Advanced Systems Engineering

Value Creation in Transition

Engineering in Germany – Status Quo in Business and Science

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Preface

In order for businesses to remain successful even in future, they need to adapt to the shift in added value and the changing market conditions. Digitalisation is highlighting a continuous shift from earlier products to mechatronic systems, to smart technical solutions. These **Advanced Systems** harbour tremendous market potential – unique opportunities and considerable competitive advantages for pioneering businesses. At the same time, developing these systems requires new skills and qualifications from the people involved.

Development must adapt to the changing work structures with globally distributed added-value networks. The collaborative, sustainable creative-design process for future products, as well as product development itself, requires talented developers from all manner of disciplines, such as engineering, IT, sociology and ergonomics. To manage the complexity of these increasingly interdisciplinary development activities, **Systems Engineering** skills, processes and methods need to be introduced and applied across the board.

Creating new offerings and business models means supplementing existing qualifications with completely new approaches. **Advanced Engineering** enables the current boundaries of engineering to be exceeded, and existing products and services revolutionised. This includes, for example, using emergent technologies such as AI and digital twins, as well as new work structures such as agility.

Particular potential arises for future added value when the trio of Advanced Systems, Systems Engineering and Advanced Engineering all work together. By adopting the integrative concept of **Advanced Systems Engineering**, stakeholders in business and science can accelerate existing strengths and collectively pursue the aim of sustainably further developing Germany as a hub for innovation. This reading material provides an extensive introduction to the topic. Analysis of the latest service levels highlights the current challenges, and provides a holistic, systematic framework for transforming the engineering strategy.

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Extended Executive Summary

Digitalisation, the global competition, the shift in work structures and the guiding principle of sustainability are seeing organisation face new challenges. The top priority is to guarantee added value. There needs to be a rethink if products, software and services are to continue to be developed profitably and generate market success. The shift towards autonomous, interactive and dynamically networked products with an increasing software and service component is posing further challenges for businesses. Complex, interdisciplinary creative-design processes can be handled by adopting structured approaches like Systems Engineering. Creative development methods, agile processes and digital tools have the potential to ensure added value even in future.

Advanced Systems Engineering (ASE) provides a framework for integrating the various system-oriented and often highly innovative approaches of engineering. It acts as an example for successfully designing innovative products, services and Product Service Systems, and for their creative-design processes. ASE stands for a comprehensive new perspective in planning, developing and operating the technical systems of tomorrow. The engineering status quo in science and businesses was ascertained and analysed through an international comparison in terms of how the guiding principle had been further substantiated. The key findings and resulting needs for action are presented below.

Advanced Systems
Goods and services of tomorrow

Megatrends in engineering: Digitalisation, globalisation and sustainability

These have a heavy influence both on future goods and services as well as on the associated design processes. The forms these mega trends take, such as the sharing economy, greentech, the Internet of Things and artificial intelligence, and the focus on global knowledge management as the consequence of the increasing skills shortage, will sustainably shape the future of engineering. It unlocks significant potential for success, though developing this requires good ideas and strong implementation skills.

Prospects for Advanced Systems: Autonomy, networking, interaction and smart services.

The autonomy of technical systems is becoming a key point of differentiation on the market. The use of autonomous systems in complex, highly dynamic environments in virtually all areas of life is particularly unlocking new growth markets. To maximise this potential, businesses need to be able to enhance their existing goods and services with key technologies such as artificial intelligence (AI), robotics and automation technology. The increasing networking of interacting, smart technical systems opens up fascinating prospects for the added value of tomorrow. This requires current systems to be interlinked with information and communications technology (ICT) and rendered capable of integrating in a networked system. Users and consumers require smart, adaptable interaction with the technical system. The human-centred design, taking into account new forms of human-machine interactions, places new demands on creative-design processes for future goods and services. Data-based Product Service Systems (PSS) are also gaining in relevance. Continuous PSS software updates enable, among other things, an expansion of operating functions and critical security updates. But developing such services poses considerable challenges for businesses in terms of assessing customer benefit and the profitability of business models.

Challenges associated with developing Advanced Systems: Development complexity, cost pressure and regulatory aspects.

The rise in complexity of future goods and services will also mean greater development complexity. Opinions are divided on whether building on existing engineering models will suffice for the disruptive innovations required, or whether an extensive refocus is necessary. By contrast, consistent interface management is collectively viewed as a key challenge. The aforementioned interfaces relate to process and organisational structures, the technical interfaces in the engineering IT infrastructure, and the interfaces between goods and services in operation and the company.

Now more than ever before, businesses are being called on to overcome the conflict of objectives between an increase in discernible customisation of goods and services and the simultaneous cost pressure on global markets. There is a lack of design methods for product architectures, production systems, value networks and business models. The surveyed businesses also continue to face the challenge of achieving shorter innovation cycles while retaining a high level of quality. They are also confronted with varying life cycles in application software (e.g. apps), embedded product software (e.g. firmware) and hardware (e.g. the basic mechanical systems). Countering these challenges requires new skills and corresponding training and continued-education measures.

In addition to the technical requirements, new requirements are also emerging in relation to compliance with regulatory aspects. Aspects such as 1) liability and responsibilities associated with autonomous systems, 2) privacy and data security, and 3) homologation and permission will significantly influence the success of future goods and services. Along with IT security, updating future systems at the factory also places new and more extensive demands on safeguarding integrated networked systems and systems of systems.

Systems Engineering
Managing complexity

Understanding Systems Engineering: A powerful tool, but perceptions are vague.

The term 'Systems Engineering' (SE) is commonplace across numerous industries. Many people associate SE with major projects in the USA, such as the Apollo program. People's understanding of it varies greatly. Most interviewees think of Systems Engineering as being a collaboration across multiple specialist fields to develop complex multidisciplinary products. Its use in later phases of the creative-design process, such as production-system development (production planning), and integrative assessments of products, production systems and services, does not figure.

The added value of Systems Engineering: Promoting a common understanding of systems.

Businesses hope Systems Engineering will generate a better understanding of systems, so as to ensure early identification of inconsistencies and errors, to parallelise development activities, and to design more innovative customer solutions. Further potential benefits of Systems Engineering particularly include the ability to trace links and relationships between the development process' artefacts (traceability) and to improve transparency in product development. The prevailing view is that Systems Engineering is a necessary approach to overcoming the complexity of technical and sociotechnical systems and associated processes, and that it increases the efficiency of creating goods and services.

Standard of system services Engineering in business: On the verge of spreading.

Despite high expectations and the vast potential for benefit, the standard of services varies greatly depending on company size and industry. Systems Engineering is considerably more established in the aerospace and automotive industries than in mechanical engineering or the automation industry. It tends to be used more at large corporations than at small and medium-sized enterprises (SMEs). Its application is focused on requirements management and the system design, regardless of size or industry.

Introducing Systems Engineering: Overcoming hurdles through incremental introduction.

A number of the surveyed businesses are planning or already introducing Systems Engineering. But they lack methods for the accompanying change management. At the same time, they face the challenge of needing to comprehensively train and motivate developers and every level of management. There are also significant costs involved with adapting the methods and processes of Systems Engineering to the business and the project. KPIs such as the amortisation period over several system generations and the lasting added value of introducing SE have so far been very difficult to quantify in-depth.

Some businesses have managed to successfully introduce Systems Engineering – particularly by doing so incrementally and in a project-based manner. Rollouts can additionally be supported by a simultaneous top-down and bottom-up approach across all levels of management, external methodological support and accompanying change management.

Roles in Systems Engineering: Unclear role models and skill profiles.

A clear job description for a systems engineer is yet to be established in the business world. Spin-off roles include systems architect and customer-requirements manager. Opinions are divided on the criteria, tasks and responsibilities associated with the relevant roles. Systems engineers are often expected to have strong methodological and social skills in order to ensure interdisciplinary co-operation between the parties involved. At SMEs, these skills frequently coincide with the role of technical project manager. There is no unanimous agreement on whether these skills can be taught at university or need to be acquired based on practical experience.

Model-based Systems Engineering: High potential with a number of hurdles.

The ability to describe and handle the increasing system complexity, as well as the notion of organising the corresponding interdisciplinary development process based on a holistic system model, is expressed by the concept of Model-based Systems Engineering (MBSE). This goes hand in hand with high expectations following consistent development work. At present, MBSE is primarily only used for formal modelling of system architectures. Although Systems Modelling Language (SysML) has established itself as the de-facto standard, a modelling method tailored to the specific company involved generally needs to be introduced in order to fully determine the systemic links. Other hurdles associated with introducing MBSE in its present-day form include the lack of amortisation concepts for the increased modelling work, the IT tools' non-user-friendliness, and the lack of integration into the existing engineering IT infrastructure.

Advanced Engineering
Rethinking engineering

Digital consistency and Product Life Cycle Management (PLM): Only standards will help further.

The vision of digital consistency describes an unimpeded flow of information between all development activities by networking IT systems at the companies and within development partnerships. Transparency resulting from traceability, increased efficiency through process automation, and improved quality through availability of information are the benefits expected from this networking. As such, digital consistency and networking complement the existing approaches to virtual product creation and Product Life Cycle Management (PLM) by comprehensively integrating all information on generating and utilising goods and services. A number of surveyed businesses are in a permanent process of transformation, with a view to achieving a high degree of networking. There are several obstacles blocking the way to full networking. For example, an increasing number of IT systems are used to create complex interdisciplinary systems, resulting in considerable expense to manage and orchestrate software tools. Media disruptions between the IT systems are the order of the day due to a lack of standardised exchange formats. Similarly, businesses cannot create and manage all necessary programming interfaces. These challenges intensify in the event of cross-company co-operations and collectively used information requiring compliance with certain security standards. In addition to technical hurdles, company-specific approaches to product creation and links between the IT infrastructure also need to be taken into account. As such, the synergies between PLM, virtual product creation and MBSE must particularly be utilised in future.

Digital twins and using operating data in engineering: Promising technologies in their infancy.

Many of those surveyed placed major importance on the concept of digital twins in engineering. In addition to digital consistency, the focus is also on networking specific data and models throughout the life cycle of a market service. Although there is no uniform understanding of the concept, various potential benefits, particularly in the usage of operating data and in designing data-based services or business models, have been identified. To tap into this potential, it is first necessary to identify, structure and assess the use cases. Practical application involves particular challenges in relation to modelling and the networking thereof throughout the entire life cycle. There is currently very limited scope for virtually guaranteeing properties based on network models. As things presently stand, operating and environmental data is only used during development in exceptional cases to optimise goods and services from generation to generation. As such, great importance is placed on implementing the engineering IT infrastructure for digital twins at a technical and economic level. It is important that cross-company usage, and particularly the interoperability of digital twins, be guaranteed here. ›

Artificial intelligence (AI) and assistance systems: A powerful tool to help people.

The key technology of artificial intelligence is also opening up new prospects in engineering. Assistance systems are already being used successfully by many companies. This goes hand in hand with the expectation that AI's clear potentials for success will continue to be unlocked. This applies in instances such as repetitive routine tasks, the processing of unstructured data, learning from empirical knowledge, and intensively improving existing IT applications. Unlocking this potential involves challenges, including identifying relevant use cases, forming domain-specific AI models, and skills shortages within companies. There is also great uncertainty regarding the use of non-deterministic learning algorithms that may end up conflicting with security-related or regulatory requirements. Similar challenges arise in terms of data protection and personal rights for systems processing staff or user data.

Agility in engineering: Great enthusiasm despite a lack of implementation.

Most businesses are planning or currently trialling implementation of agile procedure models. The rollout is generally limited to certain teams, departments or projects. Many businesses are adapting and using the Scrum framework. Introducing agility results in the empirical expectation that agile work methods heavily encourage communication and co-operation in engineering. Furthermore, businesses expect improved transparency in planning and documenting procedures, as well as increased liability for work results. The aim of transparency and regular feedback is to enable continuous improvement. Last but not least, agile procedures are designed to ensure businesses can respond faster and more flexibly to changing customer or market requirements. The associated restructuring of existing work methods involves a number of challenges. The existing procedural models and tools are reaching their limits. At the same time, there is often a lack of acceptance across all company levels and in cross-company projects. Also lacking are systematic procedural models for introducing agile work methods at companies, meeting the requirements for organisational structure (e.g. scalability across the many development departments) and the project environment (e.g. interdisciplinary products). Given this, it is important for synergies with Systems Engineering to be identified and utilised.

Creativity management in engineering: The untapped potential of tried-and-tested methods.

Creativity leads to innovative goods and services. It's about identifying an organisation's creative potential and systematically maximising it. Though businesses generally share this view, opinions are divided on the targeted use of creativity methods in engineering. Many of them hardly, if at all, apply creativity techniques. Despite the recognised relevance of creative scope, the necessary infrastructures or working-time models are not yet commonplace. Encouraging creativity in product-design processes requires a change of mentality – both in management positions and among developers. This is what will increase acceptance. On a positive note is the vast range of creativity techniques that have established themselves in practice, such as design thinking and creativity workshops like makeathons. These highlight the challenge associated with selecting the most suitable technique for each specific case.

Product Generation Engineering (PGE): Sustainable efficiency in innovation.

The ever-increasing number of product versions and generations, and their releases, can be described, structured and managed through a systematically integrated planning and development process. This brings advantages in terms of minimising risk in development activities, reducing validation procedures, and creating new opportunities for standing out from competitors. Though the models and potentials of intergenerational development founded in science, the approaches are yet to be extensively established in practice.

Impacts of ASE on the organisational structures and people within the overarching socio-technical system

A shift in organisational structure and culture: An active, people-focused creative process.

Many companies are in a phase of refocusing their organisational structure in engineering, during which the aim is to introduce flat organisational hierarchies and shift from function-oriented to process-oriented work structures. Great emphasis is placed on establishing an open corporate and error culture with transparent communications. Corporate culture's role as the foundation for promoting creativity and collaboration is also coming into focus. The prevailing opinion is that the fundamental shift in engineering needs to go hand in hand with further developments in corporate culture, encompasses all management levels and are exemplified by the management figures. The management must be aware that changing corporate culture takes a lot of time and perseverance.

Collaboration in engineering: Innovative strength through learning organisations.

Successful value creation means working collectively and collaboratively, and pooling skills and experience within and between companies. The collaboration associated with creating Advanced Systems requires a joint, multidisciplinary development language and a joint meta model for products, services and production systems. Relevant methods and IT systems for in-house knowledge management and communication need to be established. Best practices for processes, methods, IT tools and information standards also need to be identified and communicated in order to learn from one another and to facilitate development hubs around the world and cross-company collaboration within value networks.

Co-operation between business and science: Corporate, scientific and economic objectives in harmony.

The interviewees value co-operations between business, science and expect collaboration to become increasingly relevant. Given successful examples of collaborations, some parties are also calling for new collaborative methods and multilateral exchange programmes. When collaborating, it is important to factor in the frequent conflict of objectives between the companies' economic success and the knowledge gained through research. Innovation ecosystems in which people work collectively and in an application-oriented manner to develop technologies and methods are an example of how to handle this conflict of objectives.

Roles in the creative-design process: Continuous adaptation of qualifications and team members.

Parties to the development process will work in increasingly changing and sometimes completely new areas in future. This will require developers to be highly flexible and willing to learn. It will also require companies to continuously introduce and maintain the further development of new role profiles in engineering and the associated responsibilities. Particular emphasis is placed here on organisational interface functions in engineering and supportive administrative departments, such as a coach for managing processes, methods and tools. Personnel planning, project-team members and qualification planning in development will need to be adapted accordingly to avoid any discrepancy between the roles defined and those actually applied.

Required skills: Conflict of objectives between well-founded expertise and a holistic understanding of the system.

