FORSCHUNGSBEIRAT INDUSTRIE 4.0

The Engineering Roadmap of the Research Council Industrie 4.0

Preamble

This Engineering Roadmap of the Research Council Industrie 4.0 has been developed by a strategy com-mission, set up specifically for the preparation of the roadmap together with the Research Council. The aims of the roadmap include offering orientation for the work of the Research Council, providing a "common thread" for expert reports, impulse reports and other formats, and simplifying communication and thematic coordination with the Plattform Industrie 4.0 and the federal ministries involved. The roadmap addresses a period of 10 years (starting in 2024), which is divided into three main periods. In terms of content, four main topics are distinguished. The thematic blocks arranged in the resulting structure address important research questions which, assuming that certain developments will occur, follow on from one another in a meaning-ful way. The thematic blocks form a framework for specific research priorities that can be addressed within the specified period. The research priorities still need to be developed as a refinement of the thematic blocks and detailed up to the level of specific research work. It can be assumed that this refinement pro-cess can be carried out more reliably for research topics that are near term than for research topics that are set far in the future. The arrangement of the thematic blocks describes the chronological order of the re-search work, i.e. not the time at which the results will be available. Due to the fact that this is a research roadmap based on the research focus of the Research Council, it does not contain any information on when the research results will be implemented in practice.

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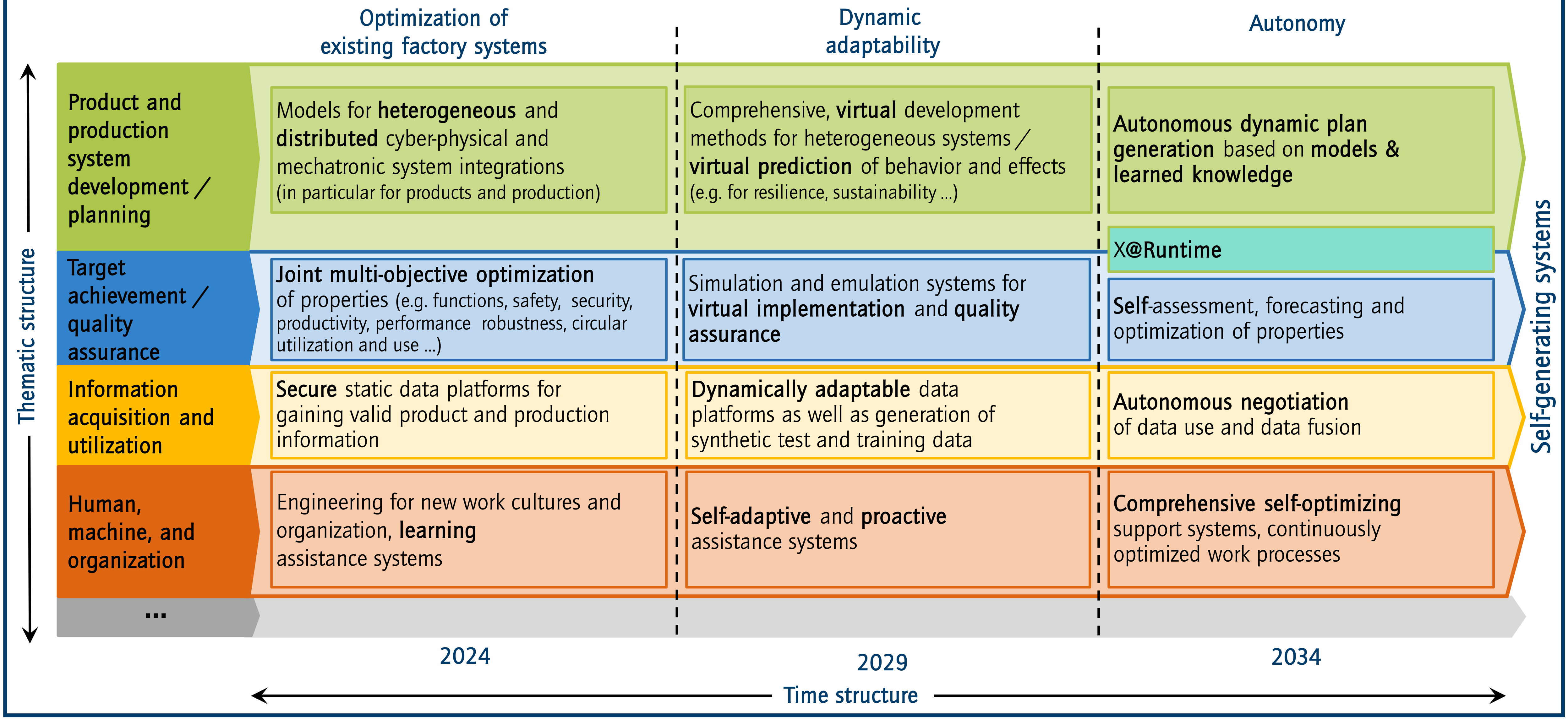

