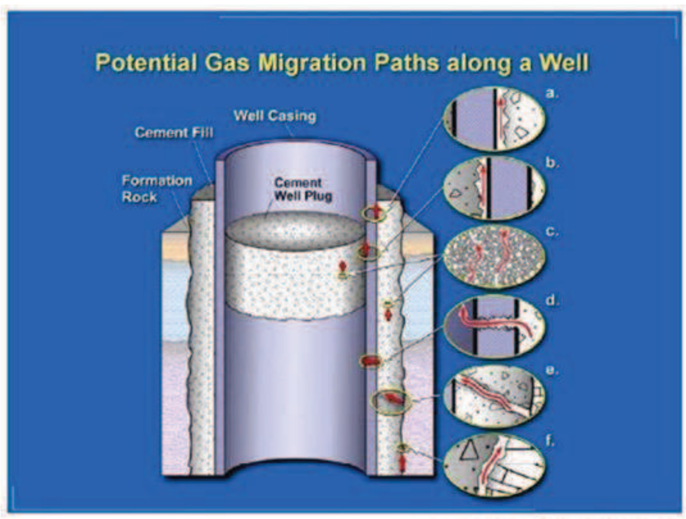
Offshore wind structure integrity

Offshore wind structures must survive in a harsh environment with dynamic loads (wind, waves, current), chemical loads (salt sea water)and microbiological loads (see figure). Important contributors to offshore structure degradation are corrosion and fatigue, and especially their combination. Fatigue degradation accelerates in the corrosive sea environment. When a fatigue crack grows, it may reach its critical length with a sudden fast crack growth that can result in large reduction of the structural integrity or failure of the structure.



Well integrity

A well casing has a telescope design to be able to reach the required depths up to 5 kilometers, with a stack of pipes with increasing diameters and cement to fill the annulus between the pipes and formation (see figure). The main purpose of the casing and cement is to prevent leakage between zones, i.e., to obtain 'zonal isolation'. The failure modes are diverse and complex. Several leak paths are possible as shown in the figure. These leak paths can develop from different mechanisms of degradation, chemical (Cl, H2S, Co2, etc.) and/or mechanical due to formation movement. Both cement and steel can be affected. The degradation rate is affected by the down hole conditions such as temperature, pressure and mechanical load.



Source: Alberta Energy Utilities Board

7.4.1 State-of-the-Art

Typically, a condition survey is done by visual inspection or traditional NTD techniques, often involving a time-based norm to define when to measure or inspect. Major shortcomings of these techniques are that they provide mainly surface information and very limited information on defects of the inner parts, their limited accuracy and sensitiveness to (human) errors. The available advanced sensor techniques are often not well-fit-for-purpose, quite difficult to handle and relatively expensive, especially when used for existing structures. Last but not least, determination of the appropriate KPI (key performance indicators) for condition monitoring is far from being straightforward, often leading to unsatisfactory setups for gathering condition information.

Assessment of structural integrity using the limited condition data is currently performed with standard models with rather high model uncertainty. Acceptable assessment methods are basically only available for new structures as the models are often lacking the capability to take into account the active deterioration mechanisms and progressive damage as well as information from monitoring the deterioration. The damage progress and performance drop for certain essential degradation/failure mechanism, the measurement thereof, and the load effects for these mechanisms are not yet adequately captured in models.

For adequate condition evaluation it is essential to capture the time-dependent effect of various treatment scenarios including preventive, remedial or strengthening interventions or load restrictions. At this moment condition evaluation methodology for existing infrastructure does not enable doing so. In particular, predictability of effectiveness and durability of repair and rehabilitation methods for existing structures in terms of recovery of structural performance is often unsatisfactory. Hence, accuracy of post-intervention performance prediction is often unacceptably low.

7.4.2 Technology lines 2015-2018

It is important that the sensing and inspection technology as well as the models for structural integrity are developed in this single program. The output of sensing and inspection is input for modelling. Hence, the input data that models require and the information that sensing and inspection can produce must fit. This fit will get constant attention.

<u>Advanced sensing and inspection technology</u>

Advanced acoustic sensing, fiber optic sensing and sensor system design and usage tools will be developed for monitoring loads and degradation in all three use cases. The development will be partly tuned to different requirements of the use cases.

(1) Acoustic sensing technology to measure the inner material for defects

Acoustic emission (AE) sensing will be further developed for monitor cracks and corrosion in steel structures and monitoring (global) structural behavior related to structural failure mechanisms such as bending, shear, torsion, de-bonding etc. (e.g. in combination with real-time FEM analysis for structural assessment). Multi-component AE sensing may enable a more detailed identification of the deterioration involved.

Quantitative information on defects such as corrosion possibly can be obtained with active acoustic sensor systems as those based on guided-waves. Guided-wave tomography is capable of mapping local wall loss, but due to the relatively large wavelength it is not capable of imaging individual corrosion pits. Generalizing this measurement concept by including wave modes that are capable of imaging corrosion pits while not being affected by local wall loss provides a more comprehensive integrity assessment.

The heterogeneity of the materials involved and the surrounding materials and the huge differences in the material properties, cause acoustic imaging to be a major challenge. However, only detection with acoustic signals is sufficiently promising, but even acoustic waves suffer from the large contrasts present, leading to multiple reflections and complex, multi-modal wave signatures, dispersion, low signal-to-noise levels, wave conversions, etc. These effects obscure the information to be retrieved

from the acoustic recordings. Moreover to ensure sufficient penetration e.g. for application in wells, a fairly large wave length needs to be used, meaning that the features that need to be detected are in the order of the wavelength of even smaller. Such challenges push acoustic sensing to its limits. So far in TNO we have developed active acoustic sensor systems based on either reflection (imaging) or transmission (tomography). However, a combination of reflection and transmission is expected to improve the results. Note that indeed this increases the number of recording channels and amount of sensors required.
Acoustic inversion technology strongly relies on the availability of acoustic transmission/reflection models that model wave propagation both accurately and efficiently. Our current modeling technology (3D finite-difference, full elastic modeling, multi-modal) is rather accurate already. However, several major limitations have not been solved yet: (1) it is inherently unstable in the case of large contrasts such as present in well materials, (2) it is based on linear acoustics, whereas reality is non-linear, and (3) it is extremely computationally expensive. E.g., our current software may run for weeks to compute a single case. Inversion technology is based on tens of iterations, which would take years with our current state-of-the-art software. It is our aim to develop efficient-yet-accurate modeling technology that solves the above mentioned issues related to stability, linearity and computational efficiency.

*(2) Multi-*parameter *fiber optic sensing to measure loads and the inner material for defects*
In the last decades, fiber optic sensing has gained increasing acceptance for multi-parameter sensing, over long distances and in harsh environments. There are two main classes of fiber optic sensing technology: distributed sensor and (multi-)point sensor. Current developments are Distributed Strain Sensing (DSS) and Distributed Acousting Sensing (DAS). Among the different point sensor types, Fiber Bragg Grating is most widely used due to its commercial availability and the unique multiplexing potential. The latter feature enables the development of large sensor arrays and/or sensor networks for multi-parameter sensing, e.g., to measure temperature, strain, pressure, vibration, flow, etc. Different types of fiber optic sensors can be manufactured and integrated in a single optical fiber for multi-parameter sensing. Data from the different types of sensors will be merged and processed through special data mining algorithms to generate unambiguous information. Both classes of fiber optic sensors have their specific advantages.
The main parameters which can be used to monitor structural integrity are: strain, pressure, humidity, chemicals concentration, thermal conductivity and temperature distribution, mechanical vibration, flow. The current TNO chemical sensor is based on a polymer coating. On the basis of these parameters, optical sensors systems will be developed for monitoring various loads, leakage, corrosion with MIC as special case, bonding state and open space in/between materials, and/or deformation.

(3) Design and usage of sensor system
To optimize the monitoring strategy both temporally and spatially, the concept of Value of Information will be further developed for assessing whether an inspection and/or monitoring strategy is actually beneficial – before it is implemented. The forecasts will be established through probabilistic structural models accounting for the uncertainty associated with future structural performances, the uncertainty associated with the relationship between monitored performance indicators and life-cycle costs, reliability and safety as well as the uncertainty associated with the precision of the monitoring techniques.
Tools will be developed to optimize the placement of (a minimum number of) sensors/inspection points, the sampling rate, and the data reduction of recordings. The optimal sensors system that is aimed for is hierarchically organized with global sensors having a wide detection range but not necessarily giving very detailed information which scan the complete structure, and sensors giving detailed information that can be placed at spots where (a precursor of) deterioration has been detected. Specific issues to be addressed in the development of the sensor systems are: wired or

wireless, in case it is wireless how much of the processing must take place locally; service life, robustness and ease of installation of the sensors/system.
Optimal condition survey involves sensor fusion systems combined with advanced modelling and simulation techniques. Heterogeneous multi-sensor data fusion systems for assessment and evaluation of ‘load and service history’, degradation and structural performance will be designed and applied. Sensors generate an enormous amount of information that is only partially relevant so that the amount of data needs to be reduced without deleting essential information, to feed that into the condition assessment. The ambition is to develop a framework to reduce sensor output data and to evaluate and expand sensor information to the structural integrity and service history of the complete structure.

<u>(Multi-scale, multi-physics, probabilistic) models</u>

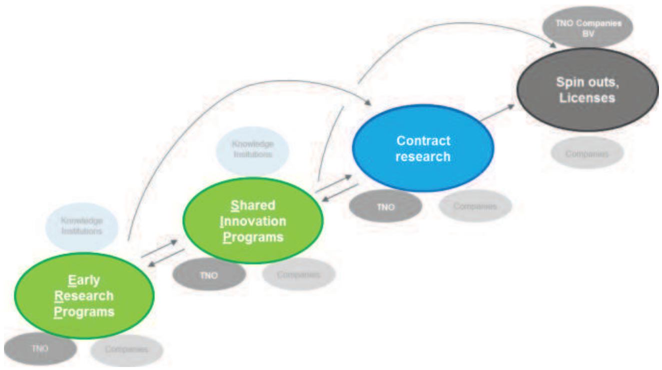
(1) Transport, corrosion and de-bonding
Models describing the intrusion of chloride and carbon dioxide (both individually and combined) through the concrete and models describing the chemical rust process of re-bar in time. These needed to be combined with the models for predicting of the associated pressure development on concrete and local fracture of cover due to re-bar corrosion (rust-expansion-crack). To capture of the effect of reinforcement corrosion and corrosion-induced cracks on constitutive relationships for reinforced concrete, multi-scale modelling of gradual deterioration of bond (de-bonding) between corroding steel and concrete is required.

