Smart Industry roadmap

Research agenda for HTSM, ICT and the route for NWA

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Frontpage: the Shaver factory of Philips in Drachten

1. Societal challenges and economic relevance

1.1 Definition of industry and smartness

Smart Industry is the Dutch strategy to develop the Dutch industry fit for the future [1]. *Industry is defined as* our value creation activities that ultimately result in value created for customers and society. *Smart can be defined as* possession on intelligence. Intelligence has been defined as one's capacity for logic, understanding, self-awareness, learning, planning and problem solving [2]. Intelligence or smartness can be more generally described as the ability or inclination to perceive or deduce information, and to retain it as knowledge to be applied towards adaptive behaviors within an environment or context. To realize intelligence in products and manufacturing systems one needs embedded computing/intelligence or computational devices with network connections.
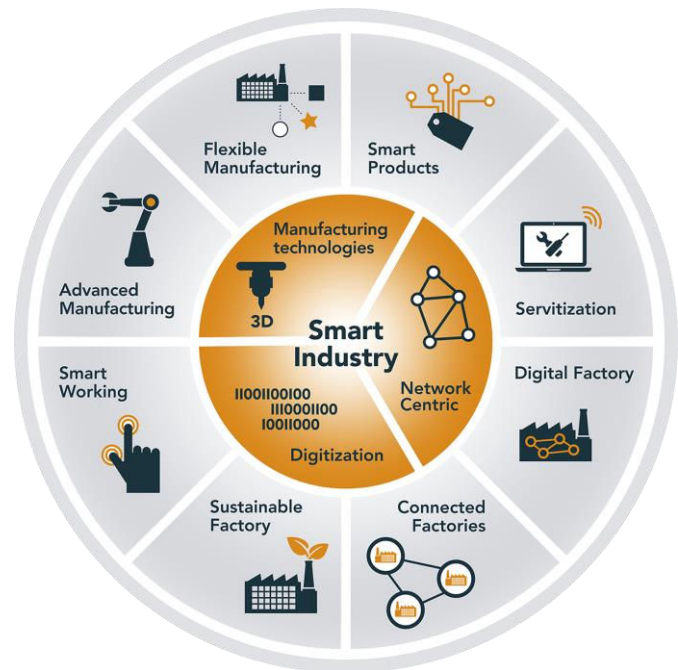

Figure 1 The Smart Industry wheel

1.2 Impact on Society, Business and Technological developments

Today's Smart Industry implementations might seem simple in the context of the above definition of smartness. Nevertheless, internationally it is stated that we are entering the fourth industrial revolution with concepts as cyber-physical systems. In this roadmap route, we restrict ourselves to solutions that can be applied between today and 5-years from now and the knowledge questions for solutions for the coming 10 years as well as a business outlook for 2030. But even in the 5-year time frame it will have huge consequences for technology, business and society. In this introduction paragraph, we define smart industry and describe the consequences in terms of technological development, business transformations and smart societal responses.

Smart Industry is about future-proof industrial & product systems; these are smart and interconnected and make use of Cyber-Physical Systems. Digitization, connectivity and new manufacturing & product technology are drivers for this:

1. High-quality, network-centric communication between organizations, humans and systems, in the entire value network, including the product or service used by the end-users.
2. Digitization of information and communication among all value-chain partners and at all levels in the production process.
3. Granular, flexible, and intelligent manufacturing technologies, adjustable on the fly to meet highly specific end-user demands.

In the coming decade, a network-centric approach to production will replace linear production processes with intelligent and flexible network approaches. These networks will interconnect parts, products and machines across production plants, companies and value chains at a highly granular level. The network-centric approach will radically optimize production in existing value chains and, more importantly, the notion of network-centric production finally spells the end of the 'value chain' and the birth of the 'value network'.

One of the key enablers of the third industrial revolution was the digitization of information and communication. The Internet was instrumental in this, as was further software development. Smart Industry raises digitization to another level. Not only will it enable communication between all partners in the value chain, but digitization of, for example, product quality, user-characteristics and production parameters based on sensor systems (Internet of Things, Blockchain registration and Artificial Intelligence) will also be crucial to new innovations in the production process, products and services and business models. See for the different domains in Smart Industry figure 1.

Within the Smart Industry domain, ICT, Mechatronics, Robotics and Manufacturing are essential in enabling technologies to tackle the big challenges our society is facing. Proper design of machines is necessary for production and manufacturing, semiconductor fabrication, healthcare, etc. and will soon involve functional integration (with e.g. AM), distributed mechatronics (in CPS), active (metamaterial) structures (product design), and further miniaturization. Novel robot technologies, precision motion systems, and energy-efficient drive techniques can, for example, constructively help to address problems we are facing in Climate Change (environmental monitoring, but also more efficient production), Energy (efficient design of machines), Health (novel diagnostic or robotic intervention), Mobility (coordinated intelligent transportations) and Security (Monitoring and Intelligent prevention or Screening).

The technology that lies behind Smart Industry has a great social importance that manifests itself in semi-products, products and services such as health care equipment, energy transitions, automotive etc. and of course the service in which internet and cyber security plays an important role. In fact, Smart Industry plays an important role in all currently relevant National themes in the efficient delivery of technology around processes, products and services. In addition, Smart Industry ensures that these can be delivered efficiently and locally to local, speeding up innovation and realization by a close connection of them and thus the time to market.

In 2016, the NWA (Dutch: Nationale Wetenschapsagenda) route Smart Industry was formulated around the topics as shown in Figure 2 with the impact of Smart Technologies, Smart Production, Smart Products and Services on Technologies themselves, on Businesses and on Society. At the same time, the topsector HTSM (High-Tech Systems & Materials) roadmap in Smart Industry was constructed with a narrower focus. In this NWA/HTSM 2018 Smart Industry document, both the NWA route and HTSM roadmap are merged and extended with the ICT topsector contributions. This results in a broad range of topics, both beta/technical as well as gamma/social. Based upon a SWOT as well as discussions in the field in the regions – national and international – we decided to focus on eight transformations to make Dutch industry fit for the future.

The developments that come together in 'Smart Industry', which can be summarized as smart products, smart production, and smart systems, offer many opportunities as a game changer. However, it is also clear that capitalization on these opportunities will not take place automatically, since it will involve massive reshuffling of production systems, business models and urban and regional organizations. Without a 'smart response', SI developments may have a disruptive effect on Dutch

industry, similar to the effects the failure to catch on to a transition had on Detroit and Manchester in the past.
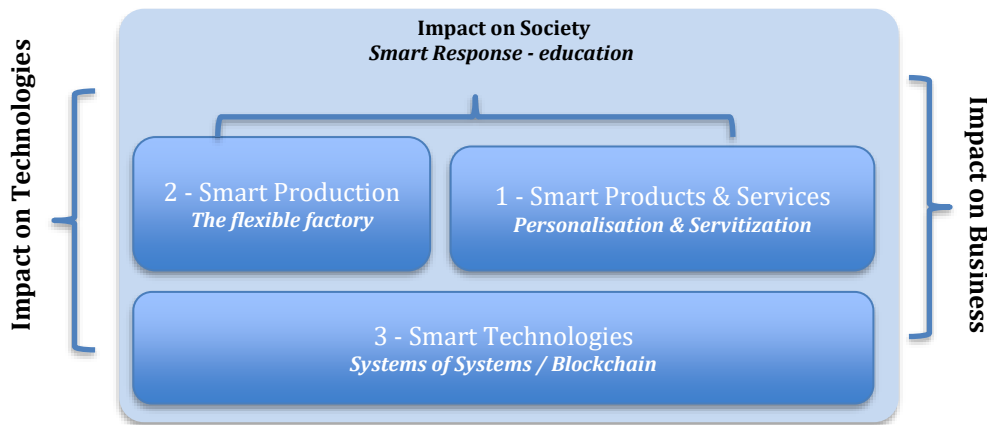

Figure 2 The NWA 2016 Smart Industry model

1.3 Smart Response

Smart Response deals with the response of economy and society to the changes caused by Smart Industry and the disruptive technologies (robotics, AI, embedded sensors and Internet-of-Things) connected to it. The question is not only how we respond to the acceleration of the digitization process but how we can anticipate these developments to realize the desired economic and social impact or avoid the negative effects for specific groups. Smart Response covers: technologies, business and society. Which technological choices need to be made? How do we adapt businesses? What is possible and desirable from a societal point of view?

Smart Industry has a societal impact and leads to radical changes in production processes, business models and consumption patterns. It is important to *explore* the potential societal effects. How do the concepts opened up by Smart Industry affect society? On which points will they put pressure on the existing social order? How will economic ecosystems/networks, sectors, business models, organizations and jobs change? Besides exploring the effects, attention needs to be paid to the question in which areas the Netherlands can develop *unique positions* (points on the horizon) and how these ambitions can be realized (Smart Industry, Smart Society). What is our 'smart response' or smart interaction by consumers, employees, politics, media, etc.? On which aspects will we focus our offensive and on which aspects do we have to be more defensive? Examples are cyber security in open complex systems, or involving ethical, privacy and social values into the early stages of innovation to increase acceptance, but also changes in organizational, managerial, HRM and labor market practices.

Technology can make people redundant, but it can also be used to support people in the labor process. The development of cobots and expert systems that support people in the performance of their tasks and make it possible for people to participate longer or at a higher level in the labor process. The accelerated development of inclusive technology, for instance for older employees, is an important priority.

In the next years/decade, 10% to 50% of the jobs and companies in this sector will disappear (disruptive innovation) or will change dramatically. Training and re-training youngsters and existing employees will involve quite an effort. History shows that adaptation is usually successful, but this will not take

place automatically: rapid development of new business models and new skills are required. We need to develop new learning environments that respond faster to new developments than traditional education is able to do, in particular for employees who got less initial schooling as they were less successful at school and who now face a world of lifelong learning. We need a smart response such that those people can be successful in acquiring new knowledge and digital skills.

1.4 Connection with thematic KIA's

This Smart Industry Roadmap is a part of the existing Smart Industry Implementation Program (especially in the field of AI / machine learning and sustainability), with an explicit focus on the knowledge development / innovation of these technologies within the framework of Smart Industry with key enabling technologies like ICT and engineering & flexible manufacturing. Crucial components for the knowledge base are the (1) key enabling technologies, the (2) valorisation platform and the (3) contribution to missions, prosperity and the economy (see Figure 3). Starting from the key technology engineering and fabrication technologies, this program seeks deepening and connection with other key enabling technologies in order to unlock the innovation with their potential for Engineering and Fabrication technologies. Digital technologies such as Artificial Intelligence are at the heart of Cyber Physical Systems, one of the core technologies of Engineering and Fabrication technologies and Digitalization in general. In addition, Advanced Materials, Nanotechnologies, Photonics clearly offer new opportunities to develop Smart Products, which can lead to new product ranges, new business models and more sustainable solutions.
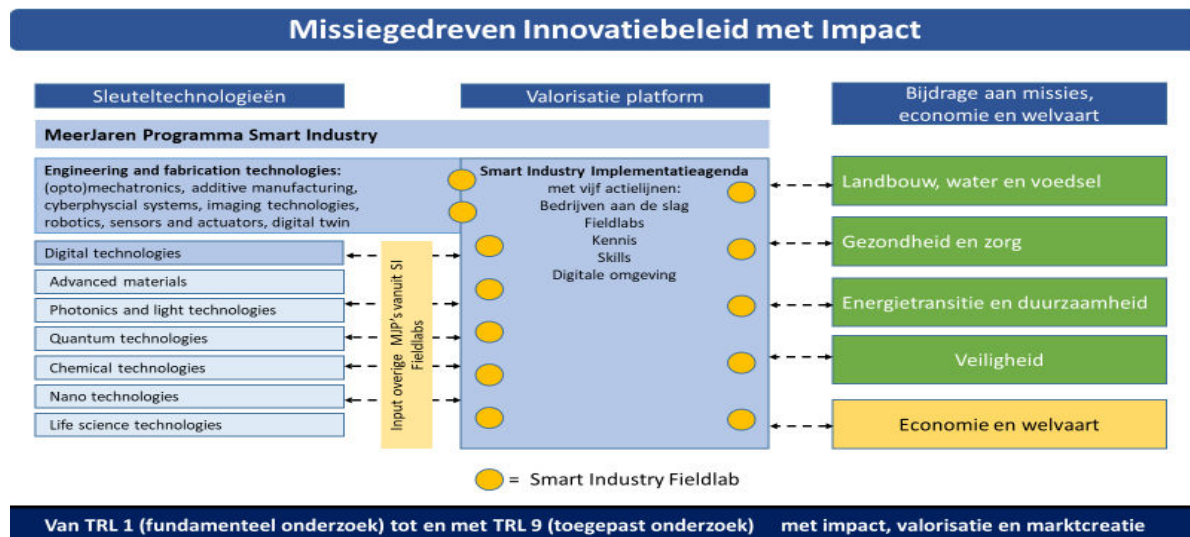

Figure 3 'Missiegedreven Innovatiebeleid met Impact'

The impact of this will be able to cover the full industrial bandwidth, so in addition to the discrete manufacturing industry, for example, also process industry, energy transition, agriculture/ food industry, construction/ utility world, especially where flexibility, automation and digitization are the greatest challenges for the future. These new developments take place via the current Valorisation platforms, which currently consists of more than 600 companies, more than 40 field labs, 5 Smart Industry HUB's, knowledge and educational institutions and digital environments. The key enabling technologies and the Valorisation platforms are an important contribution to realize the missions, the future economy, including jobs and prosperity.