Now more than ever, there needs to be a balanced trio of technical, methodological and social skills. The players involved in future creative-design processes will also be required to handle the conflict of objectives between deep technical experience in one discipline and a holistic understanding of the overall system. The ability to think systematically will become a prominent key competency. This is based on a good understanding of the respective application context and the fundamental systemic solution approaches. Though the specialist disciplines involved are relevant in principle, IT skills play a particularly crucial role in this age of digitalisation, especially as an integrative cross-sectional skill. Last but not least, social skills – most notably communication skills and ability to co-operate – are also rapidly gaining importance. Despite this amplitude of new and in some cases 'soft' skills, well-founded technical expertise is also critical for concretising a complex system, so as not to perpetuate the fallacy that 'soft' skills are replacing 'hard' ones. Players in the development process are thus being called on – more than ever before – to substantiate their strengths in well-founded technical and methodological expertise with 'soft' skills.

Education pathways in engineering: New incentives in training and continued education.

Engineer training should increasingly focus on imparting a comprehensive understanding of the importance of interdisciplinary collaboration and communication. University courses within an established specialist discipline should also be continuously further developed through new teaching formats, such as interdisciplinary projects in a team, involving problems drawn from the business world. Such formats aim to apply methodological skills to specific tasks and hone social skills. At the same time, more young people need to be inspired to study engineering, so as to counter an emerging skills shortage early on. New pathways to visibly enhance the appeal of the system design must be sought here.

Not all of the required competencies can be taught to the necessary extent solely through tertiary studies. Practical skills and abilities must thus be imparted and tested through continued education on the job. The continued-education programmes need to cater to the dynamic nature of new technologies and methods, as well as facilitate a sustainable transfer of know-how.

Engineering: an international comparison

An international comparison of Systems Engineering in research and teaching: Germany in competition against the USA and China.

Germany is a leader among European countries when it comes to Systems Engineering. Both in teaching and in research, Systems Engineering is gaining in importance worldwide. While the extent to which this subject has been incorporated into curricula at Germany's nine universities of technology (TU9) varies greatly, it does already figure at the different faculties. At an international level, most Systems-Engineering graduates complete their studies in the USA, China and Japan. The many different ways of potentially interpreting course content make it impossible to properly compare the education infrastructures.

The scientific publications increasing annually by 8%, Systems Engineering continues to gain relevance in the German research landscape. In terms of international comparison, the USA and China have both the highest number and also the highest quality of publications, based on the number of citations, with China recording the highest annual growth rate at around 30%.

An international comparison of Advanced Engineering: Germany well behind despite cutting-edge research.

The research KPIs recorded in relation to Advanced Engineering underline the superiority of the USA and China in this field. The USA lead the way in the number of publications on creativity and agility in engineering, while China dominates the topic of digitalisation in engineering. Germany is well behind in terms of quantity of publications on AI and creativity, but it is one of the frontrunners when it comes to PLM and digital twins.

Initial Advanced-Systems approaches Engineering – an international comparison: ASE can effectively assist with the shift in added value.

The study shows a particular increase in publications on combinatorial analyses of AI and SE, as well as agility and SE. This confirms the view that we are on the right track with AI and agility, and that the only way to unlock the corresponding potential benefits fast enough is to incorporate ASE.

1 Introduction

Goods and services are increasingly shifting from previous mechanical products to mechatronic solutions, and now to smart, cyber-physical systems. These future Advanced Systems are shaped by a high degree of dynamic networking, autonomy and interactive, sociotechnical integration.

They are the result of close co-operation between many specialist disciplines, such as engineering, natural sciences, IT, sociology, psychology and ergonomics. The increasing incorporation and networking of specialist disciplines, coupled with the associated rise in complexity of projects and companies, require holistic, interdisciplinary Systems Engineering.

New technical and workflow trends in engineering are continuously developing simultaneously with Systems Engineering. Advanced Engineering takes into account the processes, methods, tools and work organisational structures in order to rethink established engineering approaches with creativity, agility and digitalisation.

Advanced Systems Engineering (ASE) is the model for successfully designing innovative products, services and Product Service Systems, as well as their creative processes. The model incorporates approaches from Systems Engineering and Advanced Engineering to successfully create Advanced Systems. In doing so, Advanced Systems Engineering particularly takes into account the impacts of increasing digitalisation, multidisciplinarity and networking to handle the technical and organisational complexity of future value creation. It integrates system-oriented and highly innovative engineering approaches, and stands for new perspectives in designing, developing and operating the technical systems of tomorrow.

This publication identifies and analyses the current status quo of engineering in the worlds of business and science in Germany. To do this, it conducted a qualitative study of engineering trends and the latest challenges and possible solutions in Advanced Systems, Systems Engineering and Advanced Engineering. This qualitative study was conducted as part of a series of interviews with over 100 participants from the academic field and industrial practice. The results were examined in terms of impacts on organisational structure and the people within the overarching sociotechnical system for holistic classification purposes. A final quantitative KPI survey across the research landscape showed how engineering is structured in Germany compared to elsewhere around the world. ›

The results are intended to help establish strategic recommended actions for implementing the Advanced-Systems-Engineering model, while the status quo is designed to serve as a well-founded basis and orientation framework for further research activities. The performance-status study came about as part of research accompanying the 'Innovations for the production, service and work of tomorrow' research programme on 'handling the complexity of sociotechnical systems – a report on Advanced Systems Engineering for the value creation of tomorrow (PDA_ASE)' conducted by the German Federal Ministry of Education and Research. The authors bear sole responsibility for the content of the study

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Structuring the performance-status

Chapter 2 introduces the change in value creation and gives an overview of the three areas of activity in the Advanced Systems Engineering model. The three areas of activity include Advanced Systems (AS) as future market services, Systems Engineering (SE) and the innovative technologies and methods of Advanced Engineering (AE).

Chapter 3 describes the objective of ascertaining the status quo in engineering. The various preliminary studies showed that there is a need for research.

Chapter 4 represents the findings of the qualitative survey that had been carried out, in which the status quo of engineering in Germany was investigated based on the areas of activity. Section 4.1 describes the megatrends that are having a fundamental and lasting influence on both our engineering and our future market performance. Sections 4.2 to 4.4 show the effects on the three areas of activity of Advanced Systems (Section 4.2), Systems Engineering (Section 4.3) and Advanced Engineering (Section 4.4). The last section describes the effects on the organisation and the personnel in an overall socio-technical system (Section 4.5).

Chapter 5 includes the findings of the quantitative investigation of the status quo of engineering in the form of an international comparison. Sections 5.1 and 5.2 investigate the subjects of systems engineering in research and teaching and that of Advanced Engineering in research, both nationally and internationally. Finally, a combinatorial consideration of these two subject areas takes place in the form of a brief insight into Advanced Systems Engineering (Section 5.3).

Chapter 6 summarises the contents of the status quo and draws conclusions. It also provides an outlook on future needs for action.

The appendix in **Chapter 7** includes additional information on the accompanying research project, AdWiSE, and the institutes involved.

2 Advanced Systems Engineering
New prospects for the value creation of tomorrow

2.1 A shift in value creation

Megatrends such as digitalisation and artificial intelligence (AI), as well as mounting pressure from a new, sustainable form of technical products and services, will critically shape the value creation of tomorrow [BUN16]. In industrial production and product development, for example, digitalisation is being driven by the Industry 4.0 future project. Smart, digitally networked products, services and production systems are forming the technical basis of Industry 4.0. The systems of tomorrow are characterised by flexible combinations of services and non-cash benefits, coupled with a high degree of autonomy and networking. Designing these technical systems in a holistic manner requires a new approach to future engineering (SEE INFOBOX 1). To achieve this, it is important to highlight the current level of engineering performance and analyse the emerging trends for future value creation.

Traditionally speaking, value creation describes a corporate activity that results in added value. [SCH13]. The conventional, industrial value chain addresses the entire process from initial idea to delivery of a product. The environmental responsibility and growing importance of sustainability also require returns and disposals to be examined throughout the entire product life cycle. As such, the value chain of industrial products encompasses following activities: product planning, development and validation; production planning and procurement of raw materials, product materials and components; actual manufacturing and production; distribution and sales; customer service during usage; and returns, disposal and recycling at the end of a product's life cycle.

INFO 1 The understanding of 'engineering'

The term 'engineering' is very broad. It is often equated with product development, though it is more about product creation and design, which also includes strategic product planning, production-system development and the actual manufacturing process.

Engineering is a task in which an understanding of science and technology is utilised to invent things, develop and manufacture systems, and solve problems. Systems encompass technical solutions such as machinery and facilities, as well as buildings, infrastructures, processes and procedures. Software and service engineering is gaining importance given the increasing prevalence of smart, networked and highly integrated Product Service Systems. ›

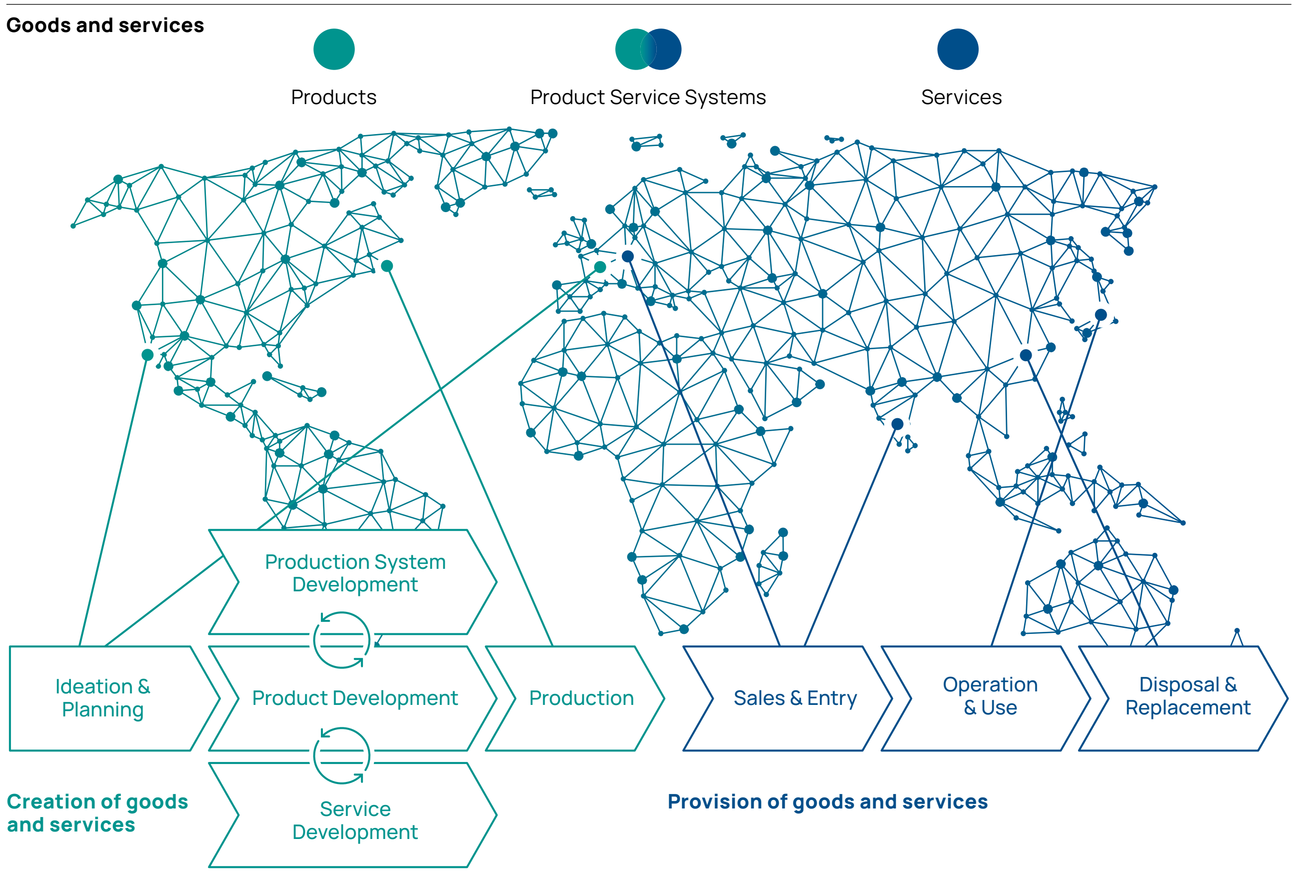


Fig. 1: Aspects of change in value creation

In future, value creation will no longer only take place in predominantly closed value chains, but rather also based on open, collaborative and decentralised value networks. Digital technologies are acting as the driving forces and enablers of this change [RMW18]. The digital change in value creation is giving rise to new forms of partnerships, organisational structures and business models,

— increasing dissolution of traditional industry boundaries,
— and innovative services that can no longer be clearly classified as part of the productive industry or services sector.

Innovative products, services and Product Service Systems are of critical importance to the corporate success of Germany's industrial sector, and thus take high priority in the value creation of tomorrow. The particular relevance of value creation through innovation is illustrated by the innovation KPIs of the German industrial sector [RBD+17; DBF+17] and highlighted by Germany's position as the most innovative country when compared internationally. In the following discussion, the concept of innovation will be characterised by three aspects – goods and services, inventiveness in the creative process, and the profitable implementation thereof [AHW+18] –, which in keeping with value creation, are continuously changing (SEE FIGURE 1):

Goods and services: Goods and services to be rendered encompass products (non-cash benefits) and services/solutions that bring the provider, customer and user a bona fide benefit. In recent years, we have seen that adopting an integrative view of Product Service Systems and digitalising goods and services can generate additional benefits for customers. More digital goods and services, based on new, corporate approaches and business models (e.g. the platform economy), are now emerging as supplements or even replacements for previous goods and services [DFH+19]. Data, algorithms and virtual models become more important in a digital economy [PH14], which is why a growing proportion of future product properties and functions are being created or at least supplemented by mechatronic solutions and software. In addition to the increasing software component, Product Service Systems also require integrated planning, development and usage of the service and non-cash-benefit parts, including their production and intrinsic software components. The aforementioned developments place tremendous demands on the process for creating future goods and services.

Invention: The future shift in goods and services requires continuously implementing new ideas in products, services or production processes. Successfully doing so simultaneously necessitates technical or organisational innovations in strategy-planning, product-development, service-development and production-system-development activities [MS14]. The creative process from the initial idea of a new good or service to the production thereof is characterised by increased and multi-location networking of all kinds of players, stakeholders, departments and companies. The goods and services of tomorrow will be based more on interactions between various specialist fields such as engineering, IT, sociology, ergonomics and economics than ever before. In addition to rising multidisciplinarity and networking, the individual activities associated with creating a good or service will be increasingly supported by information and communications technologies. Given this, there needs to be a new approach to creating goods and services, taking into account both the growing influence of digitalisation and the interdependencies within the activities and between added-value partners.

Profitable implementation: As with the creative process, the implementation of goods and services will increasingly be taking place on networked markets scattered all over the world. On the one hand, global sales and distribution provides attractive potential for unlocking new markets. On the other hand, the country-specific standards, rules and regulations for approving a good or service pose a huge challenge for the creative process [SCH13; ROG03; AHW+18]. Forms of consumption, as well as the understanding of ownership and property, are also changing. Across multiple industries, we are seeing the emergence of platforms enabling various providers and added-value partners to become joint owners of goods and services. In the case of sharing models, goods and services are used temporarily without acquiring ownership, thereby shortening the usage phases for each individual customer. Companies also need to be aware that networked products can also change and further develop even after they have been sold. The aforementioned aspects must be taken into account in the creative-design process in order to map out both the digital and the physical life cycle of goods and services.