(2) Corrosion fatigue, fracture initiation and propagation
Where fatigue of steel in air is quite well quantified and predictive models are available, this is not the case for fatigue of steel in presence of corrosion. The ambition is to develop a toolbox that will predict material degradation under combined fatigue and corrosion conditions that vary in time and severity and consider both crack initiation and crack propagation. To reduce the costs to validate the toolbox, multi-physical models and means to accelerate corrosion need to be developed to match corrosion speed with the mechanical load test frequency. In particular, the effect of corrosion (pitting) on the crack initiation time, the effect of corrosion products in the fatigue crack on the crack propagation and conservatism in high cycle (low stress) fatigue for structural steels will be researched. If a (fatigue) crack has grown to a sufficient size, fracture may occur. The ambition is to execute the early development of a fracture material model of steel operating in the ductile to brittle transition region and to explore possible ways to experimentally validate such a model. The steel fracture community is divided in pure brittle and pure ductile approaches. Though very relevant for maritime, offshore and infrastructure, a model for steel operating in the transition does not exist. Both the start of fracture growth and the crack arrest properties will be considered.

(3) From local degradation to present and future structural integrity
There is a need to know how the limit states beyond which a structure is considered to be not safe, are related to the local states of the components and materials. To assess this and the present structural safety and remaining service life, adequate models for (global) response of the structural system affected by local degradation are needed.
Game changing approaches are required to develop multi-scale and multi-physics models for reliable prediction the remaining life time, and the related financial and other risks. There is currently no measure/model that can predict with sufficient accuracy the probability of failure or the remaining lifetime. In order to improve this situation, it is required to develop coupled simulators and to develop appropriate modelling workflows. Coupled simulators need to be accompanied by a probabilistic framework and a sensitivity analysis tool to reduce the uncertainty in the prediction.

7.4.3 Growing the ecosystem 2015-2018

This ERP will be the start of the development of Shared Innovation Programs (ShIPs) centred around the three use cases. Ultimately these will evolve towards a combined Shared Innovation Program on the integrity of large structures. The ShIPs will be the basis for B2B contract research and spinouts for valorisation of IP developed in the ERP and its sequels (see figure)



Challenges that will be addressed in this ERP are: 1) proving the feasibility to implement reliable structural integrity monitoring at acceptable costs 2) design a system with coupled monitoring and forecasting models that can used by non-specialized personnel and 3) get it accepted by stakeholders. Involving stakeholders and crucial peers (see section 3.3) from the start and by organizing field tests of the technology developed for each of the three use cases, will be useful in addressing these challenges

7.5 Activities and deliverables 2015

7.5.1 Advanced sensing and inspection technology

(1) Acoustic sensing technology to measure the inner material for defects

A. Forward model of acoustic wave propagation / reflection in a multi-layer environment:

- Study the Full Waveform Imaging method as currently being developed at TU Delft – Delphi;
- Identify what modifications are required to make the method suitable for the application of imaging well structures / integrity; specific issues: extreme contrast such as fluid/solid material boundaries, dispersive, multi-model character of guided-waves and non-linear wave propagation;
- Study how to realize/implement the required modifications; computational efficiency must be high for application in inversion.

B. Inversion technology:

- Inventory and selection of inversion technologies (quality, computational efficiency).
- Proof of concept based on numerical modelling: (a) model the acoustic response in a multi-casing well with and without defects using the existing 3D finite-difference full-elastic code; this will be the input data (both transmission and reflection, and multi-model) to the inversion method (b)carry out the inversion using the newly developed modeling method in combination with the chosen, most suitable inversion strategy;

C. Structural baseline assessment by proof loading, sensing en FEM

- Design, for combination with proof loading and FEM, of fit-to-purpose system for monitoring global and local structural performance;
- Improve AE for monitoring of condition development during proof loading.

Deliverables:
- Efficient, accurate forward model for acoustic propagation/reflection in multi-layer environment;
- Proof of concept inversion technology based on an experimental set-up;
- Design for monitoring structural performance during proof loading with improved AE.

(2) Multi-parameter fiber optic sensing to measure loads and the inner material for defects
Cement degradation or steel corrosion are part of processes that change physical and chemical parameters. Measuring these parameters using either FBG or Fiber Optic distributed sensing technology can detect the relevant loads, precursors or degradation. Activities:
- Ranking of the physical parameters for steel reinforced bridge and for well-integrity measurement;
- Selecting and evaluating the suitable fiber optic sensing technology for measuring the parameters;
  Design a multi-parameter fiber optic sensing system to measure the relevant parameters. This includes the possibility to integrate distributed sensing technology with FBG point sensors;
- Special attention will be given to sensor (system) lifetime (robustness) and ease of installation.

Deliverables:
- Design of fiber optic systems for bridge and well integrity monitoring;
- Setup that demonstrates the feasibility for a few relevant parameters in relevant conditions.

(3) Design and usage of sensor system
A. Optimization of the monitoring strategy with Value of Information concept
Development of a procedure to assess the value of information and the optimize the monitoring strategy based on the utility/value associated monitoring data for a parameter:
- Inventories of reliability assessment and life-span prediction in use case fields (pre-posterior analysis, Bayesian Updating, Particle filtering);
- Selection of performance indicators (PI) and optimal sample size (SS) using Design of Experiments and the Taguki method to find the optimal sample size with respect to the respective PI.
- Operationalization of Value of the Information as the difference in the expected value of the costs conditional on the failure event in absence of monitoring and when monitoring is performed.

B. Transition to new monitoring strategy concepts
Introducing an alternative framework for monitoring structural integrity requires full understanding of the current frameworks and how the new framework will address the main concerns. The new a monitoring strategy depends among others on the contribution of structural details to the structural integrity, the probability and expected speed of degradation of such details and its effect on the structural integrity over time, the availability of sensors, the possibility to position and operate a sensor, and the reliability of a sensor (/network).
- Development of a (domain specific) templates (largely based on stochastic approaches) that addresses the transition from the current framework to the new monitoring strategy concepts.

C. Heterogeneous multi-sensor data fusion system for reinforcement corrosion propagation
Design of a heterogeneous multi-sensor data fusion system that comprises of a number of indirect corrosion sensors e.g. for steel potential and resistance, concrete resistivity, temperature and humidity. Activities:
- Development of a cost-effective multi-sensor corrosion node;

- Developing a data fusion model with measured data as input and corrosion condition as output.
- Developing an interpretation model for assessment of the degradation at the local structural scale.

D. Heterogeneous multi-sensor data fusion system for offshore steel structure
- Combining information from several sensors to model the time-varying, stochastic relation between measured primary load data and response data (strains, accelerations).
- Develop a framework to reduce sensor output data and to evaluate and expand sensor information to the structural integrity and service history of the complete structure. The framework will focus on degradation due to fatigue and corrosion.

Deliverables:
- Implementation of the Value of Information method for use case bridge;
- Framework for data interpretation of stochastic dynamic loaded structure with structural properties that changes over time and intervention by operator;
- Inventory of data reduction possibilities for the degradation process fatigue;
- Template for offshore wind for the transition to the new monitoring frame work;
- Design of sensor fusion system for reinforcement corrosion;
- Design of sensor fusion system for corrosion of offshore steel structure.

7.5.2 (Multi-scale, multi-physics, probabilistic) models
(1) Transport, corrosion and de-bonding
A. Corrosion initiation and propagation models based on chloride concentration and coupled cations;
- Modelling the critical corrosion initiation conditions and formation of related corrosion products;
- Modelling the coupling between the chloride and the other ions in the pore water (coupled transport) in relation with the binding isotherms.

B. Multi-scale modelling of de-bonding of reinforcement for corrosion propagation
- Analysis with 3D FEM of the relation between corrosion and rebar de-bonding;
- Modelling relation between macro-scopic concrete response and local responses in concrete;
- Meso-continuum corrosion-dependent constitutive bond model for implementation at macro-level structural analysis.

Deliverables:
- First elements coupled models for chloride transport, corrosion and de-bonding

(2) Corrosion fatigue, fracture initiation and propagation
- Fracture initiation for steel operating in the ductile to brittle transition zone;
- Fracture propagation steel operating in the ductile to brittle transition zone;
- Corrosion fatigue

Deliverables:
- First elements coupled models for corrosion fatigue, fracture initiation and propagation

(3) From local degradation to present and future structural integrity

A. Structural safety level and the service life for reinforcement corrosion

Concrete bridge have intrinsic large variability in mechanical properties together with a load pattern that is both spatially and time-variant, thus leading to complexity in modeling and computing global reliability and in estimating the expected damage for different sections at different moments of the life span. In addition, when evaluation existing structures, corrosion, deterioration and fatigue "symptoms" arise, thus suggesting a more proper model of spatial variability of the capacity including local "defects". Activities:

- FEM model to predict the corrosion effect on a whole structure;
- Long-term corrosion tests on beams to validate the FEM models;
- Probabilistic model of corrosion effects on a local scale;
- State of art and literature review on SFEM for use case bridge, review of solution methods and implementation of the method for the study case.

B. Well barrier failure

- Study uncertainties on the initial state of well barriers in view of limitations of currently available well testing tools;
- Develop well barrier failure scenarios due to separate or coupled physical processes. Initially, two scenarios are envisaged: the first scenario considers mechanical failure of cement due to internal/external radial loads on the well, possibly enhanced by chemical degradation due to interaction of cement with formation gases and fluids. The second scenario considers axial (vertical) deformation as a result of reservoir compaction/decompaction leading to de-bonding along casing/cement interfaces and creation of leakage pathways (micro-annulli).
- Identify suitable codes for multi-physics modeling and treatment of uncertainties;
- Develop workflows for code integration;
- Implement coupled models integrated with a tool for treatment of uncertainties in the initial state of the well barrier materials and the future THMC-processes affecting a well barrier. A probabilistic framework will be established (e.g. Monte Carlo/BBN/Markov).