2. Applications and technologies

The 2018 Smart Industry rigorous roadmap update [3] made the connection between the Key Enabling Technologies & Societal Challenges of the national mission-driven innovation policy and the research and technology fields within the scope of the Smart Industry scope. Also, the NWA route Smart Industry has been integrated, which resulted in a powerful roadmap for the coming years.

An important role of this roadmap lies in the guidance of development of adequate knowledge and technology ranging from various scientific research areas, via applied research towards industrial innovation. Therefore, the 2018 roadmap revision provided an extensive description of 17 challenges that cover the field of knowledge and technology for the Smart Industry roadmap. The positioning of these challenges against the main impact/development areas on the one side, and Smart Industry innovation themes on the other side is given in the table below (numbered 1 till 17).

Table 1 Positioning of the 17 challenges

	IMPACT/development areas		
	Technologies	Business	Society
Smart Products & Services	1. Smart Design & Engineer. 2. Integrated Life-cycle Mgt.	11. New Business Models	15. Human Centered Technology
Smart Manufacturing & Processes	3. Additive Manufacturing 4. Advanced Manufacturing 5. Robotics& Mechatronics 6. High Precision Equipment	9. Mass Customization 10. Production Mgt. 13. Condition-Based Maint. 16. Employee Mgt.	15. Human Centered Technology
Smart Systems	5. Robotics & Mechatronics 7. Cyber Physical Systems 8. Digital Twin 14. Cyber Security	7. Cyber Physical Systems 13. (Trusted) Data Sharing	17. Smart Response 14. Cyber Security

From this table it is clear that Smart Industry innovation reaches out to a very broad scope of scientific fields to deliver new knowledge and technology as seeds for future applied solutions.

2.1 Updating the roadmap challenges

The full text of the 2018 roadmap challenges description will not be restated here. Instead, after a slight revision, it can be found as an appendix to this Smart Industry roadmap. This appendix will be leading in the judgement whether research proposals, initiatives etc. fit within the Smart Industry roadmap scope or not, as such judgements are requested in the Top Sector's and NWO approval processes.

This 2020 roadmap update will briefly review the most recent and relevant developments in the field over the last two years, and project those into an outlook for the new roadmap period.

2.1.1. Smart Industry Implementatie agenda 2018-2021 – Dutch industry fit for the future

This [4] document maps out a broad innovation scope along a few clearly described Action Lines:

- Action line "**Bedrijven aan de Slag**", stimulates companies to take action and start available technologies and knowledge into first industrial applications in the factories. This is relevant for the roadmap challenges, since it will bring practical feedback on what really works, and where complications are found or knowledge gaps appear.
- Action line "**Fieldlabs**", to further develop the powerful concept of joint and application oriented innovation in Fieldlabs, where all players are working together to develop new solutions and show others what is possible. This is a good vehicle for this roadmap to funnel knowledge and technology towards application and ultimately adoption in industrial practice.
- Action line "**Kennis**". This is directly related to this roadmap, since its core is the development of new knowledge and technology and mobilize collective expertise and scientific disciplines to serve future Smart Industry needs.
- Action line "**Skills**", to make sure that innovation really gets in the hands of people working in Smart Industry applications. Knowledge on the shelve is not really helping industry, so it is essential to also be aware to timely develop new skills such that it lands in real applications.
- Action line "**Digitale omgeving**", making the point that a digital environment providing access to all kinds of data, information sources, connected communication and protocols for secure data sharing, is a prerequisite for almost any Smart Industry innovation. This is why this roadmaps covers a lot of these topics and also keeps an eye on related developments in the ICT domain.
- Action line "**Samenwerking met de regio's**", to connect innovation power at bigger regional scopes. This roadmap is about the content, and encourages research initiatives that bring relevant areas of expertise together, irrespective of where they might come from.
- Action Line "**Internationalisering**", even expanding to international scope of developments.

2.1.2 Meerjarenprogramma Smart Industry – Digitalisering van de maakindustrie

December 2019 (in Dutch). This program is the result of broad consultation of industry, suppliers, knowledge institutes and system integrators, and therefore provides a solid and actual program of industry needs and shared views on routes for innovation.

- "**Flexibele productietechnologie**", the urgent call for solutions to deal with high mix, low volume in a flexible, efficient and defect-free way. For many challenges of this roadmap flexibility is a key driver for innovation.
- "**Smart & Sustainable Services**", introducing more emphasis on sustainability and servitization as topics for innovation and knowledge development.
- "**Digital Twinning**", which is already a separate challenge in this roadmap, since the 2018 update.
- "**Data-ecosystemen – veilig industriële data delen**" is about digital infrastructure, data sharing, cyber security, which are all topics already represented by challenges in this roadmap.
- "**Mensgerichte Technologie**", is about human-technology interaction, and also the new set of skills for people working in industry, especially manufacturing. In this roadmap this is covered by a separate challenge.
- "**Smart Response**", is introduced as a challenge in the 2018 update roadmap, and addresses strategies and guidance in dealing with changes induced by Smart Industry at various levels.

2.1.3 Business outlook 2030

Recently the European Commission further enforced CO_2 targets for 2030. It is expected that this will impact in particular the energy and process industries. New high-tech systems will be needed on short notice to realize any impact by 2030. But given the size of the challenge this will evolve a huge new market and therefore many opportunities for process equipment manufacturing companies and their suppliers. For example, new technologies and huge manufacturing capabilities are needed to evolves today's largest electrolysers of 4 MW into solution to provide by 2030 40 GW at European level alone (and 1.000 FTE in NL Bron CE Delft expected jobs). But, …

The costs of CO_2 avoidance, reduction and taxes will impact the price of materials as used in the manufacturing industry, plus for the manufacturing industry the same CO_2 target apply. First of all companies will evolve in energy and material/waste reduction in their own manufacturing operations (type 1), but they will also be force by the customers who want to reduce CO_2 and material consumption within there supply chain (type 2), for examples from less transport movements between partners to optimizing grid load with e.g. energy supplier. Those suppliers soon have to perform on price and quality as well as on sustainability. But the main challenge in due time will be the sustainability of the use of the manufactured products by customers and the end of life actions, the type 3 challenge. How this will impact industry is not known yet, but some scenarios are likely. One possible scenario is described below.

The Dutch industrial society can be characterized as leading in specialized eco-systems in which suppliers are part of several different high-tech value chains with a proximity, a high trust level, knowledge spillover function at regional level (a unseen mechanism behind Porter's competitive advantages of nations/regions) and a highly educated workforce. This all lead to a position in which the Dutch perform in realizing cost-effective complex high-tech equipment hardly any other industrial ecosystem can realize. "It has to be so complex no-one else can make it"'. One particular competitive competence is the non-hierarchical multi-disciplinary cooperation's and the breadth of start-ups, SME, hidden champions and large world players and the triple helix cooperation's between companies, knowledge/teaching institutes and national/region government. This provides us with the basis of an even more integrated eco-system.

Each high-tech equipment OEM-er and all suppliers will have to further improve flexibility (smaller series, more autonomous processes), automate and digitalize their internal operations and become part in a full digitalized transparent chain-deep, real-time planning and controlled value chain. In the development this decade towards sustainability with CO_2 reduction, material scarcity and higher material prices, it is expected that OEMs evolve toward or create new entity as ESP's (capital Equipment Service Providers/lease companies) which will remain the owner of the equipment (material) and sell solutions based upon the usage of the equipment.

ESP's will create a re-x market (repair/reuse/refurbish/disassembly-component-and-remanufacture/ recycle/warehouse storage). This re-x market will create new and different dynamics for the suppliers and OEM-ers. In these eco-systems more flexibility (product changes) and value chain/cycle transparency (rescheduling, component reusability) will be key to be competitive at world level. This requires that all partners (suppliers, OEM, ESP, re-x-ers) become digitally interconnected and use the same data spaces with digital twinning information product design/manufacturing/usage/component traceability and (historic) status information of each product.

The short time focus is to accelerate digitalization and flexible manufacturing to be able to supply at world class level, zero defect, zero delay, zero surprise processes. That can be in robotics, AGVs, cyber-physical systems, digital twining, data space, human-technology interaction, virtual reality/simulation, hyperconnected systems, decentralized/autonomous systems, etc. But also progress must be made in use (cyber secure) open systems, standard equipment data interfaces, paperless operations, chain deep MRP, use of AI as well as maintain a competitive edge (more precise, faster, better yield, cost-effective small series, etc.) and expand cross-domain cooperation from precision to mechatronics and from (smart-)materials to software and from additive manufacturing at macro to nano/surface scale. This should lead to faster development and maintain/strengthen our competitive position, in particular once we remain able to spill over new insights and knowledge in our eco-systems.

Today's focus on internal as well as ecosystem digitalization will be the basis to realize the re-x ambition as only with access to (old) data and extreme flexibility the re-x business can become economic viable (type 3 sustainability, as e.g. with the re-x aspect). Inside each supplier/OEM-er (and future /re-x-er) own factories/warehouses an even higher degree of digitalized operations and flexible automated manufacturing equipment is essential. That is, higher than the already high ambition for the linear transparent supply value-chains digitalization and flexible production we fore for the coming 5 years. In general one can describe these 2030 systems as autonomous systems, which will be more and more AI based as e.g. in an re-x a robot or operator who gets every day complete different older products back and has to be able to immediate know what it is, what the status is and perform the proper operations. That is one step further in flexible manufacturing of today where each order is only released for production when all equipment, tools and components are ready. It does help if products get more and more own embedded intelligence and it requires that all information is available as digital twins in manufacturing/product data spaces.

As described above the digitalization and flexible manufacturing in this roadmap for the coming years will provide the basis for the goal of reduction of energy and material use of the manufactured products during the life-type usage. So any competitive edge and innovation investment in today's ambitions, strengthens the preparation for the nearby future when sustainability market demand become mainstream. As stated the target is 50/55/60% CO_2 reduction in 2030 as set by society.
The roadmap is clear, the question/worry is that in order to achieve the impact society wants, we might need to accelerate and increase our investment in applied research and development significantly.

2.1.4 Trends, technology accelerations and research priorities

From the review above, the conclusion is justified that the roadmap challenges of this Smart Industry roadmap are still well-aligned with the future knowledge and technology needs. There does not seem to be a need for adding new challenges or abandoning any of the existing challenges. However, some trends and technology breakthroughs give rise to shifting emphasis or reconsidering priorities.

Recent developments that stimulated research and enabled acceleration of innovations towards Smart Industry needs, and are therefore important drivers for this roadmap:
- Significant advancements in computational power, enabling more complex calculations to be executed in shorter time, processing more data and having results available nearly real-time.
- Broad availability data and sources of information with an increasing bandwidth of (wireless, 5G) connectivity and data transfer.

- Improved algorithms for data analytics, artificial intelligence, machine learning.
- Rapid development of digital twinning and other advanced modeling tools. These benefit strongly from all the above (computational power, growing access to data, and more powerful algorithms).

Two upcoming/rising subjects that generate an increasing push for knowledge and technology development are:

- **Sustainability**: The urgency for sustainability within industry is growing. This involves the broadly acknowledged attention for energy efficiency, recycling and waste, renewable energy. More recently, we have seen international, and national agreements on CO_2 and N impacting many industrial sectors. This calls for research towards more advanced solutions to serve both the industry and the environment.
- **COVID-19**: The COVID-19 pandemic confronted industrial manufacturing with serious consequences. It has shown how vulnerable the world-wide supply chain is that under normal circumstances has been taken for granted. There is a call for more manufacturing sovereignty: what is needed to guarantee access to essential products through local production under own control in times of global crisis? This provides us with huge challenges in terms of technology, workplace organization and infrastructure, but also strongly links with new business models and smart manufacturing innovations:
  - Reshoring critical / essential production. How to get parts of production back from low wages countries to our own region, but still be competitive? How to decide what is essential and what not? Is reshoring without vulnerability across the supply chain as such possible?
  - Economic recovery in general; many industries have been hurt or even went bankrupt. How to start up again and recover from gaps in the supply chain? Should we, or can we go back to normal? Or do we have to find new ways to organize industrial processes and production? What infrastructure, work place facilities are required for that?
  - New working / manufacturing standards within COVID-19 protocols
    - How to organize manufacturing with social distancing?
    - How to maintain productivity while following additional procedures for cleaning and other overhead time that reduce productivity?
    - How to preserve productivity when complete shifts fall out because of 10 to 14 days quarantine periods in case of infection of co-workers? How to increase levels of automation to be less vulnerable?
    - How to solve manufacturing aspects of testing material, processing, tracing, handling of samples, packaging, sealing, disinfection machines and washing lines?