In view of this change, companies need to be able to profitably and efficiently create both innovative goods and services as well as their future design processes. The increased networking and extensive digitalisation in production are already being highlighted as part of the Industry 4.0 future project. The upstream activities in the creative-design phase raise the fundamental question of how a new model needs to be established for research, development and design/planning to ensure Germany can maintain its innovative capacities in the global competition. The initial stage in formulating this model involves examining the current status quo and emerging engineering trends through this publication. The examination is based on specific fields of action. Advanced Systems Engineering – as the subject of the examination – is first structured (SEE SECTION 2.2), pooling the various aspects of future engineering into one joint outlook on the model.

2.2 The three fields of action of Advanced Systems Engineering

The aforementioned shift in the value creation of tomorrow requires examining things holistically based on the new model of Advanced Systems Engineering (ASE), which builds on three fields of action - Advanced Systems, Systems Engineering and Advanced Engineering (SEE FIGURE 2).

Advanced Systems
Goods and services of tomorrow

Digitalisation has been driving technological developments in industrial value creation for years. We are seeing a shift from the earlier mechanics-oriented systems to mechatronic systems, to smart, cyber-physical systems. These future systems will be characterised by a high degree of dynamic networking, autonomy and interactive, sociotechnical integration. Coupled with this is an increasing range of internet and platform-based services, and the availability of large quantities of data, which create promising opportunities for innovative and data-driven services (smart services), Product Service Systems and attractive business models [GDE+18]. This potential will also see increased customisation of systems from a customer and user perspective. Networking products, services and production systems will, in future, enable new flows of information between providers and customers – to facilitate profitable, customised mass production, among other things [PIL07].

This shift away from traditional services or non-cash benefits and towards Advanced Systems will critically shape the future understanding of goods and services. The aforementioned development does, however, mean that both the systems and the design and development activities will become more complex, resulting in an urgent need to explore new approaches for designing and creating goods and services [GDE+18; DEU18].

Systems Engineering
Managing complexity

Present-day and future systems come about through close co-operation between many disciplines, such as mechanical engineering, electrical engineering and IT. No specialist discipline can profess to be able to meet all the requirements for creating future goods and services on its own. There needs to be a new way of thinking and acting, which revolves around an interdisciplinary approach to working on the system, promotes interaction with stakeholders, and enables users to experience the system being created. Systems Engineering has the potential to lay a new foundation for designing the sociotechnical engineering systems of tomorrow [DEU18].

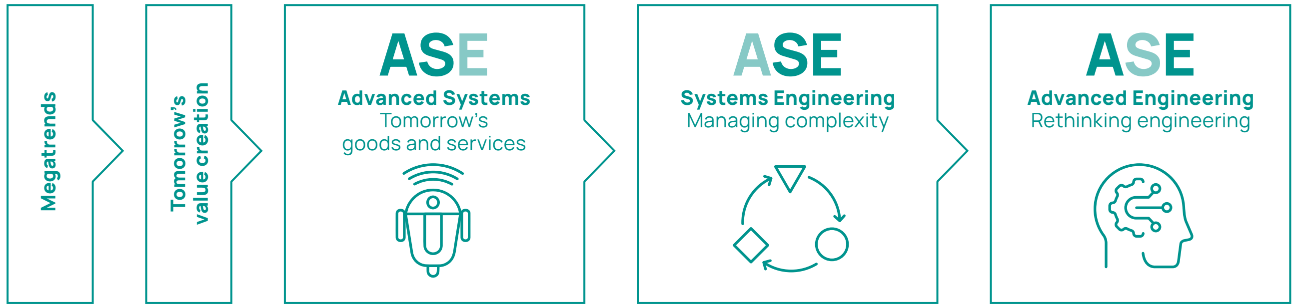


Fig. 2: Fields of activity of Advanced Systems Engineering

Systems Engineering thus claims to be able to co-ordinate the players involved in developing complex systems. The consistent, holistic and multidisciplinary approach here is aimed at the technical system due to be developed, and the associated project. Beyond the central tasks relating to the creation of goods and services, Systems Engineering also takes into account the interdependencies between these activities, extending as far as the socioeconomic environment of an entire industry. To ensure the development target can be achieved with confidence, the project-design process entails co-ordinating activities, factoring in the relevant restrictions regarding resources, time, cost and quality. The greater the number of stakeholders involved in development, the more complex this task becomes. Systems Engineering focuses on incorporating and networking further disciplines, such as sociology and psychology, and on the associated increase in the complexity of the solutions within the specific development project and company [GDS13].

The importance of formalised modelling in Systems Engineering is continuously growing. The need for Model-based Systems Engineering (MBSE) is centred on the notion of using models to describe, understand and design the systems. MBSE has the potential to successively replace document-based mapping of information via a newly developed system, and to significantly influence the future practice of Systems Engineering [WRF+15]. Implementation of the MBSE idea in an economic context is, however, still in its infancy. Extensive research activities are required in order to unlock this potential.

Advanced Engineering
Rethinking engineering

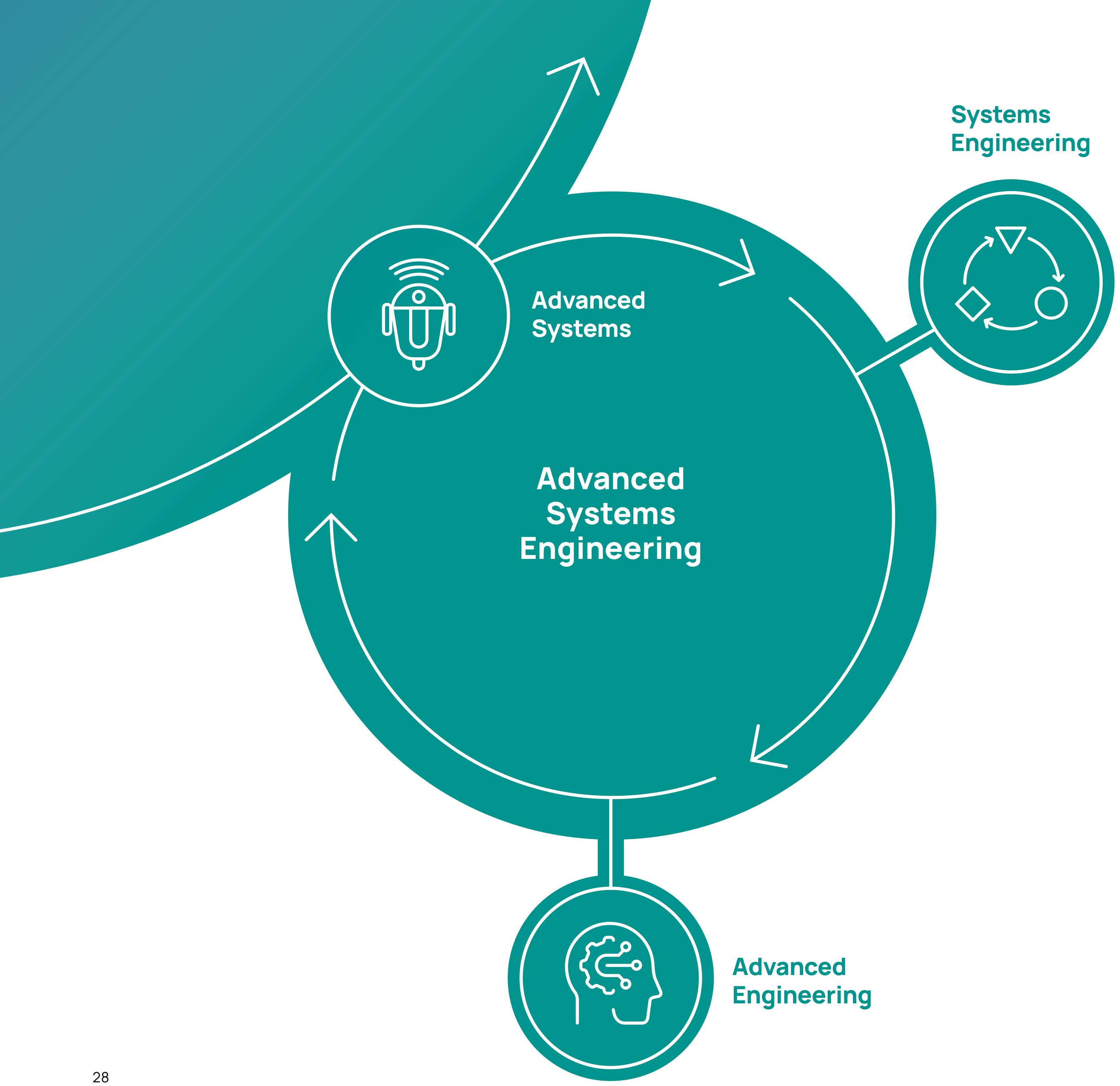
Simultaneously with Systems Engineering, development work is constantly being done on new engineering approaches that considerably influence the individual aspects and activities associated with creating goods and services. These approaches are not based solely on IT-tool innovations, but rather utilise current findings within and between engineering, economic and IT disciplines. These fundamental changes in engineering are encompassed under the concept of 'Advanced Engineering'. Advanced Engineering takes into account processes, methods, tools and work-flow structures to enhance established engineering approaches with creativity, agility and digitalisation.

Engineering is largely a creative human activity that cannot be performed by rule-based IT tools or machines. The future systems require new methods, models and techniques to encourage creativity within interdisciplinary teams, so as to devise a common language, find new solutions, and foster the potential for innovation. It is important to remember here that specialist knowledge from the necessary fields needs to be pooled with the help of completely new approaches to communication and interaction.

Agile principles and methods are increasingly also being implemented in departments and teams outside of IT and software development. But the relevant procedural models and organisational structures cannot be applied to complex, mechatronic systems without adjustments. The increasing number of non-mechanic components, such as software and services, will, however, necessitate a holistic, agile transformation in work methods, so as to enable changing requirements to be handled flexibly and proactively. In addition to human-oriented aspects, the scope and design of engineering processes and organisational structures will also continue to change in future.

Strategic design and development of the product, service and production system are becoming increasingly networked, and will have to be integratively supported by IT tools and the IT infrastructure more than ever before. Suitable visualisations and digital technologies will, in future, form the basis for clearly describing and holistically networking all development objects and aspects, and for collaborative engineering across various global locations, company boundaries and system generations. For example, the progressive integration of AI and the use of digital twins will see a number of crucial changes to engineering processes [SD19].

Tomorrow’s value creation as an overall socio-technical system



Advanced Systems

- Autonomous systems
- Interactive socio-technical systems
- Dynamically networked systems
- Product Service Systems

Systems Engineering

- Technical system
- Project
- Company

Advanced Engineering

- Creativity
- Agility
- Digitalisation

Advanced Systems Engineering

The interactions and interdependencies between Advanced Systems, Systems Engineering and Advanced Engineering require a rethink of the way companies operate, and redefinition of the interactions between humans, organisational structures and technology. The aim of Advanced Systems Engineering is to incorporate the various aspects of Systems Engineering and Advanced Engineering, and to lay a well-founded basis to create and implement Advanced Systems as innovative goods and services (SEE FIGURE 3).

In view of this, Advanced Systems Engineering is the model for successfully designing and creating innovative goods and services. It particularly takes into account the impacts of increased digitalisation, multidisciplinarity and networking to handle the technical and organisational complexity of future engineering. As such, Advanced Systems Engineering stands for new perspectives in designing, developing and operating complex systems. The principle promises strong incentives for value creation, wealth and employment by helping businesses with the necessary transformation in value creation towards Advanced Systems.

The model creates a framework for interdisciplinary approaches and thought principles, methods and procedures as a collective entity to facilitate holistic engineering of innovative Advanced Systems. Implementing the model will contribute significantly to the value creation of tomorrow by targeting efficient design processes and successful rendering of future goods and services in the context of the overarching sociotechnical system.

2.3 Application scenarios of Advanced Systems Engineering

The Advanced-Systems-Engineering model to be explored addresses the challenges associated with the shift in value creation. To ensure Germany can remain competitive as an industrial hub, engineering needs to be further developed.

The following sample application scenarios are designed to illustrate how future Advanced Systems Engineering can counter potential challenges.

Application scenario 1 – mobility systems
Joint, model-based development

In future, driverless cars, as highly automated technical systems within the mobility system, will form a complex system of systems (SoS) in conjunction with conventional, non-automated vehicles, but also in interaction with other elements, such as infrastructure systems. Decision-making responsibilities will increasingly lie in autonomy and artificial intelligence. To cope with these interactions, it will be imperative for the development process to focus on holistic approaches. This gives rise to highly complex and complicated requirements that cannot produce a simple technical solution on their own. A skilful combination of different technologies must instead be used to create optimum benefit and impact for the individual requirements.

In practice, many sub-systems within the mobility system of tomorrow will be produced by a number of different, including small and medium-sized, supply companies. Handling the complexity associated with developing vehicles meeting such various requirements involves interplay between various disciplines. This will call for specialist expertise from mechanical engineers, electrical engineers, mechatronics engineers, IT experts, transport economists, structural engineers, architects, lawyers and many others, posing major challenges for all businesses, particularly small and medium-sized suppliers.

To integrate the various subsystems and manage the complexity of things like mobility systems, the entire development process needs to be founded on model-based, systems-theory approaches and a common communications concept. One key challenge here is the high variation in development and implementation cycles, ranging from just a few weeks in software, to 3 to 4 years in automotive development, to 10 or more years in infrastructure. Securing mobility systems also poses unresolved problems for businesses. It is clear here that the present-day methods and processes cannot cater to this, as the necessary trial periods would be in the order of 100 or more years.

Application scenario 2 – Product Service Systems
Maximising the potentials of agility and early validation

Industry 4.0 and the Internet of Things (IoT) are increasingly facilitating service-oriented business models in mechanical and plant engineering. Instead of selling machinery at a fixed price, it is charged based on provision and usage. This enables customers to enjoy greater flexibility, guaranteed machine performance and reduced capital commitment and non-payment risk. But expanding existing machinery and systems to include the necessary IoT technology is just one of the technical hurdles. Refocusing to adopt a machine-as-a-service approach requires completely new business models and strategies. Establishing the associated billing and sales models and service contracts, coupled with the growing relevance of service developments, entails a company-wide rethink and a shift in the value chain.

This shift must be centred on the interactions between various disciplines, early involvement of customers and users in the product-creation process, and continuous verification of development results. This requires targeted efforts to make the existing product-creation processes more flexible, without completely doing away with the structures already established in the company's internal innovation ecosystem. The products must be agilely further developed and verified with customers, users and providers in short development cycles. The resulting development generations are tested in purpose-built validation environments to ensure the identified benefits can be verified continuously and early on. This enables emerging effects in system behaviour to be recognised in good time, providing a holistic perspective of the analysis of the Product Service System being developed. Combining flexible (e.g. sprints) and structuring process elements (e.g. milestones or, at later stages of development, approval processes) tailored to specific situations and needs must be among a system developer's core competencies, along with in-depth knowledge of the relevant domain. It is also important to bear in mind the vast breadth of the necessary discipline in future – from mechanical engineering, electrical engineering and IT to marketing and purchases, to legal and social expertise.

3 Preliminary assessments and objective

The last few years have produced a number of studies examining the need for research in the individual spheres of activity within Advanced Systems Engineering. This preliminary work is predominantly focused on assessing individual subject areas in isolation. The method for ascertaining this status quo is based on the results of the preliminary assessments, so as to extensively explore the field of Advanced Systems Engineering. Below is an excerpt from the preliminary work conducted to date:

2012 **acatech DISKUSSION**
Smart engineering

As early as 2012, acatech was documenting the fundamental need for action in engineering in relation to Industry 4.0. This came about due to the increasing integration of information and communications technology in the product-development process and the products themselves. This development gave rise to a need for more forward-thinking, system-oriented product creation, which was particularly intended to incorporate all relevant disciplines in the development process and adopt an interdisciplinary approach.