Deliverables:

- First elements of model tool-suit to process data from sensor fusion systems for deriving (local) degradation/failure mechanisms and simulation the (global) structural consequences thereof;
- First elements of model tool-suit to process data from well testing tools for determining the initial state of well barriers and deriving well barrier evolution in one failure scenario.

8 Human Enhancement

8.1 Introduction

We are currently facing an increasing level of automation of systems in e.g. the industrial (maritime and offshore) sector but also in the mobility sector (automated driving). It is broadly accepted that the behaviour and interaction of users with these systems is the key to successful innovation, which requires an optimized human-system interaction. We need further breakthroughs in our knowledge to be able to develop the next generation of adaptive systems for safe and efficient operation. New validated and transparent (human-in-the-loop) automation modules are required. The first ambition of this Early Research Program (ERP) Human Enhancement is to develop a *transparent* (human-in-the-loop) adaptive automation platform that substantially improves safety for manoeuvring and control tasks[27], based on a computational human model to assess current and predicted human task load. This will be the focus of the use case ***Adaptive automation.***

At present, almost half of all work disability is related to psychosocial factors, which is a rise from 30% since 1998[28]. Front runner companies realise that an increase of human resilience and intra-preneurship are prerequisites for improvements in human health and organisational performance. However, adequate resilience tools and interventions are lacking resulting in large personnel and organizational costs[29]. This means that measures to improve resilience are not only important for maintaining health and operational performance, but will also result in potential large financial savings. Although the importance of supporting employee's resilience is widely accepted, an integrated theory is still lacking, mainly due to the large amount of factors determining human resilience.
In order to develop an integrated model of human resilience we need further development in integrating physiological and psychosocial factors, data formats, and predictive analytics and modelling.
The second ambition of this Early Research Program (ERP) Human Enhancement will be the development of a multidimensional prospective model for ***Human Resilience*** and convert this model into individual monitoring instruments and organisational interventions.

Use case : Adaptive automation
In the mobility sector, driver support and automation of driver tasks (up to highly automated driving) is a major trend. It was first introduced by active safety functions like Automatic Braking Systems (ABS) or Electronic Stability Program (ESP), but it will for sure lead to fully automated driving. The role of the driver in this transition is clearly changing from being in full control towards having a supervisory role over automated processes. The consequences for the driver in his changing task are substantial: the boundaries of his operational tasks are becoming unclear, his attentiveness towards his operational responsibility might reduce as the vehicle takes over, while he still has the responsibility and is the safeguard of the system. This may result in the driver being out of the loop and confronted with automation surprises.

[27] Janssen, W.H., Aim, H., Michon, J.A., & Smiley, A. (1993). Driver support. In: J.A. Michon (Ed.) Generic Intelligent Driver Support. London: Taylor & Francis, 54-66.
[28] Minister Sociale Zaken en Werkgelegenheid. Kamerbrief hoofdlijnen aanpak psychosociale arbeidsbelasting. 2014.
[29] RTO-MP-SAS-095. Cost–Benefit Analysis of Resilience Training. How to reduce post-deployment psychosocial strain, psychopathology, and associated costs. V.L. Kallen & J.E. Korteling

The Maritime & Offshore sector is challenged to operate in increasingly harsh conditions, such as deeper water, colder weather, and higher waves. Many, surface and deeper sea-based, operations require precise and complex maneuvering and ROV (remote operated vehicle) based tasks. Optimized human-machine interaction is crucial for safe and efficient operations. The next generation of adaptive automation is a huge opportunity for cost-effective and safe operations and also for the competitive position of our industry. Support for minimizing risks in complex operations with potentially catastrophic effects on the environment (fragile areas like Deep Sea and Arctic) are also of societal importance.

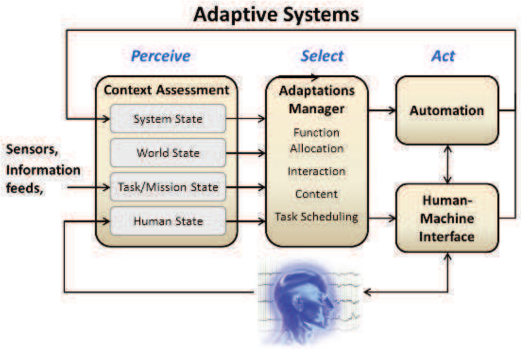


Figure 4. Descriptive function model of an adaptive automation module

The challenges in both domains as described above, require a next step in the knowledge and system development for *adaptive automation* of maneuvering and control tasks. There is need for a validated and transparent (human-in-the-loop) adaptive automation system that substantially improves safety for maneuvering and control tasks (based on a human model estimating the human performance) by adjusting the automation of maneuvering and control tasks (e.g. car driving and ship maneuvering) in an adaptive manner (Fig. 1).

Use case: Human resilience

At present, almost half of all work disability is related to psychosocial factors, which is a rise from 30% since 1998[30]. In addition autonomy in the workplace has been dropping for years. Front runner companies realise though that human vitality, mental resilience and intra-preneurship are prerequisites for innovation. These companies are seeking new ways to increase their performance in this respect. Therefore, supporting individuals to become more resilient so they bounce-back from set-backs, maintain high performance and health, and survive and even thrive during tough times, is one of the most needed developments. Also the new definition of health i.e. “health as the ability to adapt and self-manage”, implies similar future needs to support the individual and contextual resilience of the population at large. Aiming in the end for better health, initiative and societal participation.

Recently, a TNO study estimated that the lack of adequate resilience interventions in the Dutch police force leads to large personnel (110-230M€) and organizational costs (100-300M€). This means that measures to improve resilience are not only important for maintaining operational performance and health, but will also result in potential large financial savings. Although the importance of supporting employee’s resilience is widely accepted, an integrated theory is still lacking, mainly due to the large amount of factors determining human resilience.

[30] Minister Sociale Zaken en Werkgelegenheid. Kamerbrief hoofdlijnen aanpak psychosociale arbeidsbelasting. 2014.

The recently developed TNO descriptive model of human military resilience categorizes the most relevant psychosocial determinants of resilience, but knowledge is lacking to develop a validated prospective model and does not include physiological factors. Integrating physiological and psychosocial factors for resilience is the next step in development of a comprehensive model of human resilience. Furthermore, to assess which type of resources should be targeted in a specific context for a specific individual to enhance resilience, a prospective model and datasets including these factors in different contexts should be developed. This integrated knowledge on human resilience will enable high performance organizations to enhance human performance for a specific individual and context.

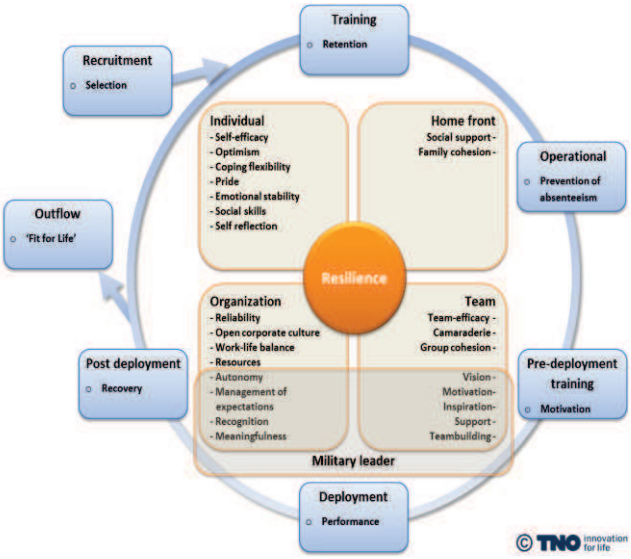


Figure 5. Descriptive human resilience model used by Defence research

8.2 ERP Environment

8.2.1 European perspective

In a changing world, the EU has to become a smart, sustainable and inclusive economy. These three mutually reinforcing priorities should help the Member States deliver high levels of employment, productivity and social cohesion and constrain the future healthcare costs. The Union has set five ambitious objectives - on employment, innovation, education, social inclusion and climate/energy - to be reached by 2020[31]. The new Innovation Union is the European Union strategy to create an innovation-friendly environment that makes it easier for great ideas to be turned into products and services that will bring our economy growth and jobs.

Horizon 2020 is the proposed new seven-year research and innovation programme of the European Union. Horizon 2020 aims to strengthen the EU's position in science, strengthen industrial leadership in innovation, and address eight major societal concerns. The TNO Strategy 2015-2018 has the ambition to contribute to solutions for these eight EU grand societal challenges with the five TNO Themes (see the introduction section for more details). The ERP Human Enhancement has the ambition to contribute with applied knowledge development on human enhancement topics in four TNO Themes.

Specifically, this ERP will connect to the three following pillars of the Horizon 2020-programme: Excellent Science, Industrial Leadership and Grand Challenges of 'Health, Demographic Change and Wellbeing", "Europe in a changing world – Inclusive, innovative and reflective societies", and "Secure societies – Protecting freedom and security of Europe and its citizens". Also we have the ambition to contribute to a new EU Defence Research programme, and the NATO and EDA programs on the resilience topic.

[31] Kamerbrief hoofdlijnen aanpak psychosociale arbeidsbelasting, 2013-0000175989

8.2.2 Netherlands perspective
The NL innovation policy has been organized in nine national Top Sectors and five social themes. These sectors have formulated short and long term research needs and are linked to the five TNO Themes as described in the TNO Strategic Plan 2015-2018.