Other research focus themes with increasing priority that bind several roadmap challenges together:

- **Autonomy in industrial manufacturing**: for flexible manufacturing without human intervention (i.e. automated) or direction at each step of the manufacturing processes, intelligence is needed at all hierarchical levels, that make subsystems act autonomously at a substantial task level. Autonomous vehicles, robots for automated manufacturing or material logistics in industry are typical applications that require multi-disciplinary knowledge and technology development around the theme of autonomy in industry.
- **Integration**: by going beyond a single system, and involving all elements in the chain of operation, assembly and logistics, we will be able to address the integrated challenges. This is relevant for the flow of physical production steps, but also holds true for the connection between design & engineering with manufacturing & assembly.

- **Automation of mainstream design, concept generation from regular specifications**. To speed up the engineering development process, both time and resources can be saved if (parts of) the expertise and process from specification to design concepts can be automated. Initially for state-of-the-art system architectures to meet regular, not challenging requirements. Automation of design intelligence and expertise is likely to be a need that will see rapid advancements when Artificial Intelligence is successfully connected to the engineering domain.

- **Digital to physical connection**. The developments towards digitalization is very dominant the last years, and will disrupt many established principles and ways of working throughout industry. To fully benefit of these development, also the digital to physical reality interfaces should be addressed. It will become increasingly important to harvest any benefit from all digital tools and software in the physical systems and manufacturing practice. We see interfacing between digital and physical at all levels. Not only a digitally connected information and data sharing backbone across a factory is sufficient. Real production and operational impact requires real-time interaction.

- **Speed everything up to real-time**. That is where real things happen in practice. We have go beyond offline processing, delay times for model simulations, or data analysis. We have to develop knowledge and technology, for example to speed up real-time AI such that it really has impact on causal and physical processes or systems of industrial applications.

- **Extreme integration of models and data**. For example Augmented and Virtual Reality technology (AR/VR) is developing rapidly, but also (coming from another direction, but ending up at the same crossroad) digital twinning. Again, manufacturing and system applications take place in the real world. Modeling is becoming more powerful, and ultimately integrates all system aspects into almost real-time simulation. On the data side, integral (but heterogeneous) data streams provide also almost real-time information streams. The integration of both model based and data driven information streams should be forged into new possibilities (accelerated by rapid advancements in computing power and artificial intelligence, making machine learning also real-time).

- **Dealing with heterogeneous information**. As a consequence of the digital developments, the sources of information, and data sharing platforms we see data piling up in unorganized large data lakes and information streams of all kinds. Such unstructured and heterogeneous big data set will be useless for identifying causal relations between physical systems. Theory and methods to obtain useful data sets will be needed to get access to the potential value of the data and lead to improvements in real life applications.

- **Dealing with change**. Including the capability of humans to deal with all innovations, changes in work routines, continuous learning. Technology without adoption will not lead to real progress. Shifting of roles and responsibilities. Getting accustomed to alternative processes to come from specification to processes. Learning to rely on results from artificial intelligence, even when the results cannot be completely understood.

- **The eternal battle for precision and speed** serves a broad industrial and knowledge ecosystem. Many of the high tech equipment applications rely on advanced mechatronics to provide motion systems that continuously improve in terms of positioning precision and speed. The underlying mechatronics and associated physics domains, as well as software, electronics, sensors, actuation and control research fields are pushed to develop new theory, tools, and technology to enable the performance increase at system level. Typically we see the interaction between model based and data driven techniques to squeeze the last drop out of system performance improvement. It of crucial importance to keep investing in this battle, because a broad ecosystem of industrial suppliers, knowledge institutes etc. depend on the success of only a few high tech companies at

the top. If those few companies fail to remain successful, because of the lack of new knowledge and technology, it will dramatically impact the whole ecosystems around them.

The above considerations provide emphasis, focus, stimulus, importance and guidance across the existing list of challenges. Not changing the contents so much, rather shifting priorities somewhat and combining them in overarching innovation themes.

3. Priorities and implementation

Smart Industry is a crucial development for our industry and forms the basis to strengthen our future welfare and our competitive position, as well as delivering solutions for our societal challenges. On a low TRL level new technologies related to Smart Industry are constantly being developed, funded by e.g. NWO, the topsector HTSM, Europe and the Dutch industry. A crucial phase that has to go hand in hand with knowledge generation is knowledge implementation and valorization, which concerns the higher TRL's. The research answers to the list of challenges of the previous section, lead to a better knowledge and technology base. However, these are in general not immediately applicable in industry, and additional steps are required to integrate and develop them further into broad implementation of Smart Industry innovations, the so-called transformations. The transformations help to bridge the gap between industry and results gained in public-private research projects.

A national implementation agenda is in place that aims to develop and valorize digital technologies for the Dutch manufacturing industries, both OEMs and SMEs. The implementation of these technologies are categorized along 8 transformation directions. These 8 transformation direction are:

Smart Manufacturing	The ultimate goal is zero-defect manufacturing. Zero-defect implies equipment with high accuracy, extensive data logging. The ambition of smart manufacturing is to make each process step, each individual equipment as smart as needed.
Flexible manufacturing	On demand, configure to order production. High complexity, low volume industries require zero-programming of robots and equipment, large scale use of 3D printing, and direct printing of electronics.
Servitization	New business models based on digital platforms where multiple applications and components work together. Predictive maintenance strategies based on physics, IoT and big data solutions.
Smart Products	Products will have embedded intelligence to communicate with their environment/users. Capital goods will be customer specific, consumer goods highly personalized.
Digital factories	The entire factory internally connected. All products, processes and equipment have a digital version (digital twin) for their entire life cycle.
Connected Factories	The ambition is to optimize, to lower costs, remove all errors and the speed delivery over a total value chain. International Industry 4.0 standards and blockchain including digital identities become a standard available technology.
Sustainable Factory	A sustainable factory uses the least amount of energy and resources as possible. It also uses as much recycled/refurbished material and components as possible. A sustainable factory in the future will also be able to assemble and disassemble in lot-size one.

Smart Working	Workers in a factory are fully supported by technologies (e.g. exoskeletons, cobots, AR/VR support) which makes them more productive and competitive on a world level. But smart working also involves (social/legal) conditions as set by the desired economy & society.

The Smart Industry implementation agenda will use Smart Industry fieldlab and regional cooperation ecosystems to bridge the TRL 4 to 7/8 technology readiness levels. Currently there are five regional Smart Industry Hubs (SIH), The regional SIHs closely collaborate with the national program office and each SIH has its own action agenda which aligns with the national action agenda. Each of the SIH have set up a plan to support the early adaptors in their developments, to assess which steps are needed in the field of production-, cyber-, data- or AI applications and support the companies in implementing these developments. These regional SIHs have a strong network of regional SMEs and have one or more physical locations with facilities for research, demonstrators, implementation in a production environment and skills development. Currently the five regional SIH are Regions of Smart Factories, Smart Industry Noordvleugel, Brainport Industry Campus, BOOST, and SMITZH.

Part of the regional smart industry hubs are the Smart Industry Fieldlabs. A fieldlab is an (physical) environment in which Smart Industry solutions are being developed, tested and implemented and where workers can be educated how to use the new technologies. Fieldlabs are Public Private Partnerships where companies, government and knowledge institutes collaborate. Currently, over 40 fieldlabs are operational in which € 314 M is invested (of which € 117 M private investments).[1]

3.1 Reference to MJPs

Within the Knowledge and Innovation Agenda for Key Emerging Technologies, MJP's (multi-annual programs) have been developed. The MJPs are consortia of companies, governmental departments and knowledge institutes which cover the entire knowledge chain from fundamental research, through applied research to valorisation and market creation. Currently 51 MJP's have been developed and some of these MJP's have strong ties with the roadmap Smart Industry. MJP 34 has the strongest link with this roadmap, as this MJP is partly based on this roadmap, as briefly addressed in the previous section. Other MJP's that have significant links with the roadmap Smart Industry are listed below as well.

Table 2 Description of MJP's that have a significant link to the Smart Industry roadmap

MJP	Title	Link
34	**Smart Industry**	**flexible production technology, robotics, smart and sustainable services, digital twinning, data ecosystems, human centered technology and smart response**
07	Quantum	Metrology, high performance computing
18	Flexible Electronics	Cost-effective and eco-friendly production processes of future microelectronics and sensor technology
20	Beyond 5G	Connectivity for high tech production, cloud computing

25	Semiconductor equipment	Sensors and actuators, imaging systems, opto-mechatronics, robotics, model-based design and engineering, machine and deep learning
26	System integration	system performance, systems of systems, digital twinning, system architecting
27	Composites	material and process development, automated production processes, recycling processes
44	AI	big data science, data analytics, AR/VR, cyber security, digital twinning
80	Material technology	production processes for advanced materials, additive manufacturing, recycling

4. Partners and process

The Smart Industry community is organized around the Dutch Industrie 4.0 program: Smart Industry [1] by FME, MetaalUnie, Chamber of Commerce, Ministry of Economic Affairs and Climate and TNO. The FME and MetaalUnie represent more than 20.000 Dutch companies in the metal and electro business from construction, maritime, agro/food till high-tech instruments and systems industries. The Smart Industry program itself consist of 5 region hubs with in total 43 so-called fieldlabs, high TRL innovation experimentation, testing, application and skills environments.

Within the research and technology community, the Smart Industry program has a route in the NWA of NWO (nationale wetenschaps agenda) and (this) roadmap in the HTSM topsector. The NWA has a scientific, broad societal focus including also the gamma sciences. The HTSM roadmap has a more technical science/engineering focus.

In the 2019 the Smart Industry route and roadmap team, in the context of the request from the ministry of EZK for 'meerjaren' programs (MJP), organized 4 sessions. Three sessions with mainly companies at FME and at the Eindhoven BIC and a fourth one with mainly academic representative with around 150 participants were held end 2019. The outcome was an update of the route/roadmap, extended with specific input from the robotics community (via the HightechNL community) and the emerging Digital Twinning community to cover the engineering and manufacturing focus area of the key technology mission program as suggested by the MJP initiative of ministry EZK.

In 2020 the flexible manufacturing/robotics and digital twinning chapters of the route/roadmap are expanded with artificial intelligence/machine learning topics for robotics/flexible manufacturing applications with a particular focus on combining AI models with Digital Twin (physics-mathematical) models. Here the Smart Industry community works together with NL-AI coalition. In parallel the servitisation & sustainability chapter is building a bridge between servitisation business models research and the circularity/recycling "uitvoering" programs of the energy mission program. Finally the data sharing chapter activities are getting more traction as in Europe the Gaia-X initiative is launched in with the IDS (industrial data space/international data spaces) is a key component and where the Dutch Smart Connected Supplier Network is the leading example. The coming years also the EU will focus on the digitalization of Industry in the "Made in Europe" program as a part of Horizon Europe, in Figure 4 there is an overview of the technical subject of this Made in Europe program.
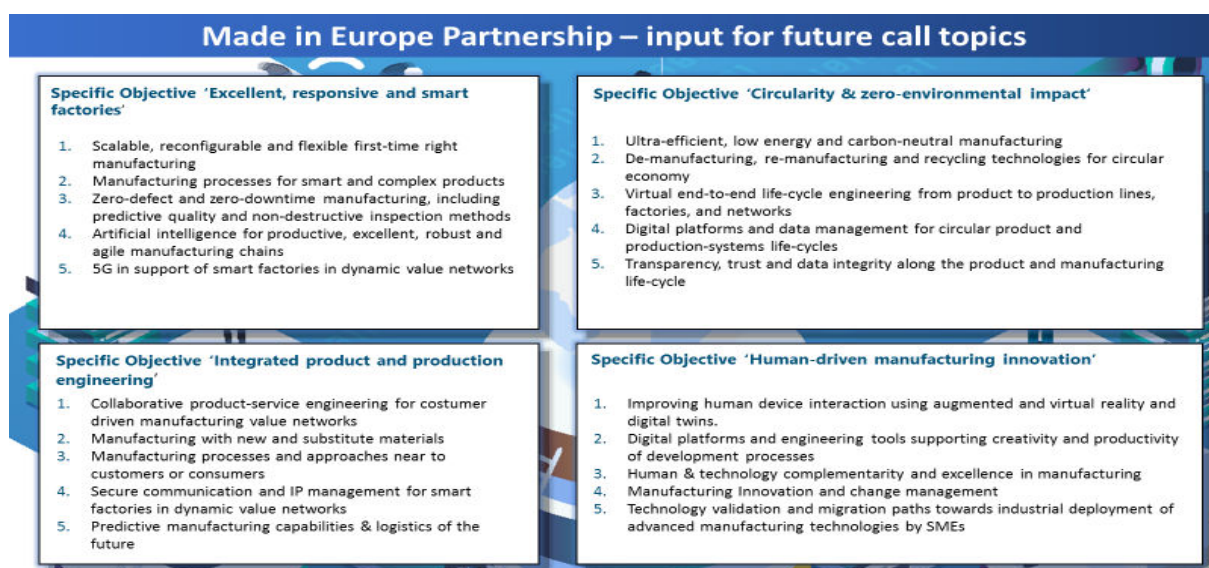
Figure 4 Extract from draft Made-in-Europe Horizon Europe plan

4. Investments[2]

At this point, a budget estimation can be presented, although it should be noted that this estimation is very much under development because of ongoing discussions with companies and expected response from broad communication about the draft roadmap draft within the above-mentioned communities and platforms.