IPEK – Institute of Product Engineering
Advanced Systems Engineering – towards a model-based and human-centred methodology:

The preliminary work in Advanced Systems Engineering dates back to 2012. The aim of the scientific publication was to present the idea of Advanced Systems Engineering as a model-based, human-centred methodology founded on Systems Engineering. The publication introduced initial concepts of Advanced Systems Engineering and reflected on selected research activities in design methodology.

IPEK – Institute of Product Engineering, Heinz Nixdorf Institute
From discipline-oriented product development to forward-looking, system-oriented product creation:

In 2012, future research requirements and approaches were described as being pre-requisites for sustainable innovation success. Forward-looking, system-oriented product creation was identified as the basis for future innovation success, while integrative assessment of product development, production-system development, strategic product planning and multi-person, cross-organisation knowledge management were identified as the fields of action.

2013 Fraunhofer IAO
Future work

In 2013, the Fraunhofer IAO examined the impacts of digitalisation on work structuring as part of its 'Arbeit der Zukunft' ('Future work') study. One of the key findings was that staff and teams must at least become equal, but ideally leading, decision-making authorities within a cyber-physical system (CPS) through new forms of collaboration between humans and technology. The division of labour between humans and machines need to be configured in such a way that better decisions are made faster through collaborations within the sociotechnical system. Innovative solutions for work structuring, work-oriented training and sociotechnological management will help here.

Heinz Nixdorf Institute, Fraunhofer Project Group for Mechatronic Systems Design
The path to smart technical systems (it's OWL)

Scientific publications had already anticipated the shift from earlier products to mechatronic solutions, to Advanced Systems as early as 2013. At that time, Advanced Systems Engineering was predicted to be a solution for designing these smart technical systems. It was presented as the key to overcoming the complexity associated with product creation in the sense of a networked, sociotechnical system.

Heinz Nixdorf Institute, Fraunhofer IEM, Unity
Systems Engineering in industrial practice

The study found that SE's prevalence in the German-speaking world was heavily industry-dependent. Systems Engineering is already well established in aerospace engineering, for example. In the automotive industry, SE is seen as an enabler that is gaining importance and being driven by OEM. But the study also showed that, despite its great importance, Systems Engineering is generally not being applied, especially not in the field of mechanical and plant engineering, which, in Germany, is dominated by SMEs.

2014 acatech POSITION
Resilience-by-design: a strategy for the future of technology

Resilience is the ability to ward off actually or potentially adverse events, to prepare for them, to factor them in, to rebound from them, and to adapt to them ever more successfully. acatech Position shows that countries such as the US, Great Britain and Switzerland are several steps ahead of Germany in terms of specifically implementing the concept of resilience. Resilience strategies will also need to be incorporated into government programmes here in Germany in future.

2016 acatech STUDIE
Engineering in an Industry 4.0 environment

The key finding of the 'Engineering in an Industry 4.0 environment' study was that of the central and increasing importance of engineering within Industry 4.0. It also confirmed the need for new engineering approaches extending beyond product development. The results also highlighted the need to adapt existing methods and develop relevant IT tools, as well as the need to modify organisational structures. The study additionally addressed engineering skills that will be required in future.

Heinz Nixdorf Institute, WZL RWTH Aachen, acatech Industrie 4.0
An international benchmark, options for the future, and recommended actions for production research

Industry 4.0 is opening up new prospects for Germany as an economic hub. While Germany is optimally positioned to operate as a key market and leading provider, it lacks a broad skills base in internet technologies and innovative business models. The study identified 44 recommended actions, such as 'Encouraging acceptance of Industry 4.0', 'Improving the innovation system' and 'Enabling collaboration'.

2017 Bitkom Research, Autodesk GmbH
Digital engineering

The study focused on the innovative capacities of industry in Germany. The idea here was to identify measures guaranteeing competitiveness through product and process innovations in view of declining profit margins resulting from digital added-value and business models. In general, the study shows that digital technologies have already significantly penetrated German industry. They are being used to accelerate product development, optimise manufacturing processes or increase the adaptability of organizational structures. ›

2018 **Plattform Industrie 4.0 STUDIE**
Engineering smart products and services

The 'Engineering smart products and services' study identified operational research requirements for engineering smart products and services. In general, the innovation and business potential associated with engineering smart products is becoming increasingly recognised within Industry 4.0. The research required includes developing new procedural models and methods integrating (for example) agile methodological components, providing detailed information on the various phases of the existing procedural V model, and devising measures for improving Product Data and Process Management.

University for the SME Sector (FHM)
SMeART learning and business-consultant requirements among Europe's SMEs in smart engineering

The 'SMeART learning and business-consultant requirements among Europe's SMEs in smart engineering' study addressed the question of how Europe's SMEs need to adapt their structures, organizational setups and processes in order to keep up with an ever-smarter industry. A survey of numerous European SMEs found that only a small percentage of interviewees considered their business to be a good example of 'smart industry'. The most commonly cited problems here relate to data storage and collection, as well as legal and contractual hurdles. These problems can be resolved through agility, because the small sizes of SMEs mean it is often easier for them to adapt their business models and strategy, making them more flexible than larger companies.

2019 **Fraunhofer IPK, Contact Software, VDI**
Smart industrial products

The study showed that around 90% of interviewees were already using smart products. The incorporation of smart products into the product range has resulted in interviewees expecting the range of services to grow, and setting revenue increases as their top objective. Very few companies are currently able to demonstrate the skills necessary for this development. And weaknesses have also been identified in relation to adapting business models and implementing the necessary IT infrastructure. These will have to be eliminated in order to successfully introduce smart products.

PaiCE accompanying research
Collaborative engineering

The study identified and analysed the challenges of collaborative engineering in the areas of technology, work organisation, economics and law. The requirements and success factors associated with collaborative engineering are, however, largely still unknown. Experience in collaborative working has currently primarily been gained in research and development, i.e. in the pre-competitive sphere.

Based on the results and findings of the preliminary work conducted in the individual fields of action within Advanced Systems Engineering, a holistic assessment thereof was established as the main objective of this engineering performance analysis. This need is underlined by the work completed to date. The holistic assessment involved conducting qualitative interviews with players from the business and scientific worlds to gain a deeper understanding of the existing challenges and possible solutions within the fields of action (SEE CHAPTER 4). On the other hand, a quantitative KPI survey was conducted to analyse the performance of the fields of action in international research and teaching (SEE CHAPTER 5). The combination of the two approaches sees the current status quo establish a well-founded basis for identifying strategic recommended actions for implementing the Advanced-Systems-Engineering model.

4 The status quo of engineering in science and business

PHASES				RESULTS
1	**Identifying the objectives**	— Identification of thematic issues for business and science as well as for other relevant stakeholders — Development of working hypotheses.	→	**Structuring the topic**
2	**Preparation of the interviews**	— Selection of relevant industries — Identification of suitable interview partners — Development of interview guidelines with over 20 open questions	→	**Structured survey panel**
3	**Conducting the interviews**	— Conducting the interviews with open questions (interview duration: 1.5 hours) — Where possible, recording the interview	→	**>100 expert interviews carried out**
4	**Evaluation**	— Preparation of a short report — Transcription and software-based coding of the interviews carried out — Consolidation of the results	→	**Core results**
5	**Appraisal**	— Assessment and discussion of the findings in an expert workshop	→	**Study findings discussed**

Fig.4: Procedure for carrying out the survey of the current performance level

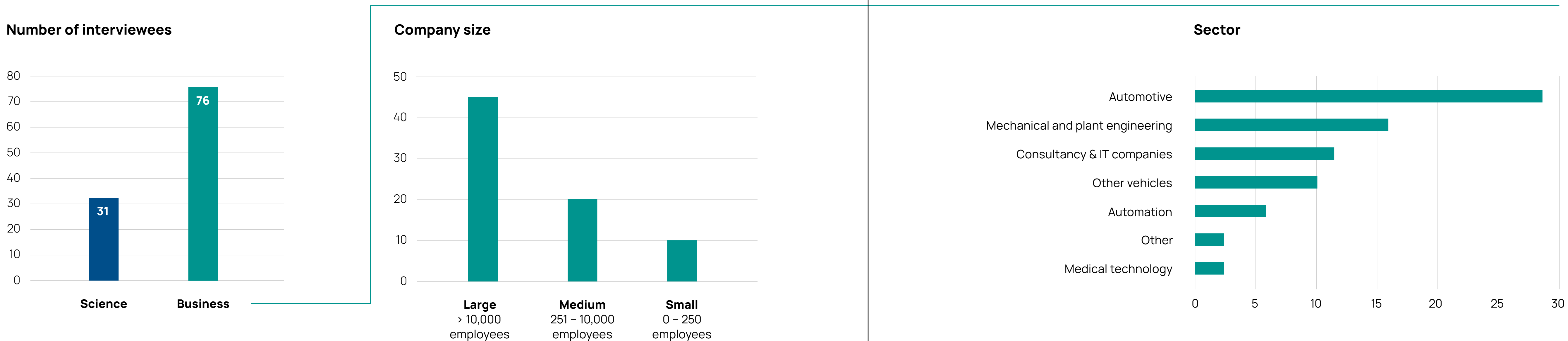


Fig. 5: Field and distribution of the interviewees

QR code: Guide to qualitative research and question categories

The qualitative assessment of the status quo of engineering in science and business is split into five phases (SEE FIGURE 4).

The first phase saw the research consortium define the objective and questions associated with the performance appraisal. The aim of the performance status is to help establish strategic recommended actions for future engineering. At the same time, the results are intended to lay a well-founded basis and provide a framework for further research activities. More specific questions were formulated to achieve these general objectives. This involved initially identifying core issues and relevant stakeholders of ASE activities. Building on this, working hypotheses on future engineering were then established and used as guides for the study plan. The working hypotheses were simultaneously used as the starting point for the quantitative KPI assessment (SEE CHAPTER 5).

The second phase involved structuring the topic and preparing the performance status. The structuring process entailed analysing existing studies, specialist literature on the status of research, and existing research activities. Based on the analysis and prior knowledge of the research consortium, the ASE model was established as a framework for the study. Structuring the topic helped create a list of 20 open questions with set categories (SEE QR CODE ON PAGE 43).

Suitable specialists/experts from the fields of business and science were identified to conduct the semi-structured interviews. The key criteria for selecting these experts were

— multiple years' experience in engineering (e.g. as development managers),
— a strategic vision as technical manager (e.g. as technical director),
— particular expertise in a field of action (e.g. as senior expert)
— or an outstanding scientific/academic reputation (e.g. as holder of a professorship).

During the survey period between October 2019 and March 2020, 107 interviews were then conducted and analysed, primarily in the German-speaking world. This corresponds with the third phase of the qualitative status-quo assessment. The selection process was centred on the fact that the candidates had to represent the field of study in engineering as broadly as possible. Two thirds of the interviews were conducted with corporate representatives from various industries and company sizes. Different roles within the value network (e.g. suppliers, integrators, OEMs) were also taken into account. The spread of company representatives was in keeping with Germany's most important industries. (SEE FIGURE 5).

The empirical assessment took the form of guideline-based interviews in the following five subject areas:

— Mega trends influencing engineering (SEE SECTION 4.1)
— Advanced Systems – goods and services of tomorrow (SEE SECTION 4.2)
— Systems Engineering – Managing complexity (SEE SECTION 4.3)
— Advanced Engineering – Rethinking engineering (SEE SECTION 4.4)
— The impacts of ASE on organisational structure and people (SEE SECTION 4.5)

The interviews in the third phase each lasted around 90 minutes and were generally recorded. Brief transcripts were then created and used to prioritise the interviews and initial category definition.

The fourth and fifth phases involved analysing the interviews, having them assessed by selected experts, and fleshing out the performance status. The transcribed interviews were initially coded with the help of software and systematically evaluated. The interviewees' comments were consolidated, analysed and pooled as findings. A workshop was then held with selected experts to critically review the findings and initially identify strategic recommended actions. The fact that only a minority of participants had already sat interviews was factored in here.

The findings detailed in sections 4.1 to 4.5 below provide a consolidated, exploratory look at the fields of action. Opinions were recorded from the interviewees' perspective, so as to draw summaries and conclusions from the general, widespread understanding. But some of the findings are also contradictory or varied. The open nature of the interview questions often enabled in-depth probing, which is why some interviewees' opinions are particularly highlighted.

4.1 Mega trends influencing engineering

Long-term mega trends are shaping the shift in added value through profound changes. These changes affect all areas of society and the economy, meaning they significantly influence future developments in engineering. The survey identified 17 individual trends having a relevant influence in engineering. An overview of the identified trends has been created in the form of a trend radar (SEE FIGURE 6). The trend radar groups the trends into one of three categories: Globalisation, Digitalisation or Sustainability in engineering. Relevance was weighted, regardless of industry, based on the number of mentions. The trends with medium to high relevance are highlighted in more detail below.

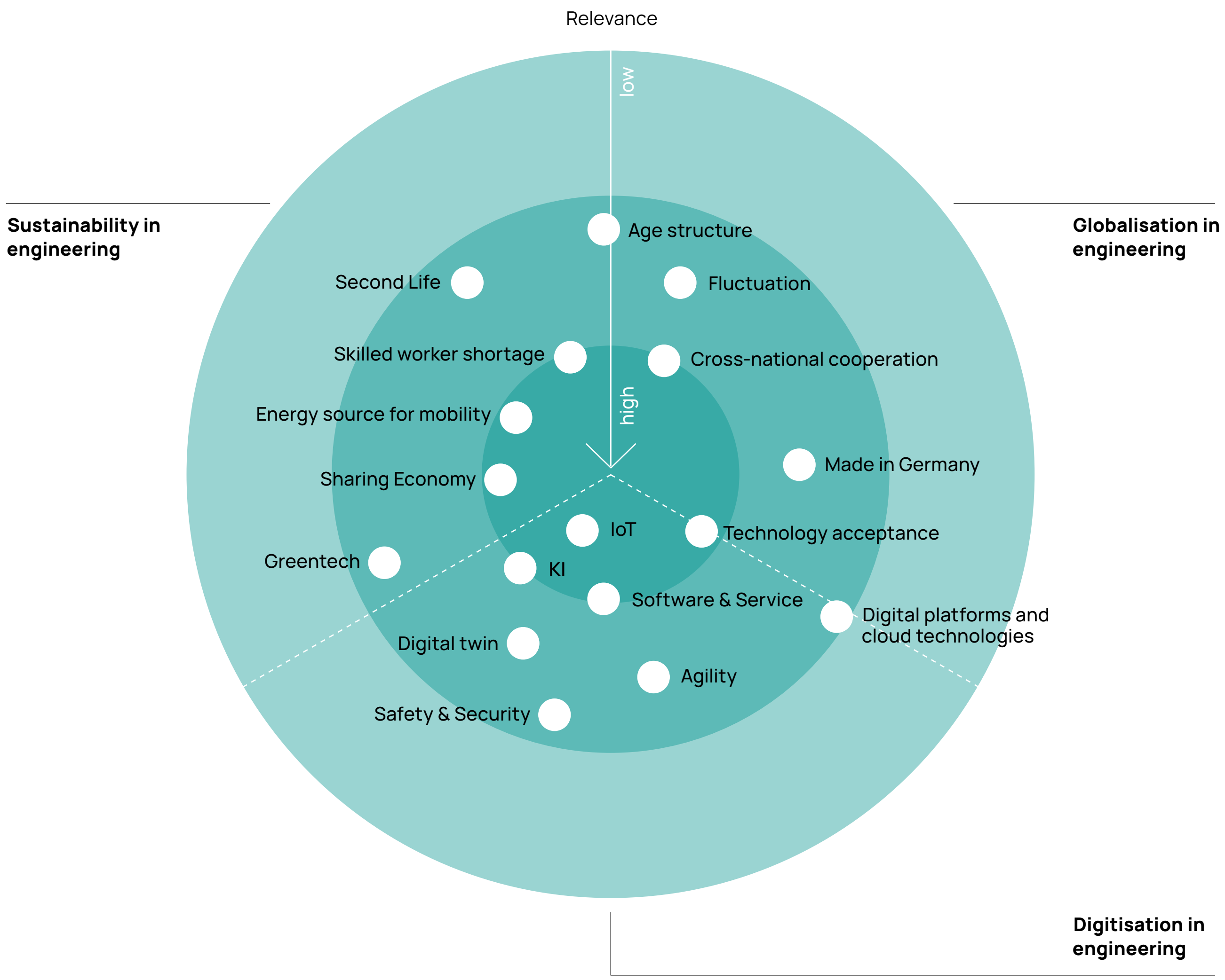


Fig. 6: Trend radar of engineering as a result of the qualitative performance survey

4.1.1 Globalisation in engineering

Globalisation describes more than just the worldwide division of labour and transnational trade. It also encompasses the international exchanging of ideas, knowledge and technologies in science and business. This internationalisation unlocks a number of opportunities for companies to develop new job markets and achieve new strategic competitive advantages. At the same time, it is also about utilising the potential of intensive knowledge transfer through global research networks. Some interviewees describe an opposite trend of de-globalisation, which is being fed by aspects such as trade conflicts. These developments involve localising supply chains, for example, in order to reduce the risk of supply shortages.