The theme Urbanisation is connected to the Topsectors HighTech Systems and Material (Roadmap Automotive), to the Topsector Logistics and to the societal theme mobility (min. I&M). Adaptive automation of the mobility system, its vehicles and its infrastructure is a dominant theme on all the roadmaps in these Topsectors. For the industries to develop or enhance the attractiveness of their products (trucks, busses, controls and electronics, logistic services) and for the government to realise challenges with respect to traffic safety, healthy living and greenhouse gas emissions. The ERP will contribute towards the role of the citizen/driver, the acceptability of the solutions and the tangible effects.
The theme Energy and more specific the roadmap Maritime and Offshore is connected to the Topsector Energy and Topsector Water. The Netherlands is a global leader in the provision of offshore services and developing complex maritime systems. Winning at Sea focuses on technological solutions for extracting energy from the sea and the offshore mining of raw materials. The Netherlands is also a leader in the construction, management and maintenance of offshore wind farms. A major competitive driver in the Maritime & offshore industry is safe automation of very complex processes. The existing human-machine control systems need a further development to stay competitive in high risk operations.

Human resilience knowledge and tooling are relevant for the Top Sectors Life Sciences and Health (LSH), Smart Industry and Social Innovation. The next strategy period , the TNO theme Healthy Living will focus on the transition “from disease and cure to prevention, healthy behaviour and participation’. As indicated the new definition of health, that is central for this transition, i.e. the ability to adapt and self-manage, very well aligns with the concepts of resilience on individual, organisational and societal level. The results of this ERP will also support the governmental innovator program for the Ministry of Social Affairs on reduction of work related stress[32] and increase of mental health and vitality with validated approaches.
The Ministry of Defence states that there should be a focus on the human, as the operational conditions require that soldiers are flexible and resilient. New education and training programs should be developed that complies with state-of-the-art knowledge. This focus on the human factor is substantiated in one of the four priorities defined in the Strategy, Knowledge and Innovation Agenda[33] of the NL Ministry of Defence: the human operation in complex and dynamic environments. The results of this ERP will feed in the TNO knowledge

8.2.3 TNO perspective
In the TNO Strategic Plan 2015-2018 five Transitions and eight Early Research Programs have been defined. These transitions were chosen based on
- The existence of an innovation-ecosystem with public and private stakeholders
- The need of solutions for societal challenges and economic growth
- The strengths of the TNO knowledge base.

The *TNO theme Urbanisation* aims to realize a breakthrough towards zero accidents with a paradigm shift based on supporting the driver with higher levels of automation and by connecting vehicles and infrastructure through communication. The objective is to develop solutions that are introduced before 2020 and that can potentially reduce both fatalities as well as severe injuries. To achieve

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[32] José Manuel Barroso, President of the European Commission
[33] Anticiperen en innoveren in een veranderlijke wereld. Strategie-, kennis- en innovatieagenda 2011-2015. Ministerie van Defensie, mei 2011.

these challenging objectives the Theme Urbanisation has defined specific game changing results such as effective collision avoidance and driver support (driver coaching and adaptive support). The theme Urbanization works along a number of Shared Innovation programs of which ‘Automated Driving’ and ‘Cooperative Mobility’ are the most relevant for this ERP. In these ShIPs a consortium of industry, knowledge partners, governments and other stakeholders develop new break through solutions. In the Automated Driving program, TNO works with different stakeholders on bringing automated driving towards public roads in (passenger cars, trucks and busses) and to logistics centers and other applications. In Cooperative Mobility, the DITCM (Dutch Integrated Test site for Cooperative Mobility) consortium is developing solutions that use communication between vehicles, smart cities and highways to support drivers and optimize the mobility system.
In order to maximise the economic outlooks the industry wants to boost the operational reliability, availability, safety and maintainability of complex, high-tech Maritime and Offshore systems and platforms. The *TNO theme Energy*, and more specifically the Maritime and Offshore roadmap, aims to support private and public stakeholders in achieving the necessary high reliability and to speed up innovative solutions for a competitive industry. A major competitive driver from the Maritime & offshore industry is safe automation of very complex processes. The existing human-machine control systems need a further development to stay competitive in high risk operations. A new SRP (Shared Research Program) program “adapted automated offshore operations” on complex tasks at sea is in development and will support the approach in manning and automation and also the next step to “unmanned” operations. The new initiatives are relevant in cooperation with potential partners like the university of Delft, Dutch ministry of Defense, Marin, ECN and NIOZ and Imares and industrial partners. The SRP/ initiative MUST (Marine Consortium of environmental Science and Technology) is initiated with NIOZ and Imares for independent Shared Research and development for Sustainable Exploitation of the World Ocean Resources.
The *TNO theme Healthy Living* is positioned in several national and international innovation-ecosystems. The results of the ERP Human Enhancement will find their way in several of the ecosystems. Next to the Health-transition, the ERP results will help the transitions Smart Industry in creating a more resilient workforce. This ERP will provide relevant knowledge for the an extensive (inter)national industrial and academic network connected to the Smart Industry/factory of the Future and to (inter)national networks on workplace innovation and human enhancement through robotics.
The *TNO theme Defence and Security* carries out research focused on the necessary defence and societal safety & security transitions. A relevant driver for the theme *Defence and Security* is the shift from autonomous action to cooperation with people, systems and other organisations. Nevertheless, and in spite of the use of high-grade technology, all defence and peace-keeping operations still pivot on resilient people. As a result the interest in the “human factor” and “human resilience” has strongly increased in recent years, because it has become clear that the ultimate effectiveness of a military operation is more and more determined by this factor.

8.3 Eco-system

8.3.1 Government policy and TopSectors

The ERP Human Enhancement will develop connections to the NL Topsectors and Programs through participation with industry, academia and TO2 partners in joint projects in dedicated tenders organised by the various TKI. Also joint projects with industrial partners are envisioned that will be part of the relevant TNO-TKI contract and thus are supported by TNO Theme participations. It is the ambition of this ERP to come to a situation in 2018 where 50% of the research budget on the topic of human enhancement is provided by external partners.

For the *TNO Theme Defence, Safety & Security* the ERP Human Enhancement results support the NL Ministry of Defence need for a more resilient workforce as described in the policy paper “In the interest of the Netherlands"[34].
For the *TNO Theme Healthy Living*, the ERP Human Enhancement feeds in with the Governmental innovator program of the Ministry of Social Affairs, network of frontrunner companies and organisations involved in technology supported and personalised prevention and the program *Ambitious Entrepreneurship* of the Ministry of Economic Affairs.
For the ministry of Infrastructure & Milieu (I&M) the effectiveness of policy measures to improve traffic efficiency, safety and sustainability is a major concern. The TNO *Theme Urbanisation* has a focus on these societal and economical challenges. Having trustworthy and validated models to predict human interaction is an important element in supporting the ministry of I&M. For the industry (and consequently for ministry Economic Affaires) developing products, technology and services to improve the effectiveness and ease of use of new solutions on Advanced Driver Support System is an opportunity for new business and a topic on which already existing bilateral projects are focusing on.
The *TNO Theme Energy* aims to support the policy initiative of the NL government (agenda of the “energie akkoord”) which is based for a part on new sustainable energy like Offshore Wind. Cost reduction and operational excellence, obtainable with next generation task automation, in the operation and maintenance of these platform by Offshore industry is therefore needed. This is where the results of the ERP Human Enhancement feed in. In addition new innovative implementation based on human enhancement knowledge are also opportunities for the Dutch Industry (e.g. in the Topsectors Energy and Water) thereby underpinning the leading position for Dutch Offshore special equipment and operations in sub and deep sea.

8.3.2 TNO Themes
The ERP Human Enhancement will have connections to four TNO Themes and programs through mutual participation in and collaboration with mixed-funding projects that are ignited by the demand driven programs of the TNO Themes. This allows the generic knowledge that is built up in the ERP, to be applied within specific domains and stakeholders context.

The demand driven program Automotive Mobility Systems of the *TNO theme Urbanisation* addresses the development of automated vehicle technology and human interaction. Both topics of ‘Transition of Control’ and ‘Driver State Estimation’ are planned as focus areas for the oncoming strategy period. The lack of availability of comprehensive, well-validated human behaviour models to support this development during the past year was the background for proposing these subjects for this ERP Human Enhancement. The deliverables of the ERP Human Enhancement have to be well-validated in the context of the mobility use case (using driving simulators and real-life vehicle tests) and have to be realised in such a manner that they can be easily embedded in (software) applications.
In the *TNO Theme Energy* the roadmap of Maritime and Offshore addresses unmanned “complex” operations as a priority area. The integration of human factors expertise in safe, reliable and predictable operations is a central issue in the development of automated operations technology and human interaction in extreme environments for humans and machine. Adaptive automation is expected to be the next step in moving from fixed levels of automation with little flexibility to more flexible automation schemes.
The roadmap Work, Health & Care of the TNO *Theme Healthy Living* addresses the development of societal and economical solutions for psychosocial stress/ effective interventions for mental health and vitality, workplace innovation and greater support for societal participation. The ERP Human Enhancement will deliver the model and tooling to enhance resilience on these issues.

[34] Nota 'In het belang van Nederland' Ministerie van Defensie, 2013.

The roadmap Human Effectiveness of the TNO *Theme Defence and Security* aims at realizing impact in the area of military mental and physical performance. Resilience improvement is identified as a central research issue to counteract the effects of stress on the individual, team, and ultimately on the entire Defence organization. The roadmap *National Security and crisis management* deals with the risks that our society faces, the approaches for strengthening the resilience of our society and innovations for improving the public and private safety and security organizations. This roadmap requires technologies and methodologies, based for a part on the deliverables of the ERP Human Enhancement, that enable their customers to solve resilience related issues.

8.3.3 Academic partners

The ERP Human Enhancement will collaborate with academia in two ways. First of all, the chairs of TNO part-time professors who are active in one the areas covered in the ERP, will be embedded in the ERP. Thereby immediately enhance the academic eco-system of this ERP. Through their academic networks, projects and PhD's and post-docs, a research volume leverage on the ERP human enhancement topics will be obtained.