The numbers presented below should therefore be considered as an indication and not a commitment. Given the nature of this roadmap, Smart Industry-related topics are part of all and any development project within the Dutch industry. Double counting is therefore inevitable.

The present status of the industry commitment to the Smart Industry roadmap is derived from the signed Letters of Intent from 2019, and these are being processed to get the correct numbers.

Table 3: Forecast of national investments related to the Smart Industry roadmap*

Roadmap	2020	2021	2022	2023	2024
Industry	20000	25000	30000	35000	35000
TNO	6000	8000	10000	15000	20000
NLR	100	100	100	100	100
NWO	6000	6000	6000	6000	6000
Universities	10000	10000	10000	10000	10000
Departments (excluding TKI)					
Regions	15000	16000	17000	18000	19000
total	57100	65100	73100	84100	90100

*All figures in thousand € per year (cash and in-kind value), exclusive the NWA

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[2] R&D in public-private partnership, including contract research; all figures in million-euro cash flow per year (cash plus in-kind contribution)

Table 4: Forecast of international related investments within the Smart Industry roadmap*

EU within roadmap	2020	2021	2022	2023	2024
Industry	30000	30000	35000	35000	40000
TNO	5000	9000	18000	20000	25000
NLR	100	100	100	100	100
NWO	6000	6000	6000	6000	6000
Universities	5000	5000	5000	5000	5000
EZ co-financing of EU programs					
European commission	10000	10000	10000	10000	10000
total	56100	60100	74100	76100	86100

*All figures in thousand € per year (cash and in-kind value), including national investments, exclusive the NWA

The above is a very rough estimate, partially based on the guideline that approx. 1% of the industries total R&D funds will be spent on this roadmap, based on the current situation and extrapolated to up to 2024.

Due to apparent overlap between various HTSM roadmaps, it is uncertain which roadmap will be applicable for specific innovation. The nature of many Smart Industry topics for innovation is that it supports many different applications (semiconductor equipment, healthcare, printing, automotive, etc.) so although the innovation topics are clearly addressing this Smart Industry roadmap, it may turn out that the activities will be collected as innovation projects in other roadmaps that exploit Smart Industry knowledge and technologies for their application.

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[3] [Online]. Available: https://www.hollandhightech.nl/smart-industry.
[4] S. Industry, „Implementatieagenda 2018-2021," Februari 2018. [Online]. Available: https://smartindustry.nl/roadmaps/smart-industry-implementatieagenda-2018-2021.

Appendix

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Challenges description
2020 update reference document

September 2020
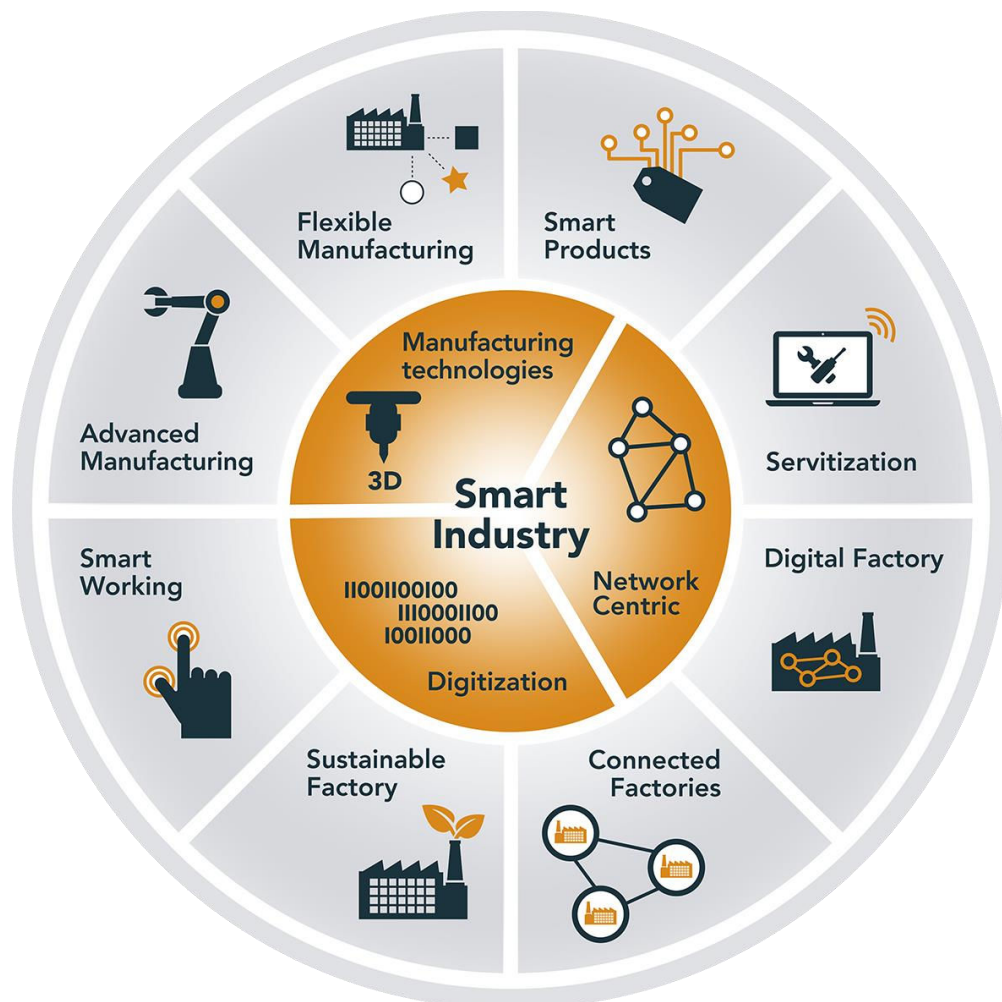
Table of Contents

Smart Industry challenges

This document covers the knowledge and technology challenges for the Smart Industry roadmap. It is a reference document to the 2020 Smart Industry roadmap update, and provides an extensive description for each challenge, for which there is no room in the roadmap document.

With each roadmap update, the main roadmap document will reflect on recent developments that are relevant for the underlying challenges, and the reference document itself will also be updated in order to align with actuality of science, technology and application developments in industry.

This document will serve as guide for judging research proposals for fitness with the Smart Industry roadmap, as this is required by Top Sector HTSM and NWA approval procedures.

The order of the challenges description below is arbitrary and does not reflect priority in any way.

	IMPACT/development areas		
	Technologies	Business	Society
Smart Products & Services	1. Smart Design & Engineer. 2. Integrated Life-cycle Mgt.	11. New Business Models	15. Human Centered Technology
Smart Manufacturing & Processes	3. Additive Manufacturing 4. Advanced Manufacturing 5. Robotics& Mechatronics 6. High Precision Equipment	9. Mass Customization 10. Production Mgt. 13. Condition-Based Maint. 16. Employee Mgt.	15. Human Centered Technology
Smart Systems	5. Robotics & Mechatronics 7. Cyber Physical Systems 8. Digital Twin 14. Cyber Security	7. Cyber Physical Systems 13. (Trusted) Data Sharing	17. Smart Response 14. Cyber Security

1 Smart Design & Engineering

An integral part of the Smart Industry roadmap is the Smart Design and Engineering challenge. The challenge addresses the lifecycle phase of design and engineering, responsible of translating customer requirements into product and manufacturing process specifications. With increasing variations in customer demands and increased automation of the factory, the design and engineering organization has to be able to address more input variations and deliver more information to the factory, while pressure on time-to-market requires faster delivery more than ever before.

The trend of work in industry is moving away from conventional manufacturing to design and engineering ("Praetimus, 'Productization of supply chain companies', white paper, 2016"). One of the key conclusions is that the added value of the manufacturing function is decreasing while that of the design and engineering function is increasing. The way design and engineering is performed will change

considerably due to increased complexity and reduced lead times. The processes will become highly integrated and automated. The challenge is to extend the current state-of-the-art in design engineering with smart capabilities. This requires attention for custom-based design for products that can be manufactured in a smart way. In fact, we are heading towards mass-customized designs that must be produced first-time-right. Consequently, we require tools for mass-customized design that strictly ensures manufacturability.

The focus of this roadmap is on adding intelligence and the use of the internet to existing solutions in design and engineering capabilities. Four fundamental areas of improvement are identified. First, intelligent add-ons to existing models need to be developed to realize the model-as-a-service while meta languages will be developed to support rapid (re)development and (re)configuration of models. Second, system integration and standardization of interfaces will be of key importance. Methods are required to flexibly integrate and reconfigure models across disciplines and organizations. Standards for data exchange and communication to support flexible, integrated, reconfigurable processes across disciplines and organizations are needed as well. Third, new control paradigms are necessary to enable experts to control operations of these complex and highly automated systems, including integrated verification and validation methods. Finally, means need to be developed to reuse data and models beyond the original scope of application. Develop methods to extend data and models with meta data to support future reuse.

This challenge is linked to other challenges in the roadmap. Integrated lifecycle management is linked to this challenge because, as the application lifecycle becomes shorter, the design and engineering organization has to focus on the knowledge lifecycle behind the application. Also Cyber Physical Systems have connections to this challenge, since the multi-physics design aspects and system engineering way of working will require even stronger interaction to deliver high-tech system solutions. Human Technology Interaction is required to enable users to address the far more complex and dynamic design and engineering process. New business models support the new collaboration strategies required to enable the integrated design and engineering process across organizations.

Mass customization and personalization does not imply that more variations of one product will be made. Industry can focus on creating more personalized added value for stakeholders, end-users and society at large. Ultra-personalization enables us to be better equipped with made-to-shape products and services, for example based on 3D scanning and anthropometric databases. Such a parameterized design offers more comfort and greater emotional attachment than any standardized size systems, enabling to better produce to sales than bulk production. This is now common for hearing aids and dental solutions, which in turn have transformed from product delivery to product service combinations – infused by big data and additive manufacturing. Similar opportunities arise for other domains that depend on human capabilities (ranging from supporting professionals to people with special needs).

Smart industry redefines the profession of design and engineering. New creative profiles are being developed such as the societal complex system designer, personal value designer, critical mass designer, advanced production designer, and intelligent interactive system designer. Although the notion of human centeredness will remain, adaptation of new methods is required, ranging from software engineering (agile, version management), robotics (reasoning/intelligence, augmented awareness), towards organizational sciences (critical system thinking).

Smart Design starts with reflections on societal changes and looks for a balance between collectivity and individuality. Uniqueness is a great good and part of the achievements of modern society, but has a downside that can negatively impact solidarity. It is becoming increasingly easy to develop custom-made products and services, but what will be their impact on sustainability? How do we create products and services that meet the need for a personalized offer? How can we create value for the end-user through digitization and information in production, content creation and design? The creative industry views this as a challenge that contributes to the Inclusive and Innovative Society; it builds on the technological challenges of the Smart Industry program and ties in with desired and desirable solutions. In doing so, it connects with the NWA Smart Industry route and offers fertile grounds for the NWA route to Art and human oriented Research and Innovation.