Basic assumptions and structure

This roadmap is based on the assumption that a central objective of Industry 4.0 is to achieve competitive, transparent, flexible, and equally value-added production and product provision in the field. However, this is not an end in itself – rather, it contributes to the achievement of goals. These include, for example, the creation of individual products, increasing resilience to internal and external influences, reacting to changes in customer requirements or the characteristics of raw materials, or optimisation in terms of increasing throughput, machine utilisation or avoiding bottlenecks. It is about constantly achieving an optimal combi-nation of the required parameters, in particular ensuring productivity, optimising sustainability and guaran-teeing safety. In addition, there are already products that essentially have to be created manually because the manufacturing process requires a certain degree of adaptability that cannot be achieved with current state-of-the-art technology. In pharmaceuticals, for example, there exist therapeutics for serious illnesses that can only be produced automatically using Industrie 4.0 capabilities. For this, the key capabilities are autonomous adaptability and transparency of the manufacturing process.

The realisation of continuous horizontal and vertical communication, accompanied by the creation of a high level of transparency based on data, provides an important basis for flexibilisation. In addition, since the beginning of the work on Industrie 4.0, a key aspect has been the best possible integration of humans in Industrie 4.0, i.e. in particular the optimal allocation of work between humans and machines, accompanied by the best possible cooperation between humans and machines and the most appropriate support for hu-mans through technology. In this context, new work cultures and organisations have to be taken into ac-count.

Thematic blocks

Models for **heterogeneous** and **distributed** cyber-physical and mechatronic system integrations (in particular for products and production)

Production environments are systems in the sense of a broad definition, according to which systems com-prise technical components and the people involved, including logistics, for example. In addition, these are hierarchical systems of systems within a production environment and along supply chains. The engineering of the technical components requires the involvement of several disciplines – e.g. mechanical engineering, electrical engineering, and computer engineering as well as operational service provision. Other disciplines such as work science and ergonomics may also be involved. In addition, it may be necessary to consider other aspects – e.g. business models – in order to carry out cost-benefit analyses. There are different ap-proaches in the disciplines involved and correspondingly different ways of modeling. Based on these mod-els, engineering can be designed within a discipline. However, cross-disciplinary engineering issues for the overall system can only be addressed if the different models can be combined to form a valid overall pic-ture. Research questions concern the combinability of models regarding specific issues as well as methods for model creation – e.g. using reliable LLMs – and for model representation – e.g. with suitable digital twins. In addition to achieving technical goals, ensuring productivity and sustainability is of high im-portance.

Joint multi-objective optimisation of properties (e.g. functions, safety, security, productivity, performance robustness, circular utilisation and use ...)

Industrie 4.0 systems must have a combination of properties that are often not free of interdependencies. Typical examples are the interdependencies between functional openness or expandability and security, security and safety or even between safety and availability. A system that is normally stable in terms of safety can develop hazards due to a security incident that were initially not present. A separate optimisa-tion of security and safety will often not identify such correlations. Safety can often be increased through comprehensive diagnostics with corresponding reactions, which is often at the expense of availability, as in case of doubt intrinsically safe states are reached in which the system no longer fulfills its function. This in turn has a negative impact on productivity. There are target corridors for many properties that have to be met. How the interdependencies between properties can be analysed needs further research.

This includes the detection of and reaction to cyber-attacks in terms of security, the ability to guarantee stable systems in terms of safety even when technologies are used that currently make safety analyses more difficult (e.g. machine learning) as well as the understanding of cross-sectoral value creation through the joint consideration of materials, information and energy, for example.

Secure static data platforms for gaining valid product and production information

Information is the basis for decision-making processes. Industrie 4.0 cannot work without appropriate, valid data to obtain information. The decisive factor for the provision of data will be the protection of data and the controllability of data usage – i.e. the creation of secure information spaces and the existence of relevant standards. It is necessary to do research on how this can be technically designed.

Engineering for new work cultures and organisation, **learning** assistance systems

Work processes and the surrounding organisation will change on the way to and in the further evolution of Industrie 4.0. This will have an impact on the engineering of products and production systems. In the area of human-machine interaction (HMI), the allocation of work between humans and machines and the optimal support of humans by technology play a central role. The aim is to create learning assistance systems that monitor the work process and tailor their support to the individual person. Usability and user experience must be considered as a cross-cutting issue in all HMI topics. Research is also required on appropriate interaction mechanisms between workers and collaborative robots as well as in hybrid team robotics.

Comprehensive, **virtual** development methods for heterogeneous systems / **virtual prediction** of behavior and effects (e.g. for resilience, sustainability ...)

In order to reconfigure systems dynamically, it is necessary to be able to reliably predict the behavior after the changes. This involves generating answers to the questions "Will a change lead to the desired objec-tive?" and "Will the behavior remain unchanged?". Obviously, these questions must also be answered for the system as a whole. Therefore, this thematic block builds on the research on "Models for heterogeneous systems". In the increasingly coupled interaction of operational data previously recorded in the factory or in the field and the digital and virtual models previously used in development, digital twins or even their net-work-like interaction may in future be a new appropriate form of representation for the underlying behavioral patterns of technical systems. An important goal is to describe the complex relationships between the technical properties of products and production systems and, for example, sustainability aspects, climate neutrality, productivity, and value creation.