Secondly, academic collaboration is enhanced by participating in relevant NWO calls. Within the ERP Human Enhancement collaboration in research projects and tender proposals with following academic partners will be sought:

- VU-MC: Body@work
- University of Leuven
- TU Delft
- University of Twente
- Nederlandse Defensie Academie (NLDA)
- University of Groningen

8.3.4 Relation with TO2 / RTO partners

TNO is founding member of the international "Network of Excellence on Psychological Resilience for Military", which includes NATO members. This network will used to disseminate the research line *human resilience* results, but also play an opportunity for consortium building. Similarly we will use our role as a founding member of INSCOPE to build our eco-system in the domain of human resilience and intra-preneurship research.

For the research line *Adaptive automation* we will explore the research collaboration with the Marin, to combine our research efforts with their extended knowledge and facilities on vessel manoeuvring. Via the NATO Task Group "HFM-RTG 247: Human-Autonomy Teaming", TNO collaborates with key international research organizations on adaptive automation for dynamically adjustable collaboration. In this community, TNO will advance its position on performance and workload modeling and assess the advancements within the Task Group.

8.3.5 EU programs

Various opportunities exist to participate in EC programs and calls, most relevant are:

- DG Employment and DG Enterprise & Industry,
- H2020 – Excellent Science, Industrial Leadership, and Grand Challenges: Health, Inclusive society and Secure societies.
- Within the European Defense Agency (EDA) upcoming call opportunities are on the topic of resilience (intervention) tooling.
- In 2015, a Horizon 2020 call titled 'Safe and connected automation in road transport MG-3.6a-2015' opens, in which main topics include supporting technologies for compensating human error and HMIs optimized to provide tailor-made information to the driver. This provides an excellent opportunity to further develop and/or apply the main deliverables of this ERP.

8.4 Research and Technology lines 2015-2018

8.4.1 Research Line 1: Adaptive automation

The ambition is to develop a proof-of-concept of *transparent* (human-in-the-loop) adaptive automation that substantially improves safety for manoeuvring and control tasks[35], that uses a human model to assess current and predicted operator state and adjusts the automation of tactical and operational tasks in an adaptive manner.
The main focus is on human tasks that require supervisory control, from highly time critical tasks (e.g. operating a road vehicle in traffic) to less time critical but highly safety critical tasks (e.g. manoeuvring a large vessel around an ice-berg). The model will be running in a real-time environment, will consist of various modules each with their own specific human features (e.g. user model, cognition, reflexes, perception) and validation. The modules are integrated such that they are automatically called by a software agent, depending on the momentary situation. The model will contain machine learning algorithms such that it automatically learns from experienced scenarios in order to improve its performance as well as the operator's experience.

This requires a layered automation system consisting of the following capabilities:

- Sensing: Detection and processing of data that describe driver state by means of diverse elements (the "observables") into a persistent human state recording with a common time frame.
- Modelling: derivation and/or deducing of the concerning human state models (an abstraction of the "observables"). This might include human-in-the-loop machine learning and recognition of behavioural patterns and cognitive state.
- Reasoning: assessing current model states and possible actions, and initiating changes in human (task) state.

This layered approach is chosen to establish persistent, trustworthy reliable and valid sensing, modelling and reasoning modules. Elements that need to be included in the layered framework are elements related to the human operator state, such as behavioural parameters, task performance, the environment, , vehicle state and automation etiquette (e.g. capabilities, limitations, ethical dilemma). An ontology will be developed and maintained, which formalizes these concepts and their relationships (as a foundation for the adaptive automation). Based on this layered framework and ontology, the elements most crucial for safe operation will be selected and will be used for further development in the first year. Additional elements will be added in the coming years (2016-2018). After this first conceptual description and formalization, the scenario definition will be made, one for road traffic (e.g. driving in free-flow motorway traffic) and one for the maritime context (e.g. operating high-speed craft in an operationally demanding context). First, algorithms need to be developed and will need to be fed with human and task data. These data will be gathered by means of simulator studies, field operational tests, naturalistic data, and expert field tests. These data will be used to fit the parameters and will enable model learning. Validation will be an integral part from component validation to real-world validation at the levels of sensing, modelling and reasoning. The project will iteratively develop and deliver a proof of concept demo for each chosen use-case.
The **knowledge breakthroughs** needed are:

- Extension of human state estimator with human state prediction (for near and future predictions in time) and formalization of its concepts in a reusable and extendable ontology.
- Layered set of algorithms that use unobtrusive measurements (camera, behavioural measurements, external data) and human input to feed the decision support model with high level of accuracy.

[35] Janssen, W.H., Aim, H., Michon, J.A., & Smiley, A. (1993). Driver support. In: J.A. Michon (Ed.) Generic Intelligent Driver Support. London: Taylor & Francis, 54-66.

- Intrinsic safe system by using graceful degradation (e.g. fall-back scenarios (with human in or out of the loop) if required level of human (task) state estimation accuracy cannot be offered or if automation cannot provide the required support).
- A modular, layered and extendable architecture that uses multiple data sources to estimate and predict the required level of automation and transition of the supervisory control task, that automatically handles multiple situations in order to be able to function on multiple use cases and scenarios.

The activities as listed in our approach description include the definition of a conceptual framework and ontology, selection of scenario's per year, data gathering to fill the model including human operator studies and technical and human factors validation per year. Deliverables include reports describing the choices that were made, descriptions of the algorithms of the model and an actual prototype and demo for each year.

8.4.2 Research Line 2: Human resilience

The research line Human resilience will develop a research platform combining three main building blocks (a modelling, sensing and monitoring, and data modelling and feedback platform). Knowledge breakthroughs entail the integration of state of the art knowledge in psychosocial and physiological scientific disciplines on resilience in such a way that it enables the development of a multidimensional prospective model. This model will provide insight in the complex interaction between factors in the different domains. This model will be the core of new individual monitoring and organisational intervention instruments. The international network ambition is that the ERP will serve as a foundation for an international research consortium in which TNO acts as integrator between the different scientific disciplines and technologies involved. Figure 3 depicts the relationships between the research modules to be developed in the research line Human Resilience.

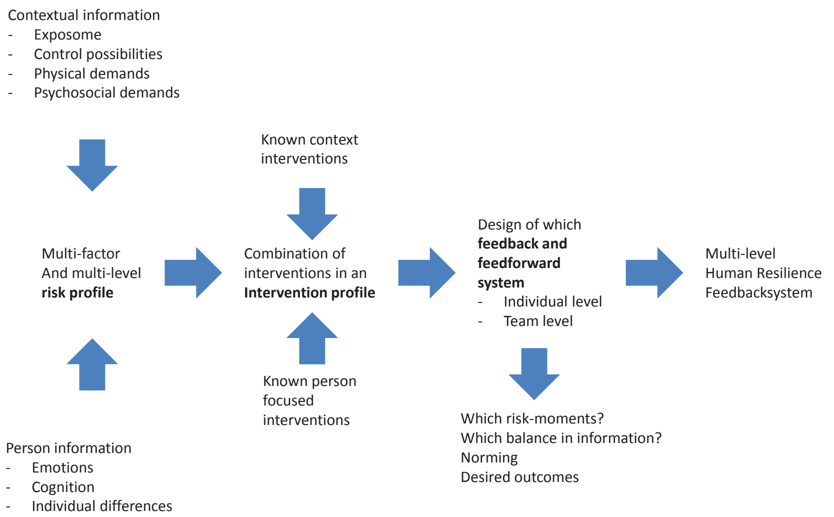

Figure 3. Basic description on the required data and functions of the prospective model of the use case human resilience.

Research activities in the research lien Human Resilience will be structured around the three building block platforms:

- For the modelling platform, a multi-factor and multi-level human resilience risk profile (MFMLHR) will be created integrating psychosocial and physiological factors that drive resilience development and a tool to calibrate the model for specific (organizational) contexts or use cases will be developed.

- Secondly, connected to the risk profile, an intervention profile will be created integrating knowledge on the separate interventions needed to improve the identified risks.
- For the sensing and monitoring platform, the identified factors in the model and the key environmental moderators will be operationalized so that it can be used to conduct semi-continuous automated data-collection that is minimally intrusive for the individual.
- For the data modelling and feedback platform, a research infrastructure will be developed consisting of a data management and modelling environment that can produce contextualized and personalized output about the status of resilience development. In addition, the data management and modelling platform will include a user-friendly feedback system that can provide individuals with feedback.

To ensure products fits end-user needs, several use cases will be identified and applied as early as possible in the research activities. In addition, relevant technological developments and new products for self-monitoring in the market will be identified and evaluated on their usefulness for self-regulated resilience development in general and potential integration in the to be developed system.

8.5 Activities and deliverables 2015

8.5.1 Research Line 1: Adaptive automation

In 2015, research activities will be focused on definition of the application scenario's and system requirements. In addition a first prototype of a human model will be designed based on a state of art assessment of leading scientific approaches and existing systems.

In more detail the following work packages will be started:

Work package 1. Description and choice of most relevant user scenario's and system requirements.

Work package 2. Development of the ontology and conceptual model framework in line with requirements of WP1. Additionally, this framework will be used to identify currently available technology, knowledge and projects as well as knowledge gaps and priorities for further development.

Work package 3. A first prototype human model, using existing and validated (technical and human factors validation) algorithms with first proof of concept demo

Work package 4. A validation framework (based on the ontology), potentially following the V-cycle approach. The design solutions (an extendable set of validated "design patterns of adaptive automation") and (corresponding) test results will be maintained in a well-structured and easy-to-access environment that supports re-use and refinement.

The deliverables resulting in 2015 are:

- Report describing conceptual model framework, including requirements & state-of-the art assessment (WP1 & WP2)
- Modelling and Tooling environment
- First integrated, modular human model implementation in use-case relevant scenario setting (WP3)
- Proof of concept demo (demonstrated at symposium event)
- Report describing validation framework, including investment plan for identified gaps.

8.5.2 Research Line 2: Human resilience

In 2015 the framework of a multi-factor and –level human resilience (MFMLHR) model will be developed and delivered in a mechanistic qualitative modelling environment; the intervention system and the calibration tool will be developed as proof of principle; the human/worker monitoring and sensing tool and the research data architecture will be developed as proof of concept. To ensure these activities are in line with end-users needs the Dutch police will be involved as a first use case.