2 Integrated Life-Cycle Management

Over the past years, the requirements made of industrial manufacturing companies have increased enormously due to ever changing market situations. Companies have to respond to external changes (e.g., increasing globalization, increasing market orientation, growing model variance, increased quantities, shorter product cycles, decreasing target costs) and internal changes (e.g., growing product complexity, increasing modification frequency of parts). New technologies like cloud computing, 3D printing etc. as well as the influence of cyber physical systems will intensify this trend towards the future. New and complex products will be developed for a customer-oriented market.

The production of highly customized products with short life cycles addressing volatile markets will require new structures and operational strategies from their supply chains. Future supply chains will need to reconfigure dynamically as customer-specific products will be based on an increasing number of specific components. This calls for new technologies, structures and ICT systems to establish ad-hoc supply, manufacturing and de-manufacturing networks for customer-specific products. These networks support decision makers in finding and establishing the best possible supply chain solution for any specific order. New supply chains that address globalization and the integrated offering of products with services will require new approaches that take into account movement of material, exploitation of clusters of manufacturing excellence alongside an ability for local customization.

Process design is gaining in significance. It is critical to the long-term success of a manufacturing company in the intensifying global competition. Processes are dynamic and call for adaptation to the changing external and internal requirements as well as for the integration of new technologies and the complexity caused by the cyber physical systems. The goal is flexible and continuous processes support the entire product life cycle from product planning and generation in engineering, procurement and production to distribution, service and recycling/end of life. In this context, information develops from a production factor with increasing meaning into an important success factor.

3 Additive Manufacturing

Additive Manufacturing (AM) is a promising and rapidly progressing field that provides unsurpassed design freedom and opens up many favorable possibilities in system architecture when combined with design optimization. AM has numerous advantages compared to conventional subtractive manufacturing. It enables efficient manufacturing of complex, personalized and customized products built up layer-by-layer with high precision, resource efficiency (near-net shaping) and cost effectiveness. AM offers the possibility to create multi-material products (combination of, e.g., metals, polymers, composites, ceramics) and parts with material gradients. Typical AM technologies are 3D printing, tape placement, braiding, laser cladding, friction stir welding, etc. Technological advances in

AM will reduce the manufacturing accuracies of micro and nanoscale features, while at the same time increasing production speeds.

Integration with design tools and CAD software will allow AM to have a significant impact on both time and cost savings, as well as weight, storage, tooling, assembly, transportation, supply chain management and maintenance. By utilizing numerous state-of-the-art technologies such as pick and place, dispensing of viscous materials, sintering, etc., additive manufacturing can leap itself from merely producing bespoke dump parts to building smart objects printed locally. AM will be an enabling technology for many applications, such as embedded and smart integrated electronics, complex high-tech modules and submodules and human centric products like dentures, prostheses, and implants.

AM requires additional technology development to improve on cost, speed and quality, and therefore developments are needed in the field of new concepts for multi-material, multi-technology digital manufacturing, and high-speed continuous AM technology. Multi-scale computational material and process-level models are required to capture textured and multi-property functionality. New models need to account for the influence of printing process parameters on the resulting mechanical behavior and functionalities. Different length scales will be relevant for proper macroscopic characterization. These can be used to investigate aspects such as three-dimensional topography, surface texture and porosity, as well as residual stresses and delamination to improve AM accuracy and quality. AM provides an overwhelming design freedom for complex 3D structures. This freedom can only be exploited to its full extent via advanced topology optimization techniques.

AM equipment should enable first-time-right manufacturing, higher throughput, better precision, larger dimensions and more versatile processes. These process developments should be accompanied by progress in advanced materials, with an emphasis on the related areas of laser and printing technologies, real-time in-line metrology, control technologies and machine learning protocols. Besides standards for materials, new design programs, machine processes, and qualifications for built parts have to be developed to turn AM into a mature production technology. Also required are protocols for intellectual property rights in part designs for a digital workflow in many locations (encryption, standard file format, security for defense).

Finally there are challenges in new "smart" AM materials. These can be used for new levels of manufacturing such as 4D printing, higher reliability trends as well as recycling, end-of-life aspects such as easy disassembly, etc., and also for advanced functions realized via structuring by combining proper material selection and structuring in e.g. sensing and actuation. These smart materials include metamaterials. Connected to structuring are integrated manufacturing, functional integration in smart devices and design. Instead of a focus on isolated material structures, there is a focus on application, integration, design and manufacturing.

4 Advanced Manufacturing

Advanced manufacturing technology contributes to the realization of three major trends in production systems, i.e. increased efficiency, quality and reliability. It requires process monitoring and modelling approaches, associated with novel optimization and maintenance strategies. Improvements in manufacturing technology will be data-driven and can be based on measurements or models (deep-learning techniques, statistics, and physically based models).

Research on integrated computational engineering in the past decades has resulted in many complex models, reaching ever higher levels of accuracy and maturity. In most cases, these models are used to

create a better understanding of the constitutive behavior of the material in question and the related production processes. However, reduced tolerances on product properties require higher accuracy of the current (simulation) models, whereas a higher level of maturity is required as well to make them useful on the factory floor as part of the control system.

The final properties of many products are the result of a sequence of production steps, where preceding steps influence the current production step. Full-process-chain simulation is still in its infancy. The design of highly accurate multi-stage manufacturing processes requires the development of efficient full-process simulation tools. Automatic (mathematical) optimization based on process models is reaching a level of maturity that is acceptable for industry. After optimization, processes tend to perform better, but also become more critical. Therefore, robustness of processes has to be included in virtual process optimization, taking account of natural and uncontrollable variation in material and process properties. A challenge for the next decade is to integrate the evolution of variation in product properties in a full-process simulation for multi-stage manufacturing processes.

Modern production machines are already equipped with a multitude of sensors and actuator systems and this is expected to increase further in the near future. The use of feedback and feedforward control systems has been essential in every automated process stage in advanced production systems to fulfil tight and rigid product specifications at each stage. Yet, such systems cannot handle natural variations in material properties and process conditions very well, which may lead to waste due to nonconformity with the specifications and may cost millions of euros a year in product, labor and energy waste for manufacturers. With the increasingly strict requirements for modern high-tech products, a new intelligent control strategy is needed that can take into account material variations in the complete control system, allow for flexible tolerances at each stage and meet the final product specification. The increasing use of ICT and Internet-of-Thing sensors in modern manufacturing has opened a new way for the development of novel control systems design that can lead to drastic improvements in production accuracy, leading towards zero defect.

Current control strategies control the tool movements, temperatures, etc., but not got the state of the product. Advanced model-based control algorithms be developed to control the product properties directly and create a zero defect manufacturing systems. Standard metrology and feedback control is not yet able to adapt to high frequency (product-to-product) variations that are observed in practice. Data processing and translation into corrective actions, adjustments and active control must be improved to bring the desired performance improvement. Improved metrology includes accurate and absolute reliable measurements, measurement setups and measurement methods. Relations between the measured signals and product properties are extremely nonlinear and are described by the process models. Since these process models are usually very time-consuming, lower order models are required for application in control loops. These reduced-order models can then be used to optimize the process or can be incorporated into a control system in a factory platform. A number of issues are very important, i.e. the simulations platform must be very robust and stable, data processing must be fully automatic and standardization plays an essential role to create platform robustness.

Advanced model-based control can contribute to all three main trends: accuracy, flexibility and efficiency improvement. Enhanced control will drive defects to near zero levels. These technological developments enable industrial principles such as Zero Defect, Lean and Just-In-Time manufacturing to reach their full potential, while dramatically reducing cost and impact on the environment.

This approach can be used in zero defect, high-volume production but is also very useful in flexible robotics to speed up the implementation on the factory floor. The adaptive learning process of the emerging flexible robotics could be based on data both from physical modelling and sensors, in combination with adaptive control. This combination will lead to more innovation speed in process development and implementation on the factory floor.

5 Robotics & Mechatronics

Mechatronics integrates electrical, precision mechanical, sensor, thermodynamic and control engineering and software for the design of products, systems and manufacturing processes. It relates to the multi-physics and multidisciplinary design of systems, devices and products aimed at achieving an optimal balance between all basic disciplines. Within the smart industry context, mechatronics systems are pervasive both in the realization of smart processes, as well as, smart products. The current level of mechatronics expertise in Netherlands belongs to the top in the world, based on many years of development in various application areas such as semiconductor equipment, healthcare systems, printing systems, but also mass production equipment, consumer product design, advanced scientific instrumentation, and automotive systems.

Smart Industry themes such as high mix, high complexity, low volume manufacturing, introduce new challenges to robotics and mechatronics. The added value of mechatronics and robotics innovations is potentially very big, e.g. through integration of many sensors, wireless networks, and information technology (artificial intelligence and control algorithms) across the industrial environment (but also other sectors such as food processing, and smart agriculture). This typically leads to integration of more feedback and feedforward control approaches and production automation/robotics technologies into the manufacturing and assembly environment. In addition, handling technology related to gripping, manipulating, complex assembly, and precise component placement can be of great value, but also, and adaptive/learning or robust control loops.

To achieve zero defect manufacturing, more data will become available at all steps in the manufacturing and assembly process. To begin with, this implies integration of many sensors, e.g. for in-line inspection of parts, supervising correct processing, placement, assembly etc. Fast communication of the resulting data and measurement signals will be required to have a clear status overview of the manufacturing and assembly process. An intelligent processing platform and decision-making system is required to initiate corrective actions to specific production equipment, manual repair actions, compensation at other stages of the manufacturing and assembly line, etc. This calls for the development of novel sensor technologies and metrology, vision integration, in-line inspection and monitoring, fast data processing and transport. The integration of machine learning with adaptive and learning control strategies will also play an important role for enabling autonomous reconfiguration of control algorithms and decision- making systems.

To enable flexible manufacturing of high-mix, high-complexity, low volume products in a competitive way, it is essential to switch fast from producing small series of one product to producing the next product. Re-programming, unproductive ramp-up, and similar production-time loss factors destroy the competitive position and need to be eliminated through smart innovations. Effective flexible manufacturing will be enabled in both a feedforward and feedback manner. Feedforward in the sense that a priori product information (e.g. CAD data, design documentation, assembly instructions) directly leads to the optimal configuration of the manufacturing and assembly environment, including all internal communication and reprogramming of robotic manipulators for handling new parts for a new type of product (self-configuration). A self-learning process evolves when feedback derived from

continuous monitoring of critical production parameters through continuous sensing and metrology leads to adaptation of machine settings or replacements of tools when quality parameters start drifting (self-learning).

In Smart Industry scenarios, smart robots will take on a range of production tasks (production, inspection, transportation) and will behave as smart production entities based on local intelligence that reacts to data from sensor-rich production environments. However, the state-of-the-art task control strategies in manufacturing facilities still lack the flexibility needed for this future scenario. Research should focus on decentralized and mixed control strategies that will enable maximum flexibility and extensibility of systems of cooperating production robots. Mobile robots need to move in 2D and 3D through known and unknown, static and dynamic, structured and unstructured environments. Besides, they must be able to deal with unfavorable conditions for sensing, mobility and manipulation, like varying light conditions, water, dust, mud, etc. This relies on the robot's observation of the world through its sensors and data acquisition through other robots and systems, such as surveillance cameras. They need to localize themselves, navigate to target destinations, while avoiding obstacles in a safe and efficient way. Intelligence and autonomy are key in this sense.

Physical interaction between users and robots is getting increasingly important. Tele-operation and haptic feedback are examples of robotics technology to deal with more complex, more diverse robots, so that they can be safely controlled by non-trained, non-professional users.

A robot needs to be able to adjust itself to changing environments and changing tasks to work efficiently. Creating flexible and intelligent robots that are able to use and update databases and knowledge about their environment requires developments in many areas, in hardware, as well as in control software. Robots need to be able to learn from humans, their environment and from other robots. Especially robots working on repetitive tasks, which is often the case, can benefit a lot from learning, while optimizing their performance. There is a need for reconfigurable systems allowing self-adjustment, learning and adaptation, correction, and control as well as networking to bring about a significant impact on changeover time/cost, tooling, programming and energy usage of those systems. Research should include aspects such as improved methods for engineering processes, communication structures, and generic resource description for 'plug and play' machine integration.

Robots will be appear in an expanding range of applications, introducing generic but also specific challenges. Wireless robots will require wireless signal and energy transfer for continuous operation , and robots suspended or powered from the ceilings or via walls require integration of passive and active elevation (gravity compensation).

Software development for integration and control of machine controller software is often time-consuming and expensive. Considering robots alone, the costs of integration are three to five times the cost of the robot hardware alone. The reuse of robotic software artifacts is a key issue in decreasing the integration costs and can be promoted by domain engineering, components, frameworks and architectural styles. The interoperability of hardware and software components for robotics is also important in forcing a breakthrough in the development of robots. And innovative robotics design might create new solution too.