Global population developments pose both an opportunity and challenge for the surveyed businesses. Stagnating societies are colliding with fast-growing ones. Resource distribution, migration and advancement of living standards are what will shape the decades to come. This creates a particularly challenging situation for Germany, because the country's growing wealth is contrasted with limited resources and an overburdened pension system. In view of the demographic shift, it is imperative to explore concepts aimed at securing know-how and methodological expertise. Knowledge-intensive engineering particularly has the potential to provide long-term support in the working world through experience and knowledge. A few key trends and their impacts on engineering will be examined below:

Transnational co-operations: This trend has generally been confirmed by many of the surveyed businesses, even though turning it into strong, rewarding alliances remains a challenge.

Staff turnover: A number of the surveyed interviewees expect high staff turnover in future as a result of more frequent job changes or international relocations. Early retirement by many staff members has seen knowledge management gain importance in engineering. The jury is still out on what successful, human-centred knowledge-management concepts might look like in future.

Made in Germany: 'Made in Germany' continues to be one of the most important quality features of German industry. And this implies more than just the manufacturing or assembling of goods. Several interviewees particularly mention the necessary innovation process and engineering as being a key added-value component of the quality feature. At the same time, some fear this quality feature will be lost, as increasing globalisation means Asia-based companies are pushing their way into established markets or core business is being moved to Asia. One particular challenge here is that of securing production, as part of the manufacturing process, under German cost conditions. In light of this, the 'Made in Germany' brand essence must be promptly further developed in a manner befitting a leading innovation hub.

During the survey period between October 2019 and March 2020, the 'resilience' trend was not deemed to have a significant impact on engineering.

4.1.2 Digitalisation in engineering

As one of the mega trends of the 21st century, digitalisation is influencing all areas of Germany's society and economy. It generally pursues three specific objectives: 1) To create value in new business fields and with new technologies, 2) to deliver added value and increase efficiency in the core processes and customer experience, and 3) fundamentally build on technological and organisational skills to safeguard the digital transformation and acceptance.

Most interviewees agree that digital solutions provide numerous potential benefits, which will need to be further developed in future in order to foster Germany's competitiveness. Potential in engineering lies in area such as the networking of information within the product-creation process or in the continuity of digital models. Several trends and their impacts on engineering will be examined below:

Artificial intelligence (AI): Many interviewees describe artificial intelligence as a key trend that can generate a relevant competitive edge even in engineering. Although most interviewees emphasise the potential of AI-based solutions and assistance systems in the product-creation process, very few companies are able to cite concrete examples in which these have been applied. There is thus a need for research and suitable transfer options for establishing AI applications in industrial practice.

Digital twins: Combining virtual design and development processes with increasing system connectivity is already enabling extensive optimisation through digital replication of products, production plants and entire factories. Although most of the companies interviewed see digital twins as a competitive advantage, their understanding of the concept's features and core aspects varies greatly. In view of this, clear, coherent approaches need to be developed and applied in practice.

Digital platforms and cloud technologies (cloud): Some interviewees believe digital platforms and cloud technologies designed to support engineering are a strategic success factor in engineering IT infrastructure. This view is largely in line with the development activities of established software providers in engineering. It is here that we see the emergence of Product Life Cycle Management or simulation software in the cloud. The widespread yet collective development work across locations and even company boundaries is deemed to offer particular advantages. Nevertheless, some of the interviewees are still yet to find promising solutions for scalable, reliable services in engineering.

Internet of Things (IoT): IoT technologies are increasingly the interviewed companies' goods and services. In addition to system connectivity, however, some interviewees believe the associated processes and impacts on the IT infrastructure pose a particular challenge. In view of this, standardising programming interfaces is deemed especially relevant for enabling consistent linking of development systems and operating data. These interviewees are of the opinion that the current system landscape is very heterogeneous, and that integrating concepts need to be duly researched.

Software & service: A number of the interviewees expect service business to grow in importance, in addition to the existing product range. Continuously expanding goods and services to include software-based components will see a change in the added-value process. Some interviewees think the development of data-based services will establish itself as an integral part of engineering. In light of this, the effects of asynchronous development and change cycles, as well as the engineering of new functions, must be examined during the operational phase.

Safety & security: Given the growing number of digital solutions, the importance of IT systems' operational safety (safety), as well as information security and data protection (security), will increase. Many companies believe this will bring additional challenges yet to be clearly defined. In addition to the current efforts to factor in various and, in some cases, conflicting requirements in the development process ('sustainability by design', 'usability by design' etc.), solutions for technical systems in terms of 'safety and security by design' also need to be explored.

Agility: Some interviewees believe the growing volatility of customer and market requirements is forcing companies to introduce new forms of working. Most of the companies consequently consider agile work methods to be key issue. At the same time, these interviewees re-iterate that agile methods and processes cannot be applied to a corporate context without adjustments. Scalable approaches based on agile and classic development methods must thus be established.

Acceptance of technology: Many interviewees believe staff and customer openness to, and acceptance of, new trends and technologies is a critical success factor for the future. And it is imperative the technical solutions are designed appropriately in order to foster acceptance at both an individual and organisational level.

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4.1.3 Sustainability in engineering

Respondents now no longer see the topic of sustainability as just a trend, but rather as an urgently necessary measure to ensure the environmentally sustainable and responsible use of existing resources. The sustainability debate, currently particularly prevalent among younger generations, is given the highest relevance in academic fields. Some companies also see great potential in engaging more strongly on the side of environmental protection and against resource waste. At the same time, however, these companies fear that far-reaching legislative action could erect considerable barriers to the approval of new products. Ensuring equilibrium between the demands of sustainability and the simultaneous need for economy and attractiveness on the market is increasingly seen as a challenge.

Industry especially finds itself obliged to strengthen efforts to reduce energy consumption, aiming to make production as carbon neutral as possible. Against this background, engineering often has to develop wholly new solutions for products, production facilities and factories. Furthermore, the entire process of value creation and product use must gain greater importance during planning and development and be considered in advance under the overarching concept of the circular economy. The desire here is to return products to the production cycle after use, say, as secondary raw materials. These developments result in new demands being made of the development of sustainable systems. The concept of sustainability is no longer exclusively associated with environmentally conscious action and consideration for future generations. Some respondents also refer to the use of resources such as human capital (specialists, engineers etc.).

Below, we consider a number of trends and their effects on engineering.

Greentech: Some respondents assign special importance to environmental technologies, renewable energy and efficient use of resources. On the one hand, these companies point to the benefit to their products, say, by improving their ecological impact through innovative material technologies. On the other, some large firms are already preparing sustainability reports at the company level. The trend towards total climate neutrality is given great weight by some respondents from science and industry. However, the majority of respondents has not yet systematically integrated aspects of Greentech in engineering. None of them mentioned concrete planning or development concepts for climate-neutral products or production sites.

Age structure: The ageing of German society is leading to a continuous loss of specialist knowledge from the workplace that affects the competitiveness of companies, meaning that comprehensive, practical knowledge management has become a decisive advantage for companies. How to realize this while gaining individual acceptance and ensuring the necessary effectiveness is seen as an important challenge for research.

Lack of specialists: Because of demographic change, the majority of companies assume they will have to deal with an increasing number of unfilled positions in the future. Particularly the SMEs are expecting difficulty recruiting suitable employees. Consistently up-to-date, practical qualification and nurturing the next generation are seen as central elements of corporate success.

Energy sources for mobility: A plurality of respondents sees great potential in electrification based on renewable energy as a means to reduce carbon dioxide outputs over the long term. At the same time, certain of them note the limited availability of resources and the carbon footprint of battery production. Against this background, electromobility based on battery storage is not seen as the sole long-term solution. Rather, certain respondents demand a mix of technologies combining diverse concepts: from combustion engines with synthetic fuels to hydrogen cells and batteries. Respondents from academia see conversion to a hydrogen economy as the central option for the future, one already addressed in the political sphere by a new hydrogen strategy.

Sharing economy: Shared use of products facilitated by digital platforms and new business models were named as trends by a large number of respondents from the automotive sector. Some respondents in the consumer and capital goods sectors also note increasing interest or describe initial attempts at implementing such business models. In the capital goods sector, usage-based business models are partly associated with the trend, in which the machine or facility is not transferred to the customer's ownership. Although there is clearly increasing interest in such models outside the field of mobility provision, respondents also report challenges in their practical implementation and gaining the acceptance of customers.

Second life: Assessing the life cycle of products is an established approach. To date, the emphasis here has been on the cost-analysis context in the development of a product, from the initial idea to its eventual return. Alongside estimating the total costs of operation, the environmental effects of products (consumption, ecological assessment etc.) are considered in engineering. A central problem, here, is making valid comparisons between simulation or calculation and reality. In addition, for products with exceptionally long life cycles, some respondents see themselves being increasingly confronted by cannibalisation effects due to the second-hand market. At the same time, particularly those from the capital goods sector point to the potential extension of use and expansion of functionality through software updates during the operational phase. In part, these aspects are already anticipated during the development process, with the potential reuse of individual modules planned in. However, the majority of industrial enterprises surveyed cannot yet discern a valid concept here and did not name any concrete engineering-related implementations.

Megatrends in engineering – digitalisation, globalisation and sustainability

These strongly influence both future goods and services as well as their process of development. These megatrends, as expressed in particular through the sharing economy, greentech, Internet of Things, artificial intelligence and the focus on global knowledge management as a consequence of the increasing lack of specialists, will shape the future of engineering over the long duration. There is the potential here for massive success, but achieving it needs good ideas and staying power.

4.2 Advanced Systems
Goods and services of tomorrow

To a great extent, the named trends influence both future goods and services, their design, and value creation as a whole. Because of the pronounced mutual dependence between the good or service to be designed and its process of development, the first task is to identify the future manifestations of innovative, technical systems (SEE FIGURE 7).

In the ASE guideline, innovative socio-technical systems are described as Advanced Systems. Advanced Systems go far beyond the current state of mechatronics and open up fascinating perspectives. In the future, they will be characterised by a significant increase in adaptivity, robustness, predictive behaviour and user-friendliness [DJG12]. These properties contain, on the one hand, extensive potential for innovation, and on the other present wholly new challenges to the planning and development of goods and services.

In section 4.2.1, perspectives for Advanced Systems will first be presented, as identified on the basis of the interviews. Then, in section 4.2.2, the challenges connected with them for business and academia will be described.

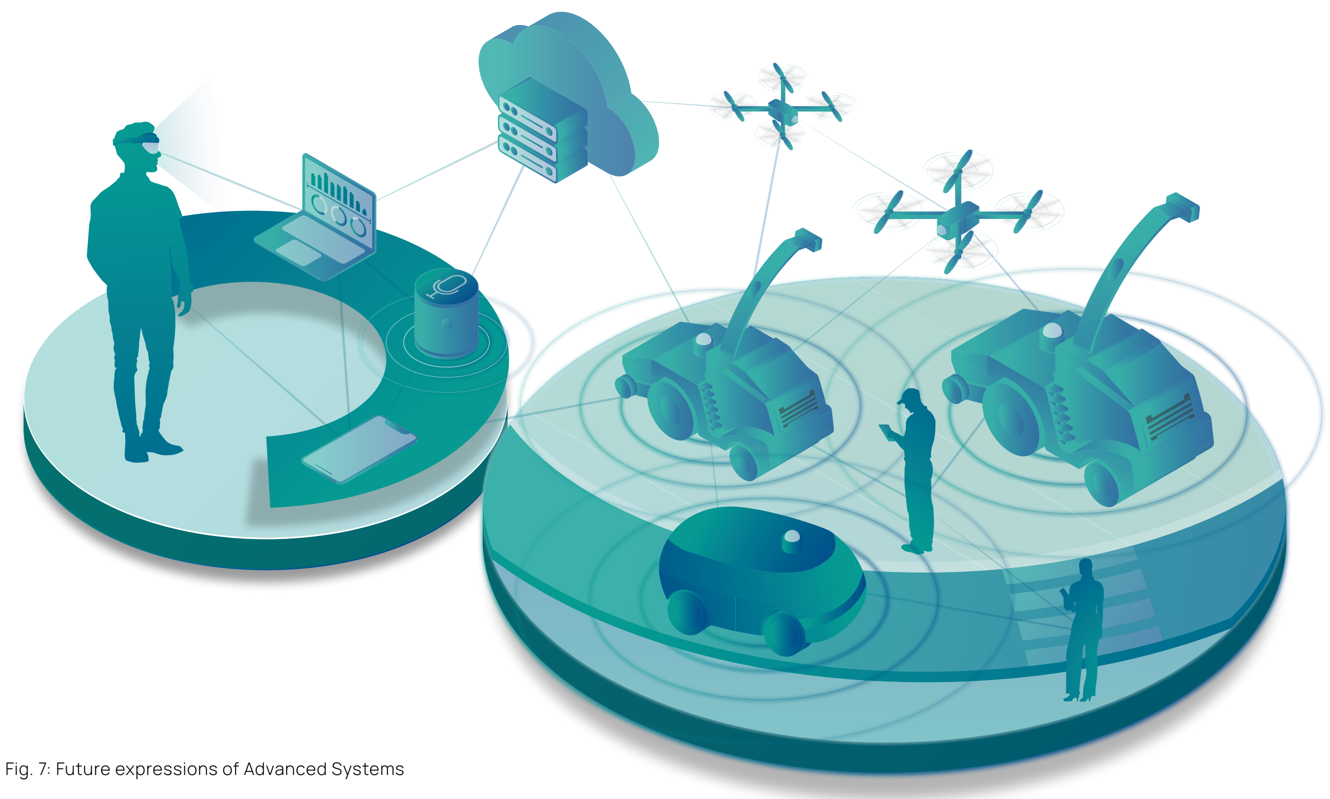


Fig. 7: Future expressions of Advanced Systems

4.2.1 Perspectives for Advanced Systems

On the basis of the interviews, the findings for Advanced Systems can be broken down under the following perspectives:

— Autonomous systems
— Dynamically networked systems
— Interactive, socio-technical systems
— Product Service Systems

Autonomous systems increase performance

For a portion of the surveyed companies, the products on offer are becoming increasingly autonomous (SEE INFOBOX 2). A few respondents described their current goods and services as highly autonomous solutions within the limits of a specific task. One pioneer in the field of autonomous systems is the defence industry. The automotive sector also sees self-driving vehicles as a success factor in the future, one in which it is investing considerable effort and research. The first autonomous vehicles able to participate in general traffic are only expected from 2035 (corresponding to level 5 of autonomous driving).