Simulation and emulation systems for **virtual implementation** and **quality assurance**

The aim of this thematic block is to investigate how the results of the work on "Joint multi-objective optimi-sation of properties" can be transferred to models in such a way that they can be applied virtually and au-tomatically during configuration or reconfiguration. Before an upcoming change, it must be determined, based on models, which properties change in which way, and whether this change can be accepted, or whether this modification would lead to a prohibited area. In this context, two aspects will be decisive for further research: (a) determining at which stages reliability should be established across companies and organisations to cope with the model diversity and operational modes of tomorrow's more complex sys-tems, and (b) identifying which digital (syntax) mechanisms, semantic forms of description, and smart in-terconnected standards based on these are useful.

Dynamically adaptable data platforms as well as generation of synthetic test and training data

If Industrie 4.0 production changes, the data platforms must be adapted accordingly because different or modified data is required, data is no longer generated or modified analyses are needed. How this flexibility can be realised in data platforms while retaining important properties – e.g. access or usage control of the data – needs to be researched. The semantic descriptions in the form of ontologies, knowledge graphs and causality graphs that have so far been considered in a more fundamental way are not yet sufficient for the future intensive use of data platforms and spaces and, with regard to dynamically networked AI compo-nents, must be significantly supplemented by machine-comprehensible functional specifications and physi-cally correct inferences and made industry-ready in further research.

Self-adaptive and **proactive** assistance systems

The "Learning assistance systems" should learn to adapt to different operating modes of workers and pro-vide suitable assistance while the production process remains unchanged. In addition to the adaptation to different workers, the "Self-adaptive assistance systems" should also enable the adaptation to changed production processes, e.g. as a result of reconfiguration. The automation of engineering itself in the form of more comprehensive assistance systems and autonomous decision-making will strongly influence further research in this field. Through automatic plan recognition, the assistance systems should be able to recog-nise the next steps intended by humans at an early stage in order to support them in an anticipatory man-ner and enable zero-defect production in the medium term.

Autonomous dynamic plan generation based on **models and learned knowledge**

The aim of this thematic block is to investigate how human planning and control interventions in Industrie 4.0 production and development can be automated in such a way that they can be carried out by the sys-tem itself. In other words, it is about the creation of a widely autonomous technical system, in some cases even using autonomous development tools such as bots. This will require appropriate coupleable models – if necessary also appropriate digital twins or networks of digital twins. In addition, the system should ob-serve itself and constantly learn autonomously. In this context, the supply chains must also be considered.

X@Runtime

X@Runtime is a generic term that describes the shifting of activities related to engineering and quality as-surance from the development into the runtime. The aim is to automate these activities and have them carried out autonomously by the technical system during the runtime. One example is "Plan-ning@Runtime", i.e. the automated generation of a production plan for a specific product. Another example is "Safety@Runtime", i.e. the evaluation of safety during runtime by the technical system. X@Runtime is related both to "Autonomous dynamic plan generation" and to "Self-assessment, forecasting and optimisa-tion of properties".

Self-assessment, forecasting and optimisation of properties

In a widely autonomous technical system, the complex system-wide assurance of the required properties must be performed by the system itself. For instance, if a production plan is generated automatically, then it must also be automatically determined whether this plan can be executed safely, economically, ensuring productivity, etc. This thematic block focuses on the research on solutions that enable the virtual safe-guarding of properties and thus also the transfer of the "Virtual implementation and quality assurance" to the technical system itself.

Autonomous negotiation of data use and data fusion

The autonomy of the Industrie 4.0 system makes it necessary to constantly adapt the provision and use of data. This can only reasonably be done in an automated manner. One research question concerns how the intentions of data providers and data users can be described in such a way that specific rules, e.g. for au-tomatic usage control, can be derived automatically.

Comprehensive self-optimising support systems, continuously optimised work processes

The high degree of autonomy leads to frequent changes in workflows and work processes, which must be absorbed by correspondingly powerful support systems in order not to overstress the people working in production and to provide them with the best possible support. In this context, research questions concern, for example, options for the automated generation of virtual training for a new production plan or cognitive assistance systems that proactively generate suggestions for changed work processes.

Information on the Research Council Industrie 4.0

As a barometer ofthe direction oftrends, the Research Council observes and assesses developments in the performance profile of Industrie 4.0 in the medium to long term. In addition, it sees itself as a source of inspiration for future research topics. In its publications the Research Council formulates new research and development needs that can be addressed at the pre-competitive stage as weil as options for action for the successful realisation of Industrie 4.0. As a strategic and independent committee, the Research Council Industrie 4.0 supports the Plattform Industrie 4.0, its working groups and the federal ministries concerned, in particular the Federal Ministry of Education and Research {BMBF).

Imprint

V.i.S.d.P.:
Research Council Industrie 4.0
c/o acatech, Karolinenplatz 4, 80333 München

Contact

Research Council Industrie 4.0
c/o acatech – German Academy of Science and Engineering

Kristina Fornell
Communications Officer
Karolinenplatz 4
80333 München
T +49 (0)89/52 03 09-865

www.acatech.de / fornell@acatech.de

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