Business and consumer interests and technological advancements will lead to wide diffusion of robotic technology into our everyday lives, from collaboration in manufacturing to services in private homes, from autonomous transportation to environmental monitoring. Building an early awareness of the

resulting ethical, legal, and societal issues will allow timely legislative action and societal interaction, which will in turn support the development of new markets.

6 High Precision Equipment

To survive global competition, high precision and high quality products need to remain a differentiator, which will demand continuous improvements in process control and system accuracy in many aspects. The existing mechatronics competence base needs to be brought to the next level in the area of precision motion and handling systems, and thus requires significant progress in control systems theory, dynamics, thermal management, sensor technology and precision metrology, fast and efficient actuation, advanced control theory, motion control implementation platforms for high bandwidth control and data processing. This holds for both motion systems and robotic manipulators for picking and placing components and handling subassemblies.

Distributed actuation, identification and control are mechatronic challenges in high-tech systems with a high numbers of carefully selected distributed sensors and specially designed electromechanical actuators, with both continuous and discrete dynamics, and with systems and control technology that is able to handle this high level of complexity. Also driven by the availability of massive computing (massive parallel systems) new avenues for control become viable. Systems may possess many sensors and actuators and all information passing through the control can be used to estimate performance and disturbances at different time and spatial scales simultaneously. Multi Input-Multi Output control and systems that are adapting to disturbance or system variations will become industrially relevant, and so will distributed control approaches to deal with the ever increasing complexity of high-tech systems and their control architecture. Such distributed systems will allow multi-rate control solutions to be designed, lifting some of the limitations in present day equipment. Diverse types of measurement data must be combined to take the right decisions and actions. Research into the numerical processing, merging 1D, 2D, and 3D metrology, data fusion, and wireless transmission of this information will also be needed.

Technologies have to be developed for mass reduction and increased speed of operation, while maintaining accuracy. New systems have to be really lightweight, able to cope with deformation (e.g. quasi-static, dynamical, thermally induced), extended actuation and metrology topologies, and operating under extreme conditions. Further increase of amplitudes and speeds of systems into the nonlinear regime can be enabled with more advanced methods for controlling their nonlinear dynamics.

Higher speeds and accelerations are required to increase productivity, leading to large driving forces introducing more disturbances and heat loads. This calls for high force-density actuation, efficient power conversion technologies advanced drive electronics, distributed magnetic structures, high precision and high power switching amplifiers, and alternative actuation principles.

This involves building further on the state-of-the-art linear and planar electromagnetic and piezo actuators, but also research into levitated manifold actuators (based on interaction between permanent magnets only), and superconducting platforms.

Increasing demands on motion profiles push the envelope of the mechanical integrity of the actuation systems. These actuation systems have to survive extreme electric fields and currents passing through actuator materials.

Multiscale models have to be developed to accurately predict the respone of materials and their structural connections under such extreme conditions (e.g. mechanical and thermal stress and possibly degradation of materials in the form of erosion due to electrostatic discharges).

The development of new concepts of power conversion topologies based on multicell and multilevel configurations may lead to reduction of the voltage stresses on switching components, increase output accuracy, and power density. Multicell topologies should also provide flexibility and re-configurability, and allow for modularity in terms of control. Advanced control methods, such as model predictive control and machine learning are among the candidates for maximum utilization of all degrees of freedom of the power converters, allowing for ultra-high performance operation.

In addition to actuator related phenomena, structural system stability should be guarded by advanced thermal control, spatial and deformation metrology, advanced materials with favorable properties, wireless machines, both for data and for power transmission, eliminating the parasitic influences of cabling. Miniaturization will increase operation speeds and frequencies, and will simultaneously increase the demand for high-bandwidth sensing, actuation and control of the dynamics of systems at the micro and nanoscale.

The field of systems and control is a strong enabling technology that ensures robustness to uncertainty of many feedback control systems in high-tech systems applications. Model reduction for multi-physics systems and hybrid system theory are also relevant topics. Modeling interconnections of multi-domain (physical/chemical mechanical) dynamical systems in one and the same framework is needed to derive new concepts to exploit the combination to the full benefit of system performance. A similar aspect is found in the integral optimization of mechanical design, topology, disturbances and controller solutions for high performance systems. In cases like these, developments of novel mathematic approaches or complete new paradigms will be needed.

Solving multi-criteria, complex design problems will be the key to really exploiting the potential in novel system architectures. This probably will quickly go beyond human mental capacity. Shape and topology optimization provide a very promising enabler in this respect to find breakthrough solutions. In the longer term, this will call for methods to design and manufacture multi-material systems. For high precision equipment, the production of complex high precision compliant mechanisms is very important.

7 Cyber Physical Systems

The digitization trend at the industrial level leads to a merger of the physical world of production with the virtual digital world of information, data and computational power. A cyber physical system (CPS) is a system (or a system of systems) featuring integration of, and interaction between the system's digital/computational and physical elements, the system's environment, within the application constraints. This calls for the development of open, networked, flexible and interactive systems that exploit this cyber physical combination.

The importance of cyber physical systems of systems in the context of Smart Industry is increasing. It involves integrating digital information technologies in products, processes and factories and connects them to perform a certain function, provide a service or produce a product with the goal to achieve better quality and to adapt automatically and instantly to, for instance, changing material conditions or customer demands.

Obviously, the networked and information intensive nature of CPS, brings about big challenges. Design, development, maintenance and control of these cyber physical systems of systems will not be possible with theories and tools from the traditional field. Collaboration between scientific disciplines to manage this development is therefore essential.

Semantically interoperable systems collect and process detailed data about embedded and physical states, events and processes, where data ownership and privacy are important. The resulting integrated approach towards design and implementation allows an increase in the overall adaptability, autonomy, scalability, efficiency, performance, functionality, predictability, reliability, safety and security. To integrate networking, computation and physical processes, wireless networked systems for sensing and control are of key importance. Examples of CPS include communicating manufacturing systems/lines, systems to track and analyze emission, communicating (wireless) sensor systems, and systems to provide situational awareness.

Management of both hardware and software (distribution of time-critical tasks, locations of processing) during their life cycles need much better mechanisms and support than currently available. Future CPS should have plug-and-play components, both the physical and cyber elements, where the overall control can cope with scaling-up of the networked systems and reconfiguration Independently developed subsystems need to support collective applications by making individual components aware of the overall CPS applications and vice versa.

The current development cycle of CPS that follows a consecutive design of physical systems, of control algorithm and of information technology has limited the potential of CPS as disruptive technology. Bringing out the potential of CPS requires an integrated co-design method within an engineering science that brings together physics modelling across various domains (mechanical, thermal, electro-mechanical, etc.), complex control algorithms, communication protocols, and computational platforms that can guarantee safety, performance and robustness.

Internet-enabled decentralized monitoring and control algorithms, using wireless sensor systems, are required to improve process and product performance and enable proactive maintenance strategies using local and global information. The CPS will utilize effective, reliable, real-time and secure data collection, multi-physics predictive modelling, and data analytics under industrial conditions. Modularity of CPS will play an important role in enabling a seamless interconnection of new CPS and/or removal of existing CPS from the network. In these CPS, next to the (wireless) sensor systems, there is also the actuation systems to interact with their environment. The design of automation, control and information technology must provide assurance of safety, reliable operation under normal and abnormal conditions, while guaranteeing performance. Self-monitoring and self-repair techniques are important. Obviously, the networked and information intensive nature of CPS, brings about big challenges with respect to security. This is covered by a separate challenge 'Trusted Data Sharing'.

8 Digital Twin

Process and product development are organized in cycles. The structuring, management and the accuracy, applicability and reliability of information is of crucial importance for the efficiency and effectiveness of these development cycles. These cycles, combined with the different stakeholders/perspectives that are involved at different levels of aggregation are so complex, that virtual models are required to provide the essential understanding for optimal product and process development. Data that is collected through the entire life cycle of the product has to feed the virtual models to improve overall understanding and furthering of the cyber physical system.

A digital twin is, roughly speaking, a virtual copy of physical processes, systems, materials, products and assets. It provides a (high-)fidelity representation and abstraction of their physical "twin" in the digital world. For the past decades, the use of the (old-fashioned) digital twin has been crucial in modern engineering systems and it has taken various different forms. For instance, during the design/systems engineering phase, CAD/CAM and FEM models are generally used for model-based design and virtual prototyping of high-tech systems, transfer function or state-space models are used for the control algorithm development, circuit models for the electronic analysis and realization of the final electronics using electronic design automation (EDA) software and finally various different computer-based formal models are used for monitoring and maintenance of the assets. In the aforementioned examples, these models are typically based on fundamental physical and mathematical laws. Moreover, they are usually formulated a priori, i.e., the models are developed and made available before the actual products/systems are realized. For such a scenario, interoperability between these different models is already identified as a key technical challenges in maintaining, reusing and exchanging information among them.

Complementary to the physical model-based digital twin, the ubiquity of Internet of Things sensors and hyper-computing capabilities have enabled engineers to directly create a data-driven digital twin based solely on data collected from the realized processes/systems/products. This approach can thus be regarded as the a posteriori approach since they are only available after the underlying physical systems are realized and operational. The models are typically used for monitoring, real-time process control and maintenance of the assets. Similar to the physical model-based approach, these different data-driven digital twins also face interoperability problems and do not allow the support of design cycles of non-existing products or processes.

A digital twin, based on real data or data from physical based models of the process, will be stored in a statistical model using Artificial Intelligence like neural network (NN) based deep learning algorithms, or on other statistical models approaches. The physical based simulations can either be analytical, phenomenological or even very complex micro-mechanical based non-linear FEM models. Of course, the digital twin can also be based on the combination of different model concepts and even the physical models can be calibrated based on real-time production data.

Processes addressed are e.g. raw materials manufacturing, product design & development, production systems engineering, process & production planning, production execution, production intelligence, closed loop optimization, and digital transformation business modeling. Simultaneously, different perspectives (like quality, sustainability, logistics, cost, …) are addressed for all such processes. The challenge is to seamlessly connect all building blocks in such a way that stakeholders can have meaningful interaction with the definition of the cyber physical product (e.g. by VR/AR Technology) at the right level of aggregation. Stakeholders should be provided with perspective-dependent ways to access the available information. The way in which the different stakeholders can interact with information and models is of crucial importance for the efficiency and effectiveness of a digital twin. Currently, the structuring, management, accessibility, connectivity, cyber security and accuracy of the building blocks in digital twinning are under developed. What is more, the fundamentally new ways of working that come within reach based on the use of digital twins are unexplored, which means that the working methods and tools have yet to be developed in the context of new business models. Therefore, the product and process development cycle is currently far from optimal and hence zero defect, zero waste, customized production for products that fulfill the highest quality requirements is

not in reach yet. Research on all levels is required to allow for building full-blown digital twins of the product development cycle, the resulting products or the production environments.

The digital twin, includes a number of sub domains:
1. Physical constitutive models of the materials, including validation
2. Meta models based on this information and the application
3. Real-time sensor data including sensor analyses
4. Industrial statistics creating the Artificial Intelligence of the Twin
5. Interoperability

9 Mass Customization

In mass manufacturing, the optimization of production processes is the primary driver for price competitiveness. Drawbacks of this approach are that it leads to "one-size-fits-all" products with standardized components, conservative product designs, limited shapes, rigid supply chains and pressures to minimize product variety. If customer satisfaction is not primarily driven by price but also by the variety to choose from, a fast but more responsive manufacturing infrastructure is needed. Modern industry has to produce smaller lot sizes efficiently, enabling more variety in products against an acceptable price level. The globalized market and new business models require the ability to launch streams of new products with a high degree of personalization, for instance adapting to an individual's biometric parameters or satisfying specific customer preferences.

Customization is a game changer in high-value manufacturing and requires a much closer integration of design with manufacturing. At a local level, higher responsiveness needs to be developed to meet customer demands, and mass customization should be implemented in such a way that high product variability can be offered with a flexible combination of limited sets of modules. To achieve this, the manufacturing companies and their production systems must combine flexibility and efficiency. Future factories will be smaller, closer to their customers and increasingly modular. Mass customization will be supported by computational design tools and tools for mass customized design which strictly ensure manufacturability to ensure first-time-right as you don't want any scrap or unnecessary material waste.