Today's self-driving systems are enormously powerful but extensively specialised. Currently, the available solutions are in no way yet suitable for activity outside of controlled environments such as automated warehouses. In the complex, highly dynamic environments of our everyday life, such as mixed urban traffic, autonomous systems cannot yet be used. Against this background, extensive research and development activities are certainly still required.

INFO 2 Autonomous systems

Autonomous systems solve complex tasks independently within a particular field of application. These systems must thus be able to act without remote control or indeed any further human interaction. The control system here can be based on an internal environmental model, allowing it to react to new events during operation or learn new actions. Numerous technological building blocks are needed to implement autonomous systems, such as sensor fusion or new fundamental planning processes [DGS+18].

Alongside technologies such as robotics and automation, some of the respondents see the use of AI-based solutions as a central component of autonomous systems. Currently, the use and integration of AI for controlling the autonomy of products at the companies surveyed (in particular among SMEs) is still at the experimental stage. In general only a few of the companies were using AI in market-ready products. The respondents from the academic field confirmed this view and saw great need for research, not only into the technological aspects of autonomy, but also into how companies can be enabled to design autonomous systems.

Dynamically networked systems open up new value-creation networks

Alongside autonomous systems, many respondents from industry and research expect increasing networking and connectivity between goods and services (SEE INFOBOX 3). Against this background, some assert that how interfaces are handled represents a special distinguishing feature in competitive situations. In particular in the automation sector, cross-manufacturer support for interfaces and standards is taking on particular importance. ›

Although a large number of respondents demanded increasing standardisation, such efforts are coming up against ever greater barriers to implementation. Some manufacturers, say, still consciously rely on proprietary interfaces and protocols in order to create barriers to change and ensure their independence.

According to many respondents, through increased networking, future technical systems will increasingly act in an integrated way (e.g. flexible production lines). Companies are increasingly required to qualify their products for interaction with further systems and integration into a network. An integrated network of non-independent systems cooperating with each other depending on the time and place is described as a “system of systems” (SoS). An understanding of how to act as part of a system of systems is much more present in respondents from the automotive and automation sectors. According to some respondents, in future, communication at SoS level through open architectures will be a relevant success factor.

INFO 3 Dynamically networked systems

Through the increasing networking between systems, new, more complex system networks are arising, whose functionality and capacities are far greater than the sum of their parts. Depending on the overall system goal, the system limits, interfaces and roles of individual systems can vary. The networked systems here can no longer be exclusively run by the control elements of a single system. If these independent individual systems interact in a time- or place-dependent way or are developed and operated by various providers, we can speak of a “system of systems” (SoS) [PH14]. Examples of this are the mobility system or smart cities. The independent systems (e.g. vehicles, receiver stations along the transport infrastructure, buildings etc.) can be integrated in or removed from the SoS at any desired point in their service life.

The change process described correlates to the increasing networking of social systems and value-creation networks (e.g. spatially distributed and intercompany development departments). Many respondents are unclear on how such systems should be created and operated. Currently, for engineering SoS, there are no standard ontologies, modelling methods or approaches to planning several system generations. Validation is considered one of the greatest challenges. In addition, at the majority of companies, the understanding of SoS is reduced simply to the idea of networking – a drastic oversimplification. Against this background, extensive research into methods and the development of support tools are urgently necessary.

Interactive, socio-technical systems relieve the burden on humans

Despite increasing autonomy and the growth in automated information exchange between technical systems, humans still play an essential role as customers and users. Alongside the customer-centric focus, a portion of the surveyed companies are placing more emphasis on viewing the technical system and the user as a socio-technical system overall. Here, the human experience as a user is central to the understanding of products and services (SEE INFOBOX 4).

INFO 4 Interactive, socio-technical systems

A socio-technical system is an integrated, cooperative unit consisting of humans and technologies [ROP09]. Here, the technical subsystems are increasingly marked by machine intelligence, expressing itself in the form of improved cognition, self-optimisation and increased autonomy [DJG12]. The outlined technological development results in new forms of interaction between humans and machines. These systems can adjust flexibly to the needs of the user and offer context-based support. In addition, the systems of the future will also be able to explain what they are doing and offer the user task- and situation-specific options for action. Interaction will be increasingly multimodal (e.g. via language or gesture) and based on new interaction technologies (e.g. sentiment or mood analysis) [DOR15].

As part of this user-orientation, the Advanced Systems are required to provide a highly ergonomic interface and intelligent, adaptive interaction with the user. A large number of respondents expects future goods and services to take on a lot more of the user's tasks. For some surveyed companies, this means user interaction will be no longer solely linked to the design of a single, static human-machine interface. In the design of product interaction, the use of diverse devices (e.g. control panel or web app), interfaces (e.g. speech or gesture control) and technologies (e.g. augmented reality or wearable computing) are being tested. As concrete examples of the development, as described, of interactive, socio-technical systems, respondents name AI speech-based assistants in car infotainment systems, or options to control household devices via smartphone. Some respondents already use the systematic recording of user interaction to optimise the user experience during operation and develop future product generations.

One particular challenge is that this human-centric design is a highly multi-disciplinary task, which according to some respondents currently lacks suitable validation methods. From this we can assert that there is a massive need for research into the logical consideration of humans as the developers of Advanced Systems as well as their purchasers as users.

Product Service Systems allow new business models

For the surveyed companies, the trend towards a service and information society results in an increasing range of combined physical products and services (SEE INFOBOX 5). Here, many respondents tend to refer to the increasing relevance of data-based services which supplement their existing range (e.g. development, leasing or maintenance). Some of the surveyed companies already offer solutions intrinsically set up as Product Service Systems (PSS). The increasing relevance of PSS is confirmed by respondents from academia. A large portion of the surveyed companies engaged in consultation weights the functionality or service range promised higher than the product itself. This corresponds to the consideration among some respondents that their range of standard products and components is moving towards individual customer solutions.

With this change in the range on offer, value creation processes and profit models at the surveyed companies also change. Some of the surveyed companies are planning or already testing PSS applications. As concrete examples of availability-oriented business models from the automation sector, they name status monitoring, predictive maintenance and usage-dependent billing models. At the same time, many respondents assess critically the expected economic viability of new services. On the one hand, these respondents find it hard to estimate customer acceptance of the new services. On the other, their profitability is difficult to predict. A portion of the respondents finds a general lack of willingness to pay even for the services on offer already. Against this background, approaches must be researched towards professionalising the assessment of the relevance of data-based services, taking into consideration customer benefit and the profitability of the solution and services on offer. ›

INFO 5 Product Service Systems

Product Service Systems (also called hybrid service bundles) rely on the close interlinking of physical products and services, providing solutions that are focused on increasing the benefit for the customer. The advantage of these systems arises, among other things, from services that are based on the recording, processing and evaluation of environmental, operational or user data. The evaluation of data from a production facility can, for example, allow breakdowns to be predicted, on the basis of which further services such as preventive maintenance and automatic replacement part ordering can be initiated. The clever combination of innovative services and intelligent systems offers promising potential benefits for new business models [KRH+15].

The majority of respondents sees continuous software updates in the PSS as a central service and integral component of future goods and services. Here, both the option of extending functions during operation and the relevance of critical security updates are mentioned. Because such systems can be updated, some respondents expect a marked increase in customer satisfaction and loyalty. At the same time, software updates offer the potential for high-quality technical systems with a longer service life to better reflect the needs of the increasingly dynamic market. However, this development requires companies to rethink the way in which future systems are developed, delivered and supported in operation. New approaches must be researched, allowing the continual transformation of operational systems. To this end, product and service development, production, sales and customer support must be redesigned to implement powerful release management abilities. This requires new forms of change management, testing and validation.

Perspectives for Advanced Systems: autonomous systems, networking intelligent systems, socio-technical interaction, data-based Product Service Systems

The autonomy of technical systems is developing to become one of the most important distinguishing features on the market. In particular, the use of autonomous systems in complex, highly dynamic situations in nearly all fields of life is opening up new growth markets. To exploit this potential, companies must be enabled to upgrade their existing goods and services with key technologies such as artificial intelligence (AI), robotics and automation technology. The increasing networking of interactive, intelligent technical systems will open up fascinating perspectives for the value creation of tomorrow. To this end, current systems must be linked to information and communications technologies (ICTs) and qualified for integration in a system network. Users and consumers are demanding intelligent, adaptable interaction with the technical system. Human-centric design, taking into consideration new forms of human/machine interaction, demand more from the development processes creating the goods and services of tomorrow. In addition, data-based Product Service Systems (PSS) are gaining in relevance. Continual software updating in a PSS allows, for example, functions to be added during operation, or critical security updates to be installed. However, when designing such services, companies come up against massive challenges with regard to evaluating the customer benefit and creating profitable business models.

4.2.2 Challenges in the design of Advanced Systems

The described perspectives on Advanced Systems offer extensive potential for innovation, but at the same time result in challenges in the planning and development of goods and services. These challenges must be addressed through shared efforts by businesses and academics. In the following, the challenges under discussion will be summarised.

Increasing developmental complexity

The surveyed companies see an unbroken trend in the increasing complexity within their goods and services. The increasing complexity of Advanced Systems has multiple drivers. On the one hand, the interdisciplinary nature of the systems and their concomitant internal complexity are increasing. On the other, networking with additional systems, some of them unknown during development, is also seeing a constant rise. In addition, the interaction of products and services is a challenge for many companies. At the same time, the future services must fulfil a wide range of different, sometimes contradictory functions and goals.

The rise in complexity caused by the goods and services in planning, development, production and sales of systems requires a new orientation within and design of the development process in companies. Activities engaged in to date such as increasing resources and carrying out stricter project management will not be sufficient in the future. A large portion of the surveyed companies assumes that current development processes are insufficient for the development of Advanced Systems. Some respondents note that the evolutionary optimisation or extrapolation of existing methods is not sufficient to reach the goal. The design of, among other things, springboard innovations requires equally extensive rethinking of the connected development processes.

Consistent interface management

A large number of respondents sees interface management as a central challenge in the context of Advanced Systems. In this regard, the interview partners reference, on the one hand, the numerous interfaces arising with respect to process and organisational structures during the development process, noting that the interdependence of the most varied actors, stakeholders, departments, fields and companies needs to be reflected and controlled. On the other, interview participants also mention the increasing number of technical interfaces within and in connection with engineering with regard to the IT architecture. The application interfaces of the technical system, its networking and company architecture, require continuous development, support and synchronisation. Some of the respondents see a particular challenge in designing consistent digital systems within and between organisations, value-creation partners and Advanced Systems.

Stronger individualisation and mass customisation

According to the surveyed companies, goods and services are becoming more individual and are increasingly tailored to the specific customer as a reaction to the volatility of the market and the accompanying increase in competition. With increasing variation, the existing economies of scale found in large-scale production can no longer be benefited from in their current form. From this, the challenge arises on the global markets of achieving increased individualisation while at the same time bearing up under cost pressure. Survey respondents in machine and plant construction particularly expect an increase in individualisation. Although the majority of respondents already uses modularisation approaches, customer-specific "mass customisation" is not yet given extensive consideration in planning and development. ›

Alongside mass customisation, there is the potential to increase the level of individualisation perceived by the customer through software, while hardware variants are reduced. To achieve customer-specific functions or services through software, the necessary hardware and software components, communications and sensor technologies may need to be extended in places. For a large number of the respondents, this form of individualisation offers enormous potential, but is not yet widely adopted. There is thus massive need for research into suitable business models and architectures.

Shorter innovation cycles

According to the respondents, the market is demanding ever shorter innovation cycles. The shortening of cycles leads necessarily to the more rapid completion of development projects and an acceleration of the product generation sequence. This has as its consequence the fact that the company needs to reduce development times for some markets and customer demands. Particular success factors here include high flexibility in the company and a change to the corporate structure. Some of the surveyed companies see an intensifying conflict of goals between the necessary use of innovative technologies and the high promises German products make with regard to quality and safety. In this context, classical project and development management is currently meeting its limits. However, the majority of respondents finds it inexpedient to bring unfinished or even faulty products to market. It makes sense to research this conflict between short development times and high levels of development and hence product security, in order in the future to guarantee the rapid development of high-quality, innovative systems.

A complicating factor is the different development cycles and life cycles of software and hardware. Hardware regeneration, for example, can take place alongside several life cycles of its operating software. A large number of respondents sees agile working methods and the asynchronous development iterations that accompany them within strategic product planning and development as lacking, to date, in support from the methodological and IT sides.

Lacking competence

The development of Advanced Systems demands new competences and qualifications in existing disciplines, alongside the integration of additional departments. A large portion of the companies to date does not consider more than a few engineers sufficiently prepared for the complexity that comes with Advanced Systems. Here, companies refer both to current employees, career-starters and graduates of engineering faculties. Respondents with a scientific background largely agreed with this assessment, but as a rule make note of the limited standard period of study. Not all the required or desired competences can be transmitted during this period. Against this background, additions to the curriculum and step-by-step changes of focus must be considered. Here, however, as emphasised by a large portion of respondents, the depth of specialism obtained in Germany's vaunted engineering courses must be maintained. Solving this contradiction is a challenge.

Alongside education, respondents underline the increasing need for further professional training and the necessity of the concept of lifelong learning. Here, suitable further training models and provision must be developed to address the needs of the large number of employees working at companies today and prepare them for the development of Advanced Systems.

Fulfilling all legal requirements

According to a large number of respondents, handling legal requirements and regulations will affect large swathes of development in the future. The perspectives of Advanced Systems offer wholly new challenges in comparison to existing goods and services. In the context of autonomous systems, the survey respondents mention e.g. legal liability questions and the unknown requirements of legally mandated safety inspections. In particular, how to handle the decision-making processes of untraceable AI algorithms is not clear. The respondents emphasise that the use of these technologies turns up numerous legal and ethical questions and thus poses a high financial risk. If future systems permanently adjust to environmental conditions and continue to learn, the established verification procedures are no longer sufficient. This is part of current AI research.

Increased networking is accompanied by legal requirements relating to the security of IT systems. Against the background of increasingly interactive solutions, many respondents find themselves confronted by challenges e.g. regarding the use of personal data. The design of PSS requires a new approach to liability for services and changes to long-term ownership structures. For this reason, respondents are faced by currently incalculable challenges because of the high dynamism in the legal environment.

These legal requirements and their fluidity also differ from market to market. A frequently mentioned example is the complex approval process in the automotive sector. Some respondents see Germany's innovative power threatened by increasing regulation, especially in comparison to China and the USA. The surveyed participants from academia do share this point of view but see a competitive advantage in just this field in safety-validated technology branded "Made in Germany". For this to be gained, the technical and legal spheres of action must be considered in an integrative manner, ensuring an early focus on the development of Advanced Systems and the creation of suitable methods and tools.