The Dutch police is selected as first use case because it capitalizes on existing relationships and activities and results in on-going projects on resilience monitoring and feedback applications. In the ERP program period other use cases will be involved based on the developed network of relevant organisations. In more detail the following work packages will be started:

Work package 1. Development of multidimensional human resilience model
A framework of the MFMLHR-model will be developed integrating contextual and person related factors that determine human resilience. The model will provide insight in the key mechanisms that drive the development of resilience and that explain individual differences in this development.
A mechanistic qualitative modelling tool containing the MFMLHR-model will be delivered in 2015 to facilitate other activities in the program and enhancement of the model.

Work package 2. Development of use case diagnostic framework for resilience model
To calibrate the model for a specific context or use case, key environmental moderators that either strengthen or weaken resilience development within this context have to be identified. A tool will be developed that enables the process of contextualizing the MFMLHR model for different contexts.
A proof of principle of this framework will be delivered in 2015.

Work package 3. Design of monitoring and sensing platform
The identified contextual and personal factors in the MFMLHR model and the key environmental moderators will be operationalized in a monitoring and sensing platform. This platform should be able to assess resilience development through a semi-continuous automatized data-collection effort that is minimally intrusive for the individual. A proof of concept of this platform (data collection, storage and reasoning) will be delivered in 2015.

Work package 4. Development of data management and modelling infrastructure
The data gathered by the monitoring and sensing platform should be managed within an infrastructure that will be used for research (collaboration) goals and feedback purposes. In 2015 a proof of concept for the data management infrastructure will be delivered. A separate research will be done on the adequate feedback and –forward for such tooling.

Work package 5. Technology scan
In 2015, a use case and technological scan will be conducted to identify relevant use cases and technological developments and new products for self-monitoring.

9 Making Sense of Big Data

9.1 Introduction

This ERP is dedicated to applied research of Big Data. Big Data is an all-encompassing term that stands for any collection data set so large and complex that it becomes too difficult to process using on-hand data management tools or traditional data processing applications. Although Big Data is in this way formulated as a problem, it holds in fact an enormous potential in various fields, ranging from health, food security, climate and resource efficiency to energy, intelligent transport systems and smart cities; an opportunity which we cannot afford to miss.

Although the topic is clearly general and relevant for a wide range of domains, we will focus on two fields where we expect Big Data methods to be a game changer:

1. Efficiency, reliability, transparency and decrease of bureaucracy in logistics, and
2. *Personalized* health.

ERP motivation and drivers

The next sections motivate the selection of the two uses cases, followed by a perspective on Big Data in general.

Leagile Logistics - a Lean & Agile Smart Logistics Corridor

Current logistic systems[36] are often inefficient due to (unnecessary) delays and low capacity utilisation. These inefficiencies lead to high costs in for instance stocks and warehouse facilities (=> business case) and indirect costs by for instance customer service levels (=> value case). Inefficiencies have different causes like lack of supply chain visibility (data of the real world situation), lack of collaboration, barriers to data sharing and – interpretation, and low data quality (consistency, completeness, correctness, volatility). Current paradigms like Internet of Things and Linked Open Data can enable data sharing across organizational barriers, but require sharing, cleaning, and processing (‘sense making’) of large amounts of data (‘big data’).

The logistics use case aims to increase **resilience** of goods flows between the Rotterdam mainport and its hinterland making it **lean** and **agile** with real time data with the objective to handle the foreseen transhipment growth of the Rotterdam port according the vision developed by the Rotterdam Port Authority[37]. Decisions of individual stakeholders in these goods flows, e.g. shippers/consignees, Logistic Service Providers, carriers, terminals, and infrastructure providers, can be improved leading to more efficient capacity utilisation (infrastructure, carriers, terminals) and reducing delays. Various parameters like ‘duration’, ‘price’, ‘safety’ and ‘environmental footprint’ can be considered in these decisions thus contributing to a better society.
The use case has a clear business case for individual stakeholders[38] in terms of service improvements and cost reduction, but also impacts the competitive position of the Netherlands, both as a gateway to Europe via the Rotterdam mainport and providing support to global logistics. The results can be applied in various Living Labs (Betuwelijn, ITS corridor R’dam-Wenen, Mainport Rotterdam, Kennisloods Rotterdam, NLIP/Portbase, Inland Links).

[36] The term ‘logistic system’ is used in a generic way. In practice, each stakeholder has a particular view of a (global) logistic system. In the context of this ERP, such a global logistic system cannot be improved, although the results of the project can be applied on an international scale.
[37] See Havenvisie2030
[38] It is generally known that implementing improvements might lead to benefits for particular stakeholders and additional costs for others. These aspects are relevant to the implementation and thus adoption of particular big data analytics.

Personalized health
Health and its rising costs are an increasingly important topic for the public and private sectors. Governments need to cut cost in the context of demographic changes, private sector needs to reduce absence levels to stay competitive. In order to transform the health sector into a more financially sustainable form, fundamental changes need to be made. This is realized by the EC, devoting 10% of its H2020 budget to health related research. Important elements of this transformation are prevention, participation, prediction and personalization. New developments in the area of ICT, sensors and *omics* analysis[39] have the potential to transform the health sector. Medical decision support will increasingly be personalized (precision medicine) using predictive modeling relying on big personal health data, improving treatment effectiveness by a large margin. More importantly, cost will decrease by an increased focus on prevention (early warning for mental / physical problems given DNA profile, self-monitoring, e-coaching) maximizing patient self-management. Lifestyle coaching (physical activity, personalized food, stress prevention) is an area where TNO has excellent domain knowledge, but also is well connected to relevant industries (e.g. food industry and ICT sector).

9.2 ERP environment

A perspective on Big Data[40]
We are witnessing a industrial revolution driven by digital data, computation and automation and most likely it is still in an early stage. Human activities, industrial processes and research all lead to data collection and processing on an unprecedented scale.

The global trend is spurring new products and services as well as new business processes and scientific methodologies. The associated resulting economic value of Big Data is shown in many market studies; e.g. one forecast expects the global Big Data market to exceed $47 billion by 2017, which translates to a 31% Compound Annual Growth Rate (CAGR) over the five year period 2012-2017.[41]

9.2.1 European perspective

In the Horizon 2020 program Big Data finds its place in all of its three core themes or 'pillars', i.e. *Excellent Science*, *Industrial Leadership* and *Societal Challenges.* It reflects the need for dedicated research on Big Data (within Pillar 1) and the way Big Data is going to drive innovation in industrial and societal fields (within Pillars 2 and 3).

Specifically, pillar 1 *Excellent Science* in the *European Research Infrastructures* addresses the topic Big Data in programs EINFRA-1-2014 – Managing, preserving and computing with big research data) and in the *Future and Emerging Technologies* (FET). Pillar 2 *Industrial Leadership* contains Big Data activities, mainly for the Key Enabling Technology ICT (Activity line *Content technologies and information management* ICT 15 – 2014: Big data and Open Data Innovation and take-up and ICT 16 – 2015: Big data – research). Pillar 3 *Societal Challenges* all challenges (with the exception of “Europe in a changing world”) contain objectives related to the need to structure and interpret Big Data.

9.2.2 Netherlands perspective

The *ICT Roadmap for the Top Sectors (2012)* recognizes Big Data as one of the leading ICT Research and Innovation Themes, which is addressed in the Action Line *Data, Data, Data*.

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[39] The term ‘omics’ informally refers to fields of study in biology ending in –omics, such as genomics, proteomics or metabolomics.
[40] Large consultancy organisations and vendors like to come up with catchy labels for (technology) developments. In Big Data, there is such a thing as the 3 (Gartner) or 4 (IBM) V’s, and others easily add other terms starting with a V.
[41] Jeff Kelly et al: Big Data Vendor Revenue and market Forecast 2012-2017 (2013)

This Action Line consists of two directions. The first direction deals with Data and Content Exploration. The challenge is to create intelligence, to take better decisions, and to learn what the customer wants from large and heterogeneous sets of data and (user) generated content streams: to extract and exploit knowledge for individuals and organization across the various forms of information: text, sound, speech, image, and videos.

The second direction is related to technological aspects of Big Data. To truly understand the complexities of use cases arising in Big Data, flexible infrastructures to dissect and manipulate Terabytes to Petabytes of raw facts are indispensable. The route forward is marked with better computing infrastructures, modern database management and software innovations.

The “Scientific Answer to the roadmap ICT for the Top Sectors”(ICT-research Platform Netherlands, 2013)”[42] presents 8 societal ICT challenges and the scientific breakthroughs that are associated with each of them. Big Data is the main theme in the majority of this strategic research agenda. Scientific breakthroughs are specified for big data handling, content and data exploration, open data and interoperability, internet of things and privacy and security.

With the use case ***Leagile Logistics*** this ERP will develop the technology that is required for realizing the long term strategic plans of the Department IenM and the Topsector Logistics. It will not only support these plans, but accelerate to realize the ambitions (‘Partituur naar de Top’).

With the use case ***Personalized Health*** this ERP contributes to the Health Vault project that runs in the Big Data Value Center (see section 0).TNO is well connected to this project proposal with an estimated budget of more than 2 M€. The use case supports the plans of the Top Sector Life Sciences and Health, especially on its objectives regarding personalized medicines.

9.2.3 TNO perspective

As depicted above, the European and Netherlands research related to Big Data are well embedded in the various ICT programmes with application in a wide range of domains. Likewise, Big Data plays a prominent and game changing role all five transitions that TNO will focus on in the period 2015-2018, whether it is smart cities, smart industry, smart energy, or ….

Existing stakeholders within the various domains will be challenged to reposition themselves in the value chain (or value web). ‘Data’ and ‘information’ handling is a decisive component of products and services; in addition, the barrier to entry a market will be lowered, hence *new kids on the block* (one of the forces in Porter’s model). It will also lead to new opportunities for cross-sector propositions, that is, companies that will extend their market outside their tradition turf. Some of these markets are (heavily) regulated, leading to regulatory challenges: government will need to balance between protecting current markets and employment, and new, innovative companies that are eager to replace the ‘dinosaurs’.