Manufacturing equipment is modularized in units of the size of containers and even smaller (tabletop factories). Each unit contains a smart, Internet-connected piece of manufacturing equipment like a 3D-multi-material printer, a CNC machine, assembly robots, test equipment, etc. With these units, one can produce all kind of products in small series. Most important for the suppliers/manufacturer is that the production system consisting of these units can manufacture different product orders without the need of changing the physical configuration. If the product mix or order volume changes substantially, the system has to be reconfigured and/or extended with more or different units. Product and production information can be uploaded to the production facility by the customers themselves or by their solution providers. The suppliers/manufacturers are able to offer a larger variety of parts/assemblies or even complete products in smaller batches. Previously, they got the order if they offered the lowest price. Nowadays they have to invest in flexibility. Any moment orders can change, product designs change and, at the same time, zero defect quality is required. The future factory is situated in a personalized customer-centric world. It combines high performance and quality with cost-effective productivity, allowing small series customization at large series manufacturing cost level. The limit to customization will no longer be set by technology but by the extent to which customers are willing to be involved in the design of their own products.

The challenge for suppliers/manufacturers is to make their factories smarter but, above all, more flexible and closer to the market [Smart Industry - A vision for Dutch Industry fit for the future]. It is expected that ultimately smart factories will be smaller than before, integrated in metropolitan areas: "Industry as a friendly neighbor". Economies of scale is no longer the paradigm, but the scale economies of networking become the rule of the game. Next-generation applications require technological breakthroughs like new printing technologies, new materials, multi-materials and advanced manufacturing concepts, and a high-level of integration. Future manufacturing systems deal with big sets of personalized data caused by the network-centric approach for single product/small series manufacturing, IP and copyright protection. The integration of Internet and Industrial automation has created a bright future for the smart factories of the future.

10 Production Management

Production management primarily addresses the decisions made for configuring a production system, either green or brown field. It considers both structural decisions (production capacity, facility design, production equipment selection and configuration) and infrastructural decisions (quality polices, supply chain logistics, production planning and control, production scheduling). The challenges for the coming 10 years are a direct consequence of three following trends:

- Firstly, producers of industrial equipment and production technologies are integrating an increasing number of hardware (i.e. sensors and automated calibration technology) to prepare their equipment to handle Smart Industry production paradigms.
- Secondly, markets are becoming much more dynamic, pushing companies to offer mass-customized products, production services systems at faster time to markets rates. Furthermore, emerging markets are expected to surpass established markets in developed economies in size and capacity in the coming 10 years.
- Thirdly, industrialized nations are tightening environmental regulations in a coordinated way in order to achieve a large reduction in CO_2 emission and a substantial increase in the material reutilization rates.

These trends require production systems to become much more flexible and resilient to uncertainties in terms of production volumes and product characteristics. In order to achieve this, the following challenges need to be addressed. First, more flexible and intelligent methods for production planning, control and scheduling need to be researched and developed in order adapt to changing demand patterns, small production batches and disruptive market events.

One challenge consists of developing methods that combine available sensor data and optimization algorithms while keeping human decision makers in the loop. Furthermore, this also calls for improved coordination between producers and suppliers, requiring more flexible contracts and increased information sharing.

Secondly, new technologies to enable reconfigurable production cells have to be developed to enable fast changes in production layouts and to maximize the product variety by minimizing investment in production technologies. Such technologies include hardware solutions that (1) enable setting-up production cells by manipulating basic production equipment building blocks, (2) control-engineering/mechatronic solutions that minimize setup times by automatically determining process parameters and machine controlling protocols, and (3) design automation tools to quickly determine feasible production cell configurations and layout characteristics. Thirdly, create symbiotic relations

between the inputs and outputs of different production systems to optimize energy and material utilization rates. The main challenge is how to integrate the facility layouts and material flows of different companies producing different products in a way that waste energy and material can be reutilized.

Finally, educate a technical workforce so that they have the capacity to operate and maintain this increasingly complex production environment. In this context, both engineers and technicians need to be trained constantly so that they can cope with production systems that are not only becoming more complex, but also much more susceptible to sudden changes.

Solving these challenges will result in competitive and sustainable production plants using innovative technology-based approaches that drastically change rigid supply chain mechanisms and product-based business models into collaborative and robust production networks capable of delivering innovative products and services in time in a very dynamic and unpredictable, global environment. Solving multi-criteria, complex design problems will be the key to really exploiting the potential in novel system architectures. This will probably go quickly beyond human mental capacity. Shape and topology optimization provide a very promising enabler to find breakthrough solutions. Future computational optimization tools should provide competitive customized design including the required manufacturing conditions.

11 New Business Models

Smart Industry challenges the validity of established business models. Reconfigurable, adaptive and evolving factories are needed to face the uncertain evolution of the market or the effect of disruptive events. Manufacturing enterprises are pushed to take metropolitan actions, i.e., thinking globally but acting and staying economically compatible with the local market. Increasing customer-market orientation and the resulting problems of varying diversity and product complexity correlates to the complexity of business processes in manufacturing companies.

The management of complexity in product and processes, the growth of servitization business models, as well as the decentralization in case of smart factories is a real future challenge. The speed of corporate reactions towards changes to obtain or maintain a stable process situation depends on product, process transparency and open interfaces. The development of integrated, scalable and semantic virtual factory models will enable the implementation of decision support tools and optimization methods to address strategic decisions such as the location of new production sites, production technologies, and the selection of products and services to be offered in the market. These models should allow a fruitful interaction among all the relevant stakeholders in the design of manufacturing strategies.

Besides, new business models that provide a fully closed loop circular economy rather than a linear economy approach need to be designed, i.e., models that reduce, reuse, remanufacture, recover, recycle and redesign. To successfully combine the use of new production technology, digitization and a network approach, companies are challenged to adapt the four interlocking elements of their business model, i.e., customer value proposition, profit formula, key processes, and key resources.

The establishment of a network-centric production system that spreads throughout the entire asset life cycle may lead to the emergence of new forms of collaboration that are characterized by a co-creation approach to value creation. Customers play a predominant role among the collaboration partners. They become an integral part of the Smart Industry by providing information on their

individual needs and use, which is critical input for optimizing existing and creating new network-centric production systems. Future key research lines are servitization as the design and implementation of new business models that allow the active integration of customers, to evolve business models into efficient and effective mechanisms based on co-creation competences, customer intimacy within an information-based business approach and the contribution of co-creation approach to the creation of customer intimacy. Future manufacturing enterprises collect customer requirements, analyze them and make the right product and service model. Enterprises are also expected to offer a comprehensive range of after-sales product services. New tools, methodology and approaches for user experience intelligence (i.e., social networks, crowd sourcing, social science methods, qualitative and quantitative, to generate insights, models and demonstrations, etc.) need to be explored and used.

Smart Industry is on the agenda in many countries, hence, managing inter-company relationships in *coopetitive settings, i.e., contexts in which competition and cooperation merge together*, have to be advanced. Since competition and cooperation may not be considered as secluded spheres, the development and adoption of new technologies required for Smart Industry solutions (e.g., automation, digitization, flexibilization, etc.) may benefit from a network approach to innovation among various competitive firms. Existing business models will change because of the introduction of big data and new applications using this data. Innovative business models are based on a dynamic network of companies, continuously moving and changing in order to afford more and more complex compositions of services. In such a context, there is a strong need to create distributed, adaptive and interoperable virtual enterprise environments supporting these ongoing processes. The establishment of coopetitive settings to foster the development of a smart industry have to be pursued. Business models have to evolve into efficient and effective mechanisms of value creation within a smart industry. The technological advancement and adoption of technological standards will be impacted by the coopetitive setting and the pursuit of coopetitive strategies.

12 Condition-Based (Predictive) Maintenance

Maintenance is vital in ensuring the availability, reliability and cost effectiveness of high-tech systems. Industry requires smart maintenance strategies to address the challenges posed by productivity, aging assets and servitization. Traditional maintenance concepts that are still commonly applied in industry rely on pre-determined fixed intervals for maintenance tasks. However, the degradation of systems is a dynamic process, governed by changes in both the system and its environment. The consequence is that many systems are either maintained too early, thereby spoiling a (significant) fraction of the system service life, or fail unexpectedly when the system is operated more intensively than anticipated. Condition-Based Maintenance (CBM) is therefore crucial to save on maintenance costs and increase system availability.

Production facilities (and public infrastructure) are subject to aging. Towards their original end of life, these assets need to be upgraded, built anew or scrapped. CBM offers the opportunity to extend remaining useful life or improve sustainability and ecological footprint. Servitization is the trend that capital goods, such as complex machines, installations, and vehicles, are not just sold as a product but also offered as a physical component of a service: the availability of the equipment is what is being sold, often in a performance-based contract. If such an arrangement is to work and to be profitable for the party offering this service, condition monitoring and maintenance (and operations) based on such monitoring is essential.

The challenge is to achieve just-in-time maintenance. Such a predictive maintenance concept can be realized by following a multidisciplinary approach, combining disciplines ranging from failure physics (failure modelling, life prediction) and structural health and condition monitoring to data analysis, maintenance process optimization and logistic challenges in resource planning.

The combination of data collection through smart sensor networks and advanced analysis of the collected data has great potential. Since many sensors are already available for process control, the specific challenge is to find out how that data can also be used for predictive maintenance. Data-mining techniques like machine learning may be useful for that purpose, but methods based on modelling system behavior and failure mechanisms are expected to perform better in this context. Moreover, additional sensors may be needed when critical parameters cannot be derived from the process-control systems. Intelligent health and condition monitoring systems, e.g., based on advanced vibration analysis, can then be added. Ultimately, the objective would be to completely monitor the (production) system health and performance from a remote control room. Moreover, the production and its degradation process should be fully captured by models and the operational and environmental conditions should be controlled so that the number of human interventions is minimized and their predictability is maximized. This will lead to a reduction of costs and an increase of system availability.

The most visible parts of Condition-Based Maintenance may not be the most crucial ones in ensuring a much higher acceptance of this new innovative way of maintaining assets. The most visible parts of the so-called data enrichment chain are data capture (through sensors) and data analysis (data handling and data analytics). A major challenge in data capture is the fact that data comes from different organizations and departments, and these may have conflicting goals and constraints towards sharing these data. The challenge in data analytics is to reconcile the perspective of the domain experts with their failure mode analyses with the perspective of the data analysts with their correlations between environmental and internal factors and degradation behavior. After that, the challenge becomes that of organizational collaboration in managerial decision-making, where financial, sales and other non-technical considerations have to be reconciled with the technical risks and opportunities. Next, the challenges come from planning and scheduling of the chosen course of action, and also from the organizational deployment of these decisions, partly through uniformly and adequately trained staff (e.g., with the aid of virtual reality and simulation) and smooth and robust IT-enabled workflows (e.g., with the aid of handhelds and augmented reality tools). Finally, the actual maintenance actions are performed in a standardized manner, with automatic logging of actions, and systematic evaluation afterwards of the effectiveness of the interventions so as to close the data enrichment cycle.

13 (Trusted) Data Sharing

More and more products (and services) will be designed, developed and produced (provided) by multiple parties, often industrial parties, but more and more also in combination with public parties and customers. Reasons for this sharing are (among others):

- **collaborative design** between producer and consumer, or within an ad hoc partnership between multiple, sometimes even public and private parties;
- collaboration in a **smart supply chain**, where OEM's work with subcontractors and these again with their subcontractors, material suppliers, etc.;
- **smart maintenance**, in which an OEM is sharing information about a product with a product user and an (independent) maintenance company;

- **extended product data lifecycle management** in which the whole history of the product, from design until usage and recycling in the field is being tracked and stored to enable better maintenance or better production;
- **servitization**, in which the actual use of a product is being sold, instead of the product itself.

To achieve a smooth and data-safe cooperation in all of the above cases, data and information about the product, the design, subsystems, use of the product, etc., have to be shared among all these parties. However, that what is being shared, here called 'data' for short, lies typically at the heart of the intellectual property and the competitive edge of the parties involved. Hence, the way the data is shared should make sure that the data can only be shared with the intended parties, and only for the intended purposes, hence, cannot be illegally handed to other parties, nor be used for other purposes than intended; this notion of sharing while keeping control is often referred to as '***data sovereignty***'. But before being able to discuss data sovereignty, questions about the actual data-sharing infrastructure need to be addressed. This includes (partly classical) themes such as data interoperability (future proof formatting guidelines, standardization), being compliant to (privacy) regulations and the secure and dependable storage itself (where, by whom, how long, until when, with which service-level agreements).
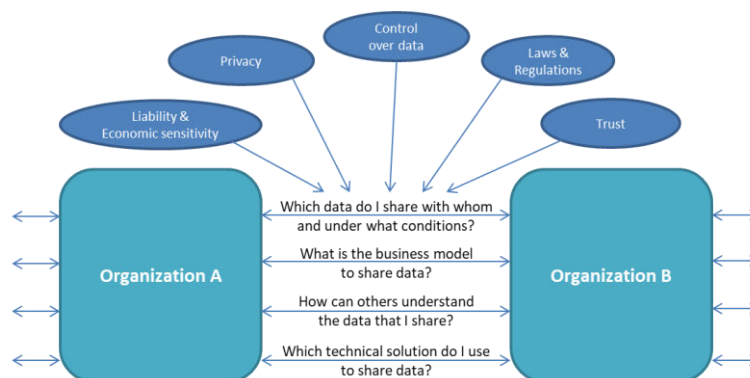

Figure 3 Trusted Data Sharing

The questions to be addressed in the above are not specific for smart industry, although they are present there quite strongly. Indeed, the broader topic of safe and secure data sharing is valid in general terms in the field of big data (in the Commit2Data program a call is planned on safe and secure data sharing, but not tailored specifically towards industrial applications). Also in the field of logistics there has been much progress on international (freight-) (EDI) data sharing, which can be of use in the smart industry context. In this case the Smart Industry community will follow contribute to an industrial Data Value Centre/Big Data Hub and contribute to international standard, in particular Industrial Data Space (IDS). Finally, the rising field of blockchain is of importance here; blockchain technology will become an important enabler for this field.