Ensuring system security and reliability

Alongside regulatory aspects, the majority of respondents notes an increasing demand for security among their customers. These fear potential tampering by third parties, or the theft of confidential user data facilitated by the increased networking of systems. With the growing importance of IT security, product updates have become accepted by customers. Already when drawing up design principles, aspects of system reliability should be considered. In this context, system reliability covers system security, dependability, confidentiality and availability. However, such requirements lead to a situation where complete traceability needs to be introduced into development. The surveyed participants from the academic field also see one of the greatest challenges being the security of networked, highly automated systems in the socio-technical SoS. Here, fundamental, applied research activities are urgently needed. This particularly applies to the safeguarding of complex autonomous systems. The necessary validation expenditure, based on the classical process, can no longer be afforded. >

Challenges in the design of Advanced Systems: Handling development complexity, the continuing high relevance of standard challenges such as short innovation cycles and cost pressure, the increasing importance of regulatory aspects such as liability for autonomous systems

With the growing complexity of future goods and services, development complexity will also increase. There is great divergence of opinions as to whether the development of existing processes and models in engineering can live up to the disruptive innovations that are in demand or whether a comprehensive new orientation must be sought. In contrast to this, consistent interface management is perceived in general as a central challenge. The described interfaces affect both process and organisational structures, technical interfaces in engineering IT infrastructure and the interfaces between the market service in the operation and the company.

More than ever, companies are called on to overcome the conflict of goals between the increase in customer-perceptible individualisation of the good ot service as well as simultaneous cost pressure on global markets. There is a lack of proposed methods for product architectures, production systems, value-creation networks and business models. In addition, the surveyed companies are also challenged to realise shorter innovation cycles while maintaining the same high quality. Here, they are also confronted by the differing life cycles of application software (e.g. apps), embedded product software (e.g. firmware) and hardware (e.g. underlying mechanisms). To counter these named challenges, new competences and suitable training and education measures are required.

In addition to the technical requirements, new demands arise with regard to the fulfilment of regulatory aspects. Here, aspects such as 1) liability and responsibilities for autonomous systems, 2) data protection and security and 3) registration and authorisation will decisively influence the success of future goods and services. Alongside IT security, the updating of future systems during operation raises greater and more extensive demands for the safeguarding of networked integrated systems and systems of systems.

4.3 Systems Engineering
Managing complexity

Analysis of the megatrends and challenges of Advanced Systems shows that an adaptation and reorientation of development processes is required in companies. Future systems will arise from the close collaboration of many specialist fields such as engineering, natural sciences, IT, sociology, psychology and ergonomics. The increasing involvement and networking of these fields, with the greater complexity in the planning, development, production and operation of systems requires comprehensive, interdisciplinary Systems Engineering (SE) (SEE FIGURE 8).

Systems Engineering is a promising, interdisciplinary approach to the creation of complex technical systems and encompasses all development processes in their entirety. It claims to manage actors in the development of complex systems. To this end, it integrates system design and project management, taking the company-specific organisation into consideration [GDE+18].

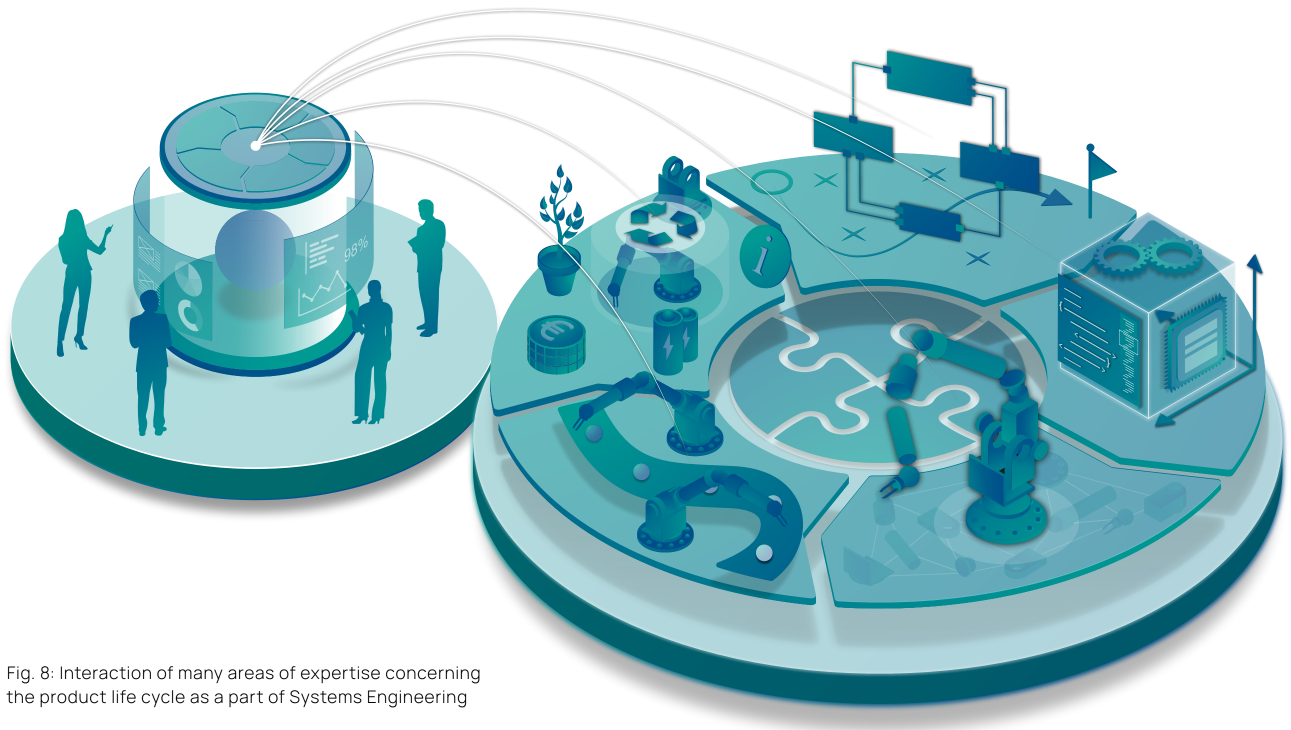


Fig. 8: Interaction of many areas of expertise concerning the product life cycle as a part of Systems Engineering

At the time of the survey, Systems Engineering is being promoted in many different regards by universities, research institutes, communities of interest and companies. For this reason, a large number of different definitions, usage opportunities and processes for Systems Engineering have been established. To shape the Advanced Systems Engineering guidelines, the status quo and current developments in Systems Engineering have been investigated.

To this end, the following aspects were addressed by the survey:

- How Systems Engineering is understood (SEE SECTION 4.3.1)
- The added value of Systems Engineering (SEE SECTION 4.3.2)
- The current capabilities of Systems Engineering (SEE SECTION 4.3.3)
- Introducing Systems Engineering (SEE SECTION 4.3.4)
- Roles in Systems Engineering (SEE SECTION 4.3.5)
- Model-based Systems Engineering (SEE SECTION 4.3.6)

4.3.1 How Systems Engineering is understood

The interviews carried out show that the concept of Systems Engineering is familiar in practice across many sectors. However, interviews partners' understanding of it is very heterogeneous. Particularly in aerospace engineering and the automotive industry, they orient themselves by the INCOSE (International Council on Systems Engineering) concept (SEE INFOBOX 6). A large portion of the respondents uses or refers to its basic definition. However, beyond this, the focus and concrete conception vary. For companies in mechanical engineering and plant construction, it is also the case that the concept of Systems Engineering is less widespread. While essential aspects of Systems Engineering are applied, they are not designated as such (e.g. in the field of requirements management or risk management). The respondents' comprehension of the topic is described further below.

INFO 6 Definition of Systems Engineering as per INCOSE

"Systems Engineering is a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods." – INCOSE (SEE [INT20])

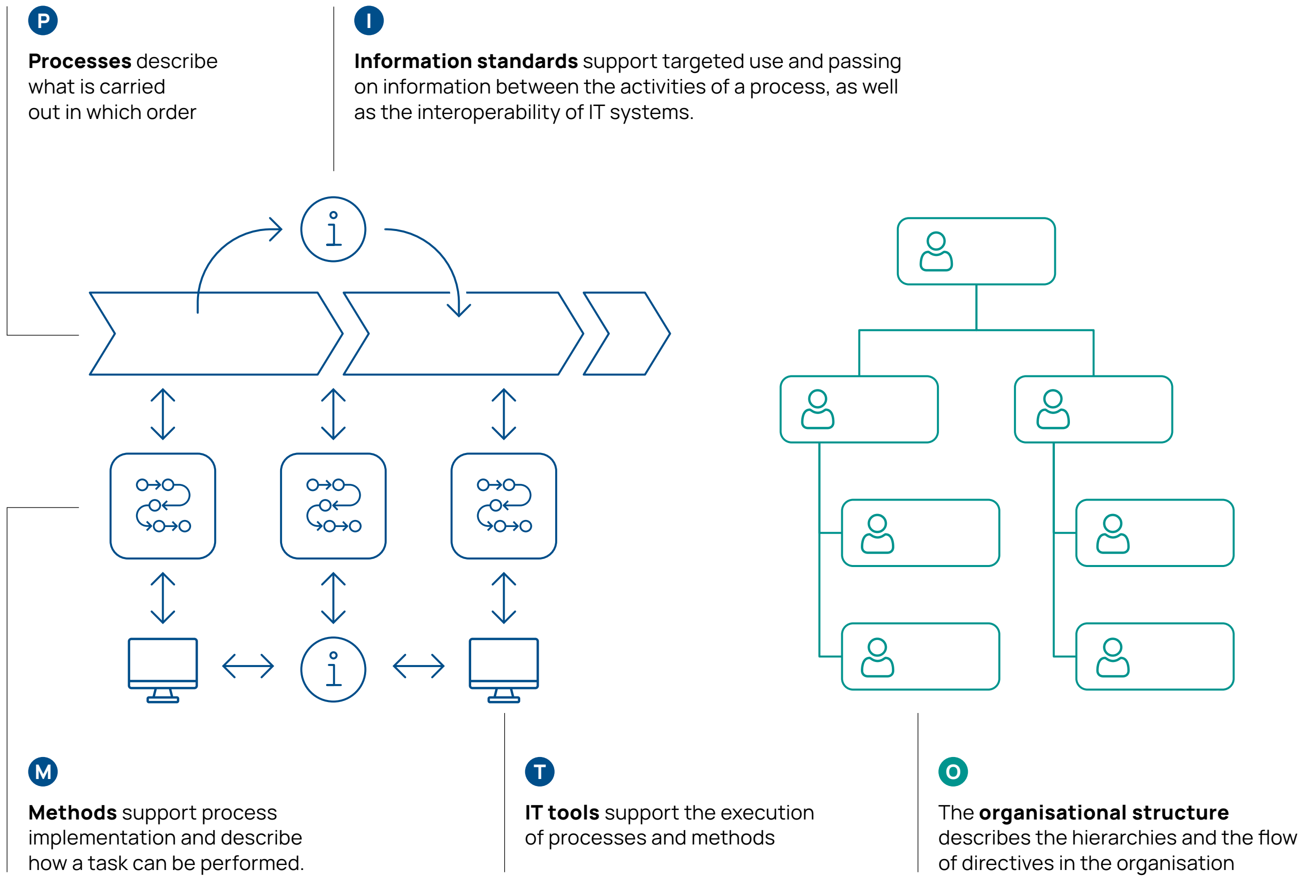
The majority of respondents understands Systems Engineering as an approach towards interdisciplinary collaboration. Several of them speak of interdisciplinarity and successful interdisciplinary collaboration where the effective and efficient overall cooperation between technical disciplines (mechanics, electrics/electronics, software, hydraulics etc.) creates added value. In contrast to the INCOSE definition, the understanding among surveyed companies of Systems Engineering as a transdisciplinary approach barely registers. A transdisciplinary approach differs from an interdisciplinary approach because the latter largely concentrates on work across disciplines where each discipline is able to apply its own methods and approaches. A unified understanding of the idea that two or more disciplines can meld and form a new, comprehensive, transdisciplinary approach to problem solving does not exist.

Systems Engineering is perceived by many respondents as a consistent approach towards system development from the initial requirements to the "end of life". Thus, in Systems Engineering, the entire life cycle of the goods and services to be developed must be considered. A large number of the respondents from industry orients itself in describing life cycle phases by the V model. However, the frequently mentioned classical V model as per VDI 2206 actually only focuses on development tasks. In larger companies, it is typical to find a specifically adjusted V model containing markedly individual details. Some respondents expand the horizons of the V model, integrating e.g. strategic planning before the development task where market and customer requirements are specified. Independently of the concrete shape of the V model, there exists the view that Systems Engineering has to connect many established concepts that were once separate to form an overarching approach. In addition, it becomes clear that the respondents give Systems Engineering particular meaning where the topic of requirements arises. In the foreground here is the identification and analysis of requirements taking all relevant stakeholders into consideration, comprehensive documentation and consistent follow-up. Many respondents from the academic side see much more in Systems Engineering than just requirements management, while large swathes of industry equate Systems Engineering with the latter concept. This discrepancy of evaluations shows very clearly that research must draw up more strongly application-oriented solutions in order to extend the understanding of Systems Engineering and demonstrate its potential.

Although the surveyed companies focus on the development phase, most respondents are at least aware of the consideration of subsequent life cycle phases such as production, distribution, operation, service and returns. From the point of view of some respondents, there is an urgent need to act and carry out research here in order to integrate production system development more logically into the Systems Engineering context. The surveyed companies have, to date, barely considered the integration of service development that fulfils the needs of customers and markets in the context of Systems Engineering. Against this background, there is clearly a need for research into the integrative development of products, production systems and services in order to drive forward the transdisciplinary design of future goods and services.

The majority of surveyed companies are of the understanding that Systems Engineering affects processes (P), methods (M) and IT tools (T). Large companies in particular are thus engaged in setting up PMT teams or departments with the goal of establishing a central service area to support development departments (SEE FIGURE 9). Certain respondents add to the PMT focus the design of process and structural organisation (O). Changes in this regard are seen as a particular challenge, as massive resistance can arise in the organisation. An essential goal of Systems Engineering PMTO, according to respondents, is guaranteeing collaboration both within the company and beyond its limits. The internal focus is on optimising the linkages between departments and improving general performance capability within them. From the external perspective, this approach is supplemented to include all relevant stakeholders, from development partners to clients and services and beyond. A minority of respondents links, within Systems Engineering, the PMT focuses with the urgently required design of information standards (I) in engineering. The standardisation of information (e.g. in the context of part designations) or exchange formats to describe technical systems is a significant challenge for the surveyed companies, particularly where interdisciplinary collaboration is involved.

A decisive aspect for the implementation of consistent SE concepts is having an expedient relationship between cost and benefit in the PMTIO spheres of activity. Against this background, the efficiency and acceptance of dedicated PMTIO services for engineering must be evaluated.



→ **PMTIO** stands for processes, methods, IT tools, information standards and organisation. Corporations in particular form PMTIO teams to design Systems Engineering

Fig. 9: Areas of activity of a PMTIO service point for engineering

How Systems Engineering is understood: Many consider Systems Engineering to be a potentially powerful tool, but their ideas of it tend to be rather vague.

The concept of Systems Engineering (SE) is in use across many sectors. Many connect SE with large-scale projects in the USA like the Apollo Program. But the conception of this field is very heterogeneous. The majority of respondents associate Systems Engineering with cross-departmental collaboration on the development of complex, multidisciplinary products. Use in the later phases of development such as production system development (manufacture planning) and the integrative consideration of product, production system and service are not firmly established.

4.3.2 The added value of Systems Engineering

Many respondents from the business field hope to open up varied potential benefits by using Systems Engineering. At the core, these companies are looking for improved quality and reduced costs and time. The following describes how these improvements can be achieved, from the respondents' point of view.