9.2.4 Conclusions

Both internationally and nationally Big Data is viewed as one of the key assets and game changers of the future. Mastering the creation of value from Big Data will enhance competiveness, change existing value webs, and will result in economic value creation and will deliver social benefit. Applied to Logistics and Health TNO will be able to demonstrate these benefits of Big Data in practice.

9.3 Ecosystem

This paragraph describes the stakeholders and supporting programs outside TNO, specified for the field of this ERP.

9.3.1. Top Sectors and Programs

The ERP Making Sense of Big Data will develop connections 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 EC. Also joint projects with industrial partners are envisioned that will be part of the relevant TNO-TKI contract and thus are supported by TNO VP contributions (SMO). It is the ambition of this ERP to come to a situation in 2018 where 50% of the budget comes from outside TNO.

Instrumental in setting up the joint projects will be the involvement of the Big Value Data Center (BDVC)[43], an (national) 'open innovation platform', located at Almere, and initiated by TNO, SURFsara, eScience Center and Economic Boards of Almere, Amsterdam and Utrecht. The BDVC has organised an extensive network of public and private organisations both from the solution (supply) and the demand side. Companies are invited to experiment with their own data sets, and other datasets in a save and inspirational environment. The experiments result in new or improved business cases. Also the BDVC can organise the setting for market orientation and dissemination of knowledge and research.

9.3.2. Academic Partners and Programs

Chairs of TNO part-time professors who are active in one the areas covered in the ERP, will be embedded in the ERP. We have already identified eight TNO part-time professors who qualify for this, and hence through their academic projects and PhD’s and post-docs, immediately enhance the academic eco-system of the ERP.

Furthermore, academic collaboration is stimulated by participating in relevant NWO calls. For instance, the Call for Proposals Innovative Public Private Partnership in ICT (IPPSI) (open since July 2014) stimulates the collaboration between knowledge institutes and innovative companies to come to innovation within one of the four cross-sector action lines of the Roadmap ICT, including the Action Line *Data, Data, Data*.
In addition to this Open Call we are also in the process of setting up a specific TNO-NWO program on Big Data. The anticipated program has to be further elaborated in the upcoming months.

9.3.3 TO2 Partners and Programs

The ERP Making Sense of Big Data will build connections with other TO2 institutes where appropriate and useful. Opportunities for collaboration are at hand with DLO (applying beyond state-of-the-art technologies for disclosure of linked open data and big data for research, policy and education in the field of agriculture and food security), ECN (which uses Big Data for decision making for wind farms) and Deltares, which participates in the Digital Delta project[44], which is aimed at the unlimited and readily accessible provisioning of water and climate services, through the use of Big Data. It’s interesting to note that ‘big data’ is a subject that connects all TO2 partners, even though the application areas might be different.

9.3.4 EC Initiatives

As mentioned in section 2.2.1 various opportunities exist to participate in Horizon 2020 programs and projects, to be reviewed on a case-by-case basis for fit.

[43] www.bdvc.nl
[44] www.digitaledelta.nl

Also of high relevance, is the European Big Data Value cPPP (contractual Public-Private Partnership)[45]. The goal of this cPPP, which is backed-up by the EC, is to tackle the main research challenges and needs for advancing Big Data Value in Europe in the next 5 to 10 years. The goal of the ERP Making Sense of Big Data is to become a participant of this cPPP.

9.3.5 TNO Themes and Programs

Besides the stakeholders outside TNO, the eco-system of the ERP has strong relations with TNO VP programs on Mobility and Logistics (Urbanisation) and Biomedical Innovations (Healthy Living) because of the use cases on Logistics and Health, and with Networked Information (Industrial Innovation) and Information Superiority (Safety) for the more generic ICT aspects of Big Data.

9.3.6 Conclusions

Within the ERP Making Sense of Big Data strong collaboration with various partners outside TNO is key. Collaboration with academia is covered through TNO part-time professors and an envisioned TNO-NWO program on Big Data. Collaboration with non-academic partners will be mainly channelled through the Big Data Value Center and the European Big Data cPPP. The options for participation and collaboration will be evaluated on a regular basis, but formally at least once per year as part of the annual update of the ERP plan.

9.4 Research and Technology lines 2015 – 2018

Here we discuss the technological requirements of each use case and how they lead to the basic technology lines in this ERP.

9.4.1 State-of-the-art, knowledge gaps, position

The trend of every increasing sizes of data sets gave initial optimism that advanced analytics would lead to the ‘End of theory’ paradigm, coined by Chris Anderson, roughly claiming that statistical relations alone would suffice to develop reliable algorithms if the underlying data sets are sufficiently large. However, somewhat obviously algorithms based on data of the past can only predict the future if the underlying systems dynamics remains unchanged. To verify this condition and for adapting to systems changes, *understanding* of the systems is required. This implies theory and models capturing this theory.

Incorporating theory in data is precisely the expertise where TNO has a strong position and a right to play. Covering a wide variety of societal and industrial areas and a deep tradition on modelling, TNO has excellent capabilities to enrich raw data with domain specific knowledge, thereby bridging the gap from statistical to causal relationships. Bridging this gap is crucial for both use cases:

- In ***Leagile Logistics***, the breakthrough in using data for prediction on time-scales from hours to weeks. Clearly, the systems dynamics of logistics is poorly understood and likely highly variable. With Prof. Lori Tavasszy and Prof. Albert Veenstra and logistics models such as World Container Model, HighTool, and BasGoed, tools demonstrate TNO’s position.
- **Personalized Health** requires the big leap from statistical relations for large groups to causal relations for a single individual. Analytics of large data sets and theory development on system biology is required. TNO has strong right to play with expertise on systems biology combined with analytical methods (Prof. Wessel Kraaij and Prof. Stef van Buuren).

On the problem side of big data, the big data challenge is commonly perceived as developing new software tools to capture, manage and process big data sets within acceptable time spans. While the usual suspects as Google and IBM have very strong positions on this area, TNO acquired a right to play in the development of heterogeneous and open infrastructures, including the governance of data

[45] www.bigdatavalue.eu

sets with many different owners and privacy issues (Prof. Hans van den Berg, Prof. Erik Fledderus, Prof. Rob Meijer and Prof. Rob Kooij). The breakthrough needs the realization of large-scale distributed infrastructures for data virtualization over heterogeneous sources.
In addition to these technological advances, first uses of big data rely on relatively straightforward, single-stakeholder business cases. TNO has established a strong position in connecting various stakeholders across an eco-system based on e.g. TNO's position in (semantic) interoperability – read: information standardization. The next step is cross-domain interoperability, and moving from business case to (societal) value case. The challenge remains to a) identify tangible and intangible created value, b) quantify this value in a way that it connects with investments done by the various stakeholders and c) come up with a fair and reasonable sharing of the value created.

9.4.2 Technological requirements of the use cases

Use Case: Leagile Logistics - a Lean & Agile Smart Logistics Corridor
Terminals that act as hubs and transport capacity between these terminals (spokes) are central in this use case. Hubs require real time information of carriers to improve utilization of their resources and carriers require infrastructure data and terminal data to optimize their behavior. Logistic Service Providers, shippers, and consignees can utilize this (real time) data to plan their goods flows and bundle shipments and/or transport capacity. These developments contribute to the Physical Internet[46] that is expected to optimize [47] logistics.

Central issue to this use case is that **the heterogeneity of data in logistic chains is an unsolved issue**. The variance occurs on all levels:
1. Not every partner in a logistic chain is willing to share data (sometimes, information carries a direct competitive advantage).
2. Data comes from a wide range of different sources, and cannot be easily judged based on quality, and cannot be easily processed because of different formats and meanings
3. Processing of data is needed on various and different levels: from descriptive analytics (real-time situational awareness, time horizon: hours), to predictive analytics (resource synchronization, time horizon: days), to prescriptive analytics (chain composition and control, time horizon: days, advanced planning, time horizon: weeks/months).

The required technology will be called *Leagile Logistics*: a data driven chain composition and control based on logistic services and real time data.

Not only the resilience of individual stakeholders to cater with (unexpected) changes will be addressed by these types of algorithms and data sharing, but also the utilization of the complete network will improve like estimated for the Physical Internet. One of the challenges is to investigate the impact of planning with real time data on the stability of this network: what will be the effects . Examples could be that transport capacity is in not available in the proper places (e.g. relevant to for instance container repositioning) and parts of the infrastructure are not properly used. Whereas the current systems is stable but requires improvement, these improvements could lead to an instable system.

Use case Personalized Health
Technological developments (non-intrusive ambulatory measurement of health markers) have opened a new market for personal health and lifestyle data. Collecting, managing and extracting value from this personal data poses technological challenges that can only be addressed in a concerted effort of interdisciplinary expertises, hence the involvement of ERP Personalized Food and

[46] See also http://www.modulushca.eu

ERP Human Enhancement in this use case. ICT and data science play a core role in cleaning, harmonizing and interpreting the data, while preserving privacy. Key challenges are the development of new methods and algorithms that process massive observational data sources to learn and quantify interactions of stress, physical activity, sleep, food intake, in order to predict outcome variables related to quality of life, physical and mental fitness in order to make an informed, personalized choice between interventions.

9.4.3. ERP Technology lines 2015-2018

According to the European Big Data Value Partnership[48], three main roles can be identified in the big data ecosystem: *data provider*, *data processor and service provider* and *service consumer*, see Figure 1. We adopt this picture to define three main technology lines: ***creating value***, ***extracting meaning*** and ***distributed data infrastructures***. These three lines can also be identified in the use cases.