14 Cyber Security

Smart Industry transformation brings about many advantages in productivity, speed, efficiency, accuracy and customization. However, it raises new concerns about the overall system level qualities of the various network-centric production processes and products that are held together using a great many digital ties. The consequences that a breach of cyber security may have for physical safety, business continuity and critical infrastructures can be quite severe and costly. Where information

systems or operational technologies exchange data, there is a growing vulnerability that needs to be kept in check. The autonomy, intelligence and adaptability of systems that allow them to reconfigure themselves and their products, further exacerbate the situation. The emerging risks and challenges call for real-time methods to ensure the cyber security of integrated and dynamic systems.

A key consideration is that security of singular component systems does not guarantee the security of overall combined cyber physical systems that are the result of 'plug and play,' servitization, custom product configurations and automatically reconfigured supply chains. There is a significant challenge to develop methods to adequately deal with security in the context of smart industries as they are evolving, with particular attention to the security of services enabling trusted data sharing between partners. This should go beyond VPN (Virtual Private Network) connections, but include also (secure) digital identifiers for all actors involved (e.g. see the configuration used in the Industrial Data Space of upcoming digital identifiers as defined in a.o. the Dutch Blockchain Coalition).

Not all research and development in the cyber security field should be conducted within the framework of Smart Industry programs. The purpose is rather to identify specific challenging Smart Industry cases - in association with fieldlabs - that require a thorough approach to their overall system level cyber security, from shop-floor equipment (IoT devices, PLCs, SCADA systems, etc.) and smart products to servitization and value chain networks. On a Dutch national level, work can be done with the program Commit2Data. In Europe, an effort could be made to further develop a cyber-secure Industrial Data Space (IDS). It should be noted that no silver bullet for cyber security may be expected and that each of the transformation technologies addressed in this agenda may require specific solutions.

When addressing cyber security in actual Smart Industry practices, it is vital to consider the need for industries to secure their systems and value chain rapidly and comprehensively. The traditional in-company approach may have to make way for a more agile and collaborative approach to accommodate the pace of industrial change and also the multi-disciplinary nature of the challenges to be addressed. Companies may, for example, also make use of the proposed (regional) DTCs (Digital Trust Centers) and the ISAC (Information Sharing and Analysis Centre) and their specific industrial knowledge. In some cases work can be shared in the context of fieldlabs with research regarding critical infrastructures for secure data exchange.

15 Human Centered Technology

To design new personalized products, industrial systems and product service systems we should employ co-creation of value, system thinking, human technology interaction (HTI) and scenario-based design involving all stakeholders. Human technology interaction will change because products & systems get smarter and become connected through the Internet of Things. And as the use of sensors has become widespread, smart products and systems will increasingly present their users with actual information on their operation, giving usage, maintenance and repair instructions.

In industrial environments classical industrial robots are replaced by and existing manual work cells operators are enhanced with service and interaction robots. Such industrial systems work with significant more sensors in more unstructured, unknown environments, slower and in direct contact or next to humans. This requires co-evolution of flexible human and industrial systems in collaborative environments that integrate and support a seamless flow of information between human and the system with person-tailored user interfaces for human technology interaction. This requires the inclusive technology design of intuitive and logical interfaces and interactions between humans and robots, equipment and IT systems. Human centered technology is technology that provides optimal

support during the performance of tasks to different specific groups of people, ranging from people with a low to a high education level and even people at a distance to the labor market.

Humans will interact with these increasingly smarter products and systems. All these devices and systems should recognize human requirements and behavioral patterns and compensate for age or inexperience related limitations. Smart systems, using sensors and more and more using Artificial Intelligence/Machine Learning/expert systems, are required to support fast and reliable reconfiguration and to minimize workload and learning time. Human behavior understanding, affective computing and social-signal processing are some of knowledge challenges. We need to understand what people are doing, how they are feeling and how they are interacting with each other and with technology.

Trust will play an important role in human technology interaction. Questions about responsibility, accountability, control and the user in the loop will become prominent. Jobs will change, some will disappear and new jobs will be created. Robots and smart ICT systems do not take over complete jobs, just some of the tasks in the job. Humans remain important to ensure flexibility. This is certainly true in 'low volume - high mix - high complexity' production processes in which Dutch industry is strong. Here the question is how new technology can optimally support humans in performing the tasks allocated to them, both cognitively and physically.

There exists many question that require further research. How do we distribute the tasks in the design phase? What are the options and how much freedom of choice (managerial choice) is there to secure both business performance and job quality aspects? How do we design dynamic task allocation, allowing for deviation from the allocated tasks in the operational phase (shifting work from humans to robots and the other way around) due to order changes, unexpected events, need to interrupt normal operation, etc. What are the effects of human-robot/device/control system collaboration on generic and more specific (e.g. trust) aspects of job quality? Which types of Inclusive Technologies for cognitive and physical support regarding allocated tasks are potentially successful? Which effects can be realized in terms of performance, job satisfaction and employability? And how do we design an intuitive, adaptive operator support system that adapts itself to the skills/experience level of the operator and to the quality measured in the primary process?

16 Employee Management

The content of work (e.g. 3D printers, virtual reality, cobots, AI platforms), the knowledge and skills demanded of employees (e.g. professional knowledge as well as some IT skills) or the social aspects (i.e. the interactions with colleagues, supervisors and people outside the organization) all evolve rapidly. People are and remain most important for any organization, but the nature of existing jobs and therefore also employee management (HRM) will change. Smart Industry requires more and more 'deep knowledge', but also more responsibility from employees and management for processes that are getting more and more critical. Workplace innovation is seen as a central practice to accomplish this stronger engagement of all actors in the company environment. Such a practice is a necessity if companies want to engage their personnel in supporting the continuous innovation process. What do employees need as competences, skills and attitudes to help generate this improved innovative performance?

Most people learn best and most by solving problems based in practice. Working, learning and innovation should be integrated once again to effectively handle the rapid development of technology. A smart connection of informal and formal learning arrangements is key for the future development

of current and new employees. Skills intensive workplaces and a pervasive learning culture within firms (see OECD) poses an enormous challenge. Informal learning practices have to be effectively combined with formal practices to further develop new forms of '*Smart Industry*' craftsmanship. Education, experience, learning and innovating are the hallmark of craftsmanship, but now they are organized in disconnected silos.

The challenge is motivating people for change, but bigger issues touch upon the topics of (life-long) training, education and continuous innovation. Tackling this will require joint efforts (e.g. employees, organizations and external parties like social partners, universities and the government). The question remains what will be required of employees themselves and what demands will be placed on both the employer in order to contribute to developing and maintaining value-adding employees. How to avoid losing your technical employees once there is a shortage on the labor market, how to keep elderly employees up to speeds with all the new digital technologies they never saw at school?

Focusing on the HRM department in general, Smart Industry not only raises questions about their work context, or more specifically the changes to HR technologies, but also questions their activities and roles. Which type of social relationships are required to deal with employee management?

In addition, Smart Industry challenges the established positions of decision-making. The potential of possessing huge quantities of real-time data and the possibility of making this available to anyone you wish triggers the question of where to place responsibilities. To what extent are we able to, and do we want to, change the hierarchical structure of existing organizations**?** What does it mean to function with zero-management-layer organizations?

17 Smart Response

The challenge Smart Response, as described in chapter 1.3, deals with the response of economy and society to the changes caused by Smart Industry and the disruptive technologies (robotics, AI, embedded sensors and Internet of Things) connected to it. The question is not only how we respond to the acceleration of the digitization process but how we can anticipate these developments to realize the desired economic and social impact or avoid the negative effects for specific groups.

Economic and social impact of Smart Industry. How do the concepts opened up by Smart Industry affect society? On which points will they put pressure on the existing social order? How will economic ecosystems/networks, sectors, business models, organizations and jobs change?

How can we anticipate on Smart Industry developments to realize the desired economic and social impact and avoid the negative effects for specific groups? Which technological choices need to be made and how? How do we adapt businesses? What is possible and desirable from a societal point of view? Besides exploring the effects, attention needs to be paid to the question in which areas the Netherlands can develop *unique positions* (points on the horizon) and how these ambitions can be realized (Smart Industry, Smart Society). What is our 'smart response' or smart interaction by consumers, employees, politics, media, etc.? On which aspects will we focus our offensive and on which aspects do we have to be more defensive?

Scenario's. Today the societal challenges as sustainable energy and resources, healthy food, clean drinking water, societal cost of health and support for an elderly population, safe, sustainable and reliable mobility etc. impact industry in many ways. A proactive response to a still unknown future requires exploration of possible scenarios. Which social directions (smart society) and economic growth within ecological boundaries, type of jobs and employability, etc. do we want? As changes occur fast, where should we focus on?

International perspective and value chains. For years, outsourcing and offshoring were the ways in which companies strengthened their competitive positions and increased their profits. The first signs of a reversal of this trend are visible. Smart Industry allows production of small series, whereas offshoring to China is only profitable at very high volumes. Can we change offshoring manufacturing to new metropolitan/regional manufacturing? And if this it possible, value chains will change and how does this affect regional ecosystems and their smart specialization (from rustbelt to brainbelt). How will supply chains for regional rooted SME and super-national OEMs change?

Platform economy. Digitization of industry, all value chains, the whole economy and all of society has led to the emergence of the 'platform economy'. The rise if new monopolies whose size and power increases through positive network effects points to the advent of a new economic order. Companies like Google and the like are so rich that they can buy any new competitor and thus smother future competition in its early stages. How e.g. should we deal with the current trend to "winner-takes-all" platforms? What could be the role of the EU? Are there critical functions or assets we have to defend? Do we have to build up new technology positions?

Regional and special impact. But Smart Industry also has a regional and spatial impact. While towns and cities in the Netherlands and Europe grow and flourish, the countryside and peripheral regions face demographic and economic decline. Smart Industry offers new opportunities for new regional development and growth. What are the relations between investments in Smart Industry and the development of regional ecosystems, national economic development and export positions? What is the spatial impact of 'metropolitan manufacturing', that stands for small-scale, ecologically sound and flexible production close to consumers?

Sustainability. There are also major developments with regard to sustainability that require a smart response in the context of Smart Industry in the need for eco-efficient production. Additive manufacturing is the best-known example of a technology that allows production with less raw material. Less waste, closed cycles and automatic disassembly are the key words. How can Smart Industry technology contribute to the Sustainable Development Goals?

Technologies and skills. Smart Industry technologies are developing extremely fast. Instead of what we expected, applications of quantum technology arise already. Which key enabling technologies will become crucial for the Dutch Smart industry agenda? Technology can make people redundant, but it can also be used to support people in the labor process; human centered technology. The development of cobots and expert systems that support people in the performance of their tasks and make it possible for people to participate longer or at a higher level in the labor process. What are the effects on different kinds of jobs and on employment as a whole as technology and the Dutch working population change? How can we develop new learning environments that respond faster to new developments than traditional education is able to do? How can we set up organizations in a way that promotes learning and development? The challenge for education is also to set up tuition for the employed and the elderly. Continuous changes, creative skills, problem solving in complex environments are examples of challenges connected with Smart Industry to which education also needs to find answers.

Monitoring. Systematic monitoring of developments and specific interventions within the frame of the Smart Industry program is important to map opportunities systematically. Which companies are successful in Smart Industry and which are not and why? What are the effects of Smart Industry on

business models, profitability, employment and environmental performance? What is the role of fieldlabs and how can they accelerate the adoption of Smart Industry? In connection with this, it is also necessary to investigate if and what kind of connections there are between investments in Smart Industry and regional and national economic development and export positions. What relations exist between R&D or ICT investments, the development of new business and growth of Gross (national/regional) Product?