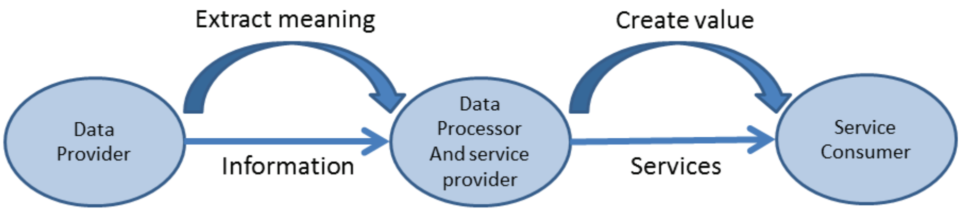

Figure 1: Three roles in Big Data eco system

Data has value to its users, thus leading to potential business models of data suppliers. This technology line explores the value of data to users for a particular business case and the potential business models of data suppliers. Basically, a data chain will be implemented in which the benefits are with all actors can operate both as data user and data supplier like illustrated in the logistics use case.

The value of data to suppliers in for instance logistics is its contribution to improved decision making and predicting the effect of these decisions in a complex system with many stakeholders. Value is on the one hand provided by predictive – and prescriptive analytics in commercial benefits of individual stakeholders, whereas on the other hand it improves the competitive position of the Netherlands (like illustrated in the logistics use case) and impacts the society by capacity optimization.

Based on value that a user is able to create with data, suppliers of this data need to address their business models. Continuity and data quality need to be constantly improved to create value for a data user. Data quality can be improved by models, that also provide data and utilize data of external sources. Methods and business models will be analyzed for data sharing, data enhancement, etc., considering new entrants providing innovative services like data sharing platforms, analytics, etc. A data ecosystem will come into existence that is currently not available (although some services are emerging and/or developed).

<u>Creating value</u>

It is often observed that 'data is the new oil', and that a new form of economic activity should be developed around this analogy. Having said that, a number of questions pop up. For oil, concepts like value, production chains, intermediate (half) products and their status have become clear in the past century. For data, these concepts are not yet obvious and need to be better understood,

[48] European Big Data Value cPPP – Strategic Research and Innovation Agenda, April 2014

especially when we want to apply big data solutions in a situation where more than one organization needs to cooperate. This is the situation in both use cases:

- In logistics, sharing of data is an issue (competitive advancement), and because of the very heterogeneous nature of data, exchange of data is a challenge not only in technological perspective (interoperability) but also organisational (data quality)
- In personalized health the issue of data ownership is of course paramount (linked to privacy issues), and valuation of personal data is a hot debated topic.

We want to be able to **predict the value of a big data application**, based on a number of key concepts. Therefore we need a number of **operational definitions for concepts needed to determine value of data**.

Value is a function of a number of concepts, like metadata, quality, ownership, processing characteristics and usefulness. Data value determines what types of products or services can be made out of data, it influences the competitiveness of the organization, it will cause restructuring effects (new value sources lead to new types of businesses and other organizational configurations) and asks for viable data-driven business models.

The underlying concepts that need to be operationalized are:

- **Metadata**: data quality (precision, validity, availability: these are addressed in the technology line Extracting Meaning), provenance, uniqueness of data
- **Organizational quality**: what is the soundness of the organization that processes and delivers the data
- **Ownership**: what control can the data provider exert on the usage of the data, and can final outcomes be traced back to the data provider(s)?
- **Processing**: how is the production process of the data governed, how is this structured? What types of processes do we distinguish and what requirements do these have?
- **Usefulness**: to what groups of stakeholders (or, application domains) is the data useful (or harmful)? Is the (processed) data actionable and understandable?

The validity of (the definition and implementation of) these concepts will be explored in experiments and model prototypes.

Extracting meaning

Judging the relevance of multiple data streams is a corner stone of this technology line. In addition to a number of generic tools that can help, domain specific models are required to assist when extracting meaning for particular (groups of) stakeholders.

Many of the currently existing tools work fine on a homogeneous set of data. The promise of big data is that heterogeneity will create value. Moreover, stakeholders and their data are part of a larger system, leading to multiple sources and interoperability issues. The challenge is make the tools work on heterogeneous data sources that have differences in

- data quality (consistent, complete vs missing values, correct, volatile),
- timescale and volume
- language (especially in global logistics, language differences may occur), and
- perspective (images, video, 3D, etc.) in time (4D).

Tools need to automatically and real-time link and fuse data of different sources, e.g. based on concepts of semantic linking and Bayesian networks, not only to *visualize* the current situation (descriptive analytics), but also future situations (predictive analytics; what-if) and allow user interaction to support and motivate decisions (prescriptive analytics). Using the domain-specific models, relevant questions and hypotheses can be generated and tested using the tools and the underlying data sources.

1. For instance, visualization in logistics to support descriptive analytics is mostly based on geographic maps with overlays, but other approaches based on for instance more abstract metro maps with overlays for user interaction might be required.
2. For health, the objective is to combine multiple heterogeneous data sets with existing human models in order to move from average causal effect (the current state of the art end result of randomized studies) to individual causal effect. This will require the development of sophisticated analysis techniques that can learn causal effects from observational data, deal with missing values and hybrid (data + theory) guided methods to select comparable subjects from a population for the best data informed individual causal effect estimate. Individual causal effect estimation needs methodologies needs technology for automatic context recognition and activity recognition in ambulatory sensor data.

Because of the sensitive and valuable nature of data and information, these tools and models should be able to operate across multiple domains, where data is kept under control by the stakeholder that generated it. To fuse, split and move data between stakeholders, the semantic framework describing the various data sources needs careful attention.

Distributed Data Infrastructures
An integrated approach with innovations in ICT is required in order to enable secure, reliable and cost-efficient access, transport and storage of the unprecedentedly large amounts of (mostly) strongly distributed data, and to make it available for further analysis, processing and enrichment. This leads to generic infrastructural technologies, that, when combined with appropriate analytic methods, can be applied within a variety of domains, including logistics and health Realization of such large-scale distributed infrastructures for data virtualization over heterogeneous sources requires research in various sub-areas, in particular:

- Data management and (semantic) interoperability, enabling unambiguous exchange and integration of data in heterogeneous environments.
    - Standards and tools for ‘plug & play’ with heterogeneous data.
- Privacy and anonymisation.
    - Scalable anonymisation techniques that ensure irreversibility of the data, while maintaining data quality as much as possible.
- Information centric networking (ICN), that enables flexible (e.g., location independent), fast and secure access to (and efficient transport of) huge amounts of distributed data, based on advanced cloud technology and emerging network virtualization techniques like SDN (software defined networking) and OpenFlow.

(Standardized) protocols, models and tools for optimal architectural design of ICNs.

9.5 Activities and deliverables 2015

The work in the ERP is carried out in three technical Work Packages, following the Technology Lines discussed in the previous section, and in two non-technical WP’s, dealing with Alliance & Industrialization (WP4) and Management & Dissemination (WP5). The two use cases are embedded in the technical WP’s, see
Figure 2.

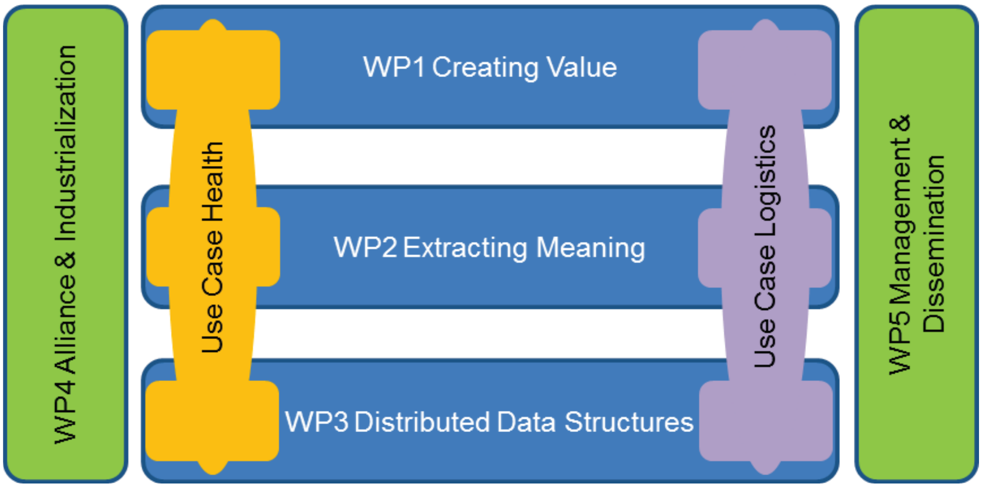

Figure 2: Work packages (WP's) in ERP Making Sense of Big Data

Below we give the Deliverables of the ERP in 2015.

<u>WP1 Creating value</u>

No.	Title	Typical KPIs
D1.1	Preliminary value model that shows what aspects determine the value of a big data application and how these are related	• Number of divisions at stakeholder that are affected by business/value model • Number of intangibles included in value model • Number of stakeholders in eco-system that are covered by value model – read: level of support for value mode • Is value a) identified, b) quantified, c) shared?
D1.2	Validation experiment of data value in logistic chains: operational testing of data value aspects in practical situations	
D1.3	Validation experiment of data value in health: operational testing of data value aspects in practical situations	

<u>WP2 Extracting meaning</u>

No.	Title	Typical KPI
D2.1	Tools for real-time data analytics in distributed data sources	• Scope of predictive model – read: number of stakeholders included • Level of validation of outcomes
D2.2	Predictive and prescriptive data analytics applied to logistics	
D2.3	Model to move from average causal effect in health situations to individual causal effect	

WP3 Distributed data infrastructures

No.	Title	Typical KPI
D3.1	Prototype for plug and play in heterogeneous data environments, using data management and semantic interoperability	• Number of different data streams that can be analysed • Size of networks, number of nodes, number of stakeholders covered for a given level of tolerated delay • Minimum delay (level of 'real-time') that can be achieved in realistic use cases
D3.2	Scalable anonymisation techniques for heterogeneous data environments	
D3.3	(Standardized) protocols, models and tools for optimal architectural design of Information Centric Networks	

WP 4 Alliance & Industrialization

Activities: development H2020 consortia, interaction with academia, establishment stakeholder relations

WP5 Management & Dissemination

Activities: Mgt & control activities; PR; Seed Ideas; Publications & Symposia

10 Signatures

Delft, 30 september 2014

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