Improved systems understanding

Nearly all respondents from business and academia see significant benefit in the improved, shared systemic understanding promoted by Systems Engineering among the stakeholders and disciplines involved. Three essential advantages arise from this:

1. Identifying errors: The improved systems understanding allows the early detection of risks and errors. According to the "rule of ten", the early identification and elimination of errors can lead to massive savings in costs and development time. The savings go beyond just development costs, as manufacture and operating costs can also be reduced through early fault detection. In some circumstances, certain errors in the underlying system architecture are unable to be resolved later. They then significantly reduce the quality.

2. Carrying out activities in parallel: An improved systems understanding can support the parallel execution of development activities and collaboration during drafting. In this, Systems Engineering demands and supports communication between the different stakeholders in the development process through the generation of a shared understanding of the system and through clear interfaces between the different process stages and disciplines. Many participants state that without clear interfaces, the desired parallel implementation and concomitant assurance of the consistency of development activities barely remains possible, as among other things the various disciplines work in cycles of varying length but still have to deliver consistent results. A frequently mentioned example is the comparison of long change cycles including procurement times for tools in mechanical engineering, compared to the short iterations involved in developing the corresponding software.

3. Designing innovative and customer-oriented solutions: Some respondents also expect innovative power to be increased because of improved systems understanding. Here, activities such as system analysis, architecture design and trade-off studies offer the ability to recognise potential for improvement and exploit it with greater rapidity. At the same time, the role of Systems Engineering with relation to collaboration and cross-disciplinary cooperation is emphasised. With a shared system understanding of goods and services, the various departments can work in a coordinated fashion towards the higher-level goal, realising in this way the actual promised benefit of the service. In this regard, several respondents emphasise the fact that the global optimum for the customer solution can be achieved by means of system engineering, while currently many departments are only striving towards the local optimum for their part of the solution.

Traceability and transparency

Many respondents expect that Systems Engineering will make a massive contribution towards improving transparency in product development. Through the simultaneous documentation of development decisions and technical contexts, changes can be made transparently even in later phases. Thus, on the one hand, records are made of why decision-makers made certain decisions. On the other, the effects of necessary changes on the requirements and stakeholders can be more quickly assessed because of the combination of all necessary information.

This ability to follow connections and relationships between artefacts within the development process (e.g. requirements, system elements, tests or decision-makers) is known as traceability. Traceability through networked development artefacts is particularly important in medical technology, aviation and the automotive industry, and is mandated by laws, guidelines and standards. According to many respondents from the automotive sector, Systems Engineering supports, for example, quality assurance for the software in the vehicle through the Automotive SPICE® standard (SEE INFOBOX 7). In general, compliance with laws and registration requirements is seen by many participants as only being possible when high-performance requirements management is used which links the requirements to later development artefacts. For the approval of medical products too, certifications need to be kept up to date, and can be supplied with much greater efficiency through the use of Systems Engineering.

INFO 7 Automotive SPICE® to [15504]

ASPICE ("**A**utomotive **S**oftware **P**rocess **I**mprovement and **C**apability d**E**termination") is a process evaluation framework specially developed for the automotive sector. ASPICE covers reference processes and assigns degrees of maturity allowing the performance capability of a software development process to be evaluated. The advantages of an ASPICE-conforming process are, among others, improved planning of the development effort required and the associated costs. In addition, unified reviews and quality assessments of work results can be carried out, allowing high quality to be maintained within the prescribed project period. Processes are graded in levels from 0 to 5. By evaluating each individual process, a detailed picture can be built up of the strengths and improvement potential of the project under inspection. However, there is no consolidated level assigned to any project or company.

Managing complexity

Considering the rapid development of technical systems, the movement from machine-centred mechanical engineering to mechatronic solutions is a challenge for a portion of the companies surveyed. Against the background of the Advanced Systems of the future, the demands made of the development process will also increase. Some respondents fear that the capability of established development methods will not live up to the future complexity of technical systems. For this reason, a large number of respondents considers Systems Engineering as a solution and an approach towards managing increasing complexity. Here, Systems Engineering supplements the existing methods of mechatronic development and offers the potential to integrate further disciplines (e.g. service development) across the entire life cycle. Depending on the complexity of technical systems, the organisational complexity of market service creation also rises (SEE FIGURE 10: SYSTEM TYPES AS PER [HWF+12] AND [UP95]).

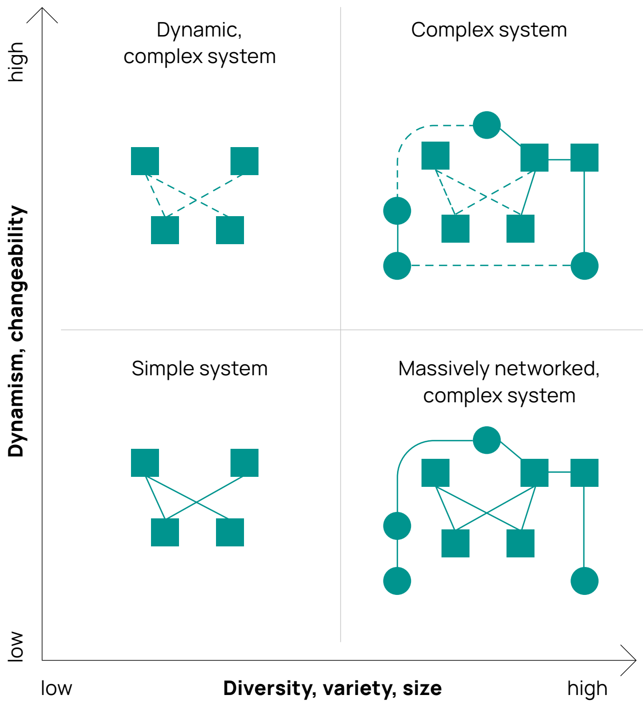


Fig. 10: System types according to [HWF+12; UP95]

INFO 8 **Complexity**

Complexity is a frequently used term in the corporate context and is also used to characterise systems. The term is defined differently depending on the point of view and discipline. Both technical systems and the means of creating them can be described as complex. In the context of dissemination, a system is complex if on the one hand it has a large number of heterogeneous elements and relationships between them and, on the other, its time-dependent behaviour changes with a high degree of dynamism. This applies, for example, to technical systems containing a wide range of mechatronic components allowing frequent changes of functionality during operation. Development processes accordingly demonstrate high complexity if a large number of employees, departments or value-creation partners are involved, and their activities are subject to continuous change. [HWF+12; UP95]

Already today, the creation of products and services in industrial value creation relies on complex global corporate networks. A portion of the respondents finds itself confronted by the particular challenge of globally distributed development locations. Different languages, time zones and different cultural influences on communication and cooperation are described as drivers of complexity. Furthermore, organisational complexity also rises because of the increasing interconnection of the required disciplines. Against this backdrop, some of the respondents see the potential for the methods of Systems Engineering to be used to control process-related and organisational aspects within the company. Some participants already use Systems Engineering to model the entire corporate architecture and corresponding processes, data and actors.

Overall, the respondents are agreed that Systems Engineering has particular strategic value in allowing all performance-related activities to be better managed in the future. Correspondingly, many surveyed companies have an expectation that they will be able, through Systems Engineering, to increase capabilities in the development of innovative goods and services. Here, research must make a suitable contribution to fulfilling these expectations. In particular, it must be assessed within what frameworks Systems Engineering can be used as an approach towards company transformation, and which interfaces are necessary between the natural sciences, social sciences and humanities.

The added value of Systems Engineering: Systems Engineering demands a shared system understanding. This is the prerequisite for the professional development of the multidisciplinary systems of tomorrow.

Through Systems Engineering, companies hope to gain a better systems understanding, in order, for example, to identify errors and inconsistencies early on, carry out development activities in parallel and design more innovative customer solutions. Further potential benefits of Systems Engineering are found in particular in the traceability of connections and relationships between artefacts in the development process and the improvement of transparency in product development. The predominant view is that Systems Engineering is a necessary approach if the complexity of technical and socio-technical systems is to be managed and the performance of market service development increased.

4.3.3 The current capabilities of Systems Engineering in the economy

Despite the high expectations and numerous potential benefits of Systems Engineering, its methods and tools are currently only used continuously over the entire life cycle and in various departments by a few pioneering companies. Some respondents report partial use or the introductory deployment of Systems Engineering. Where Systems Engineering methods are already in use, these are concentrated primarily on requirements specifications and are limited to architecture design.

A large number of the surveyed companies expects a competitive advantage from the consistent use of Systems Engineering. The central requirement for such use, they say, is broad acceptance among employees. To achieve this, Systems Engineering must be anchored at the organisation in a strategic guideline. Correspondingly, discussion of organisational development aimed at the comprehensive application of Systems Engineering as such a strategic goal, alongside system design and project management, is frequent and intensive.

The state of capabilities at each company with regard to Systems Engineering varies sector by sector. While Systems Engineering is already incorporated in large swathes of the aerospace industry, the automotive sector is predominantly in an introductory, piloting, competence-building phase. Correspondingly, Systems Engineering is only used here in pilot projects or within the framework of individual process stages. In machine and plant construction, the picture is very mixed. In particular small machine and plant constructors, while they may currently be implementing isolated measures, do not describe these explicitly as Systems Engineering. Few respondents expect no increase in the complexity of goods and services within their sector and thus do not see any need for Systems Engineering (such as the manufacturers of standard and purchased parts or of electrical equipment). Against this background, research is needed to discover what is preventing the comprehensive, cross-sectoral use of Systems Engineering and how the existing barriers can be overcome.

In all sectors it is clear that the use of Systems Engineering in company projects is most advanced where high project volumes, high complexity and high requirements of the development process are present (e.g. because of regulatory requirements such as those of the Medical Products Act). Further promoters of the increased use of Systems Engineering, according to some respondents, are projects with a high level of innovation, or those where the goods and services need to be certified for interaction within an integrated system. Overall, the survey of companies finds that the far-reaching exploitation of the potential of Systems Engineering is not yet in any way detectable. In this field, intense collaboration between science and industry is required in order to enable companies to manage the complexity of future goods and services as well as their development process.

The current capabilities of Systems Engineering in the economy: Except for a few avant-garde deployments such as in aerospace engineering, Systems Engineering is currently only on the threshold of widespread use.

Despite high expectations and numerous potential benefits, the extent of capabilities as recorded during the survey tends to vary widely depending on the size of the company and the sector in which it operates. In aerospace engineering and in the automotive industry, Systems Engineering is far better established than in mechanical engineering or automation. In large companies, Systems Engineering tends to be used more than in small and medium-sized enterprises (SMEs). Regardless of the size and sector, its deployment is focused on requirements management and system design.

4.3.4 The introduction of Systems Engineering

A large number of the surveyed companies is currently introducing Systems Engineering or plans to do so in the next few years. The introduction of Systems Engineering is seen by the surveyed participants from both science and industry as a highly demanding transformational process. The following first describes the challenges connected with its introduction and then explains the success factors named in association with this.

For many respondents from science and industry, a large number of these challenges arises from the size and scope of the topic. The following findings describe the challenges as recorded for the academic and industrial worlds.

The introduction of Systems Engineering requires extensive change

In contrast to individual technologies or specific methods, Systems Engineering affects a large number of persons and organisational units both within the company and without it – for example, by way of partner networks and supply chains. Satisfying this large number of stakeholders requires both comprehensive understanding of Systems Engineering and of internal company processes. The coordination of this knowledge, currently distributed across various different people in different departments, is certainly a challenge. Highly interlinked and distributed development responsibilities and restructured and uncoordinated interfaces, according to some respondents, complicate the introduction of Systems Engineering. Across the divisions between departments and within value networks, it can also be the case that quite different demands of SE solutions arise. Against this background, the influence of Systems Engineering on the existing work processes and organisation, as well as suitable methods of change management, must be researched.

The introduction of Systems Engineering demands comprehensive training and employee motivation

Alongside changes to the work process and work organisation, stakeholders at all corporate levels from developers to management must understand the added value of Systems Engineering. A lack of intrinsic motivation, according to a large number of respondents, is an enormous barrier to the introduction of Systems Engineering. Some respondents emphasise the fact that there is a particular lack of acceptance for Systems Engineering among developers who are able to manage their development activities independently and without external reliance. For this reason, for the successful introduction of Systems Engineering, the individuals, their motivations and the manager involved are decisive. A large number of the surveyed companies describes the task of convincing middle management as particularly laborious, as it may seek to hold back the introduction of Systems Engineering because of a lack of understanding, or at least fail to promote it because of other daily business. Some respondents indicate that the restructuring connected with the introduction of SE accompanies a loss of the existing influence of middle management on line organisation. For this reason, optimal SE development requires all actors to be distinctly ready for change. Against this background it is important to research the essential success factors and suitable motivators for the introduction of Systems Engineering that could pay consideration to the potential conflicts of goals between individual employees, organisational units and the company as a whole.

The required qualification of employees in the company is also a challenge for many of the respondents. Experienced employees such as graduates often, in the respondents' view, lack necessary SE expertise. If they have initial experience with Systems Engineering, this is often of a theoretical nature. In the view of many participants, this makes it more difficult to adjust the generic approaches of Systems Engineering to the concrete needs of the company.

The introduction of Systems Engineering is limited by structural conditions

The introduction of Systems Engineering comprehensively influences the organisational structure and processes, methods and IT tools. Processes and IT tools in particular have limiting conditions that can only be changed with great difficulty and which restrict the room to manoeuvre when introducing Systems Engineering. The reasons named by many respondents include e.g. frameworks of standards or long-term contracts with the manufacturers of IT tools. From the point of view of some respondents, this effect is amplified by the short-term thinking prevalent in evolutionary product development cycles. The necessity to reuse the largest portions of existing products leads to the tendency for existing processes, methods and tools also to be reused. Against this backdrop, more extensive changes are difficult to implement and the introduction of Systems Engineering often needs to conform to existing structural limitations. Particularly the large companies and groups surveyed considered it a challenge that implementing Systems Engineering necessarily has effects on current business processes. A large number of the respondents found itself confronted with the problem that existing SE methods and processes could not be transferred into particular companies without adaptation. According to certain respondents, a change to the entire way of thinking at the company is urgently necessary for successful introduction, as a component and discipline-oriented pattern of thought will probably not lead to long-term success. Against this background, research needs to be carried out into how to introduce the methods and processes of Systems Engineering in parallel with processes and flexibly adjust them to various organisations and project environments. There is a need for transformational approaches that combine existing methodical building blocks to form a suitable Systems Engineering framework for the required project situation.

The added value and amortisation period of Systems Engineering are hard to assess on implementation

A large number of respondents emphasises that the successful introduction of Systems Engineering can only be measured by project-specific criteria. These criteria are so project-specific that success can only be assessed to start off with by the developers involved, not by management. At the same time, different development projects can, as a rule, only be compared to a limited extent because of the individual framework conditions. Some respondents emphasise that project indicators such as product quality or the length of development can only be interpreted in a restricted sense against the background of the rising demands of Advanced Systems. In addition, this introduction is often driven forward by development departments alone. Without the support of management, however, there are few opportunities to stimulate other departments to get involved. According to some of the companies surveyed, the added value of introduction can only be assessed in the medium to long term. As Systems Engineering covers the entire life cycle of goods and services, positive effects may only be detectable on completion of a development project or during operation. A portion of the respondents notes that management's interest at these junctures is often already on other projects. For this reason, research must be carried out to investigate what quantifiable, positive effects Systems Engineering has in the short, medium and long term on development projects and the capability of the entire organisation.

Success factors for the introduction of Systems Engineering

A few companies are able already to look back on a successful partial implementation of Systems Engineering or have achieved their initial sub-goals. During the survey, the initial success factors supporting the transformation process were identified.

For some of the surveyed companies, the most important success factor for the successful implementation of Systems Engineering is an incremental, evolutionary process. According to this, individual aspects of Systems Engineering should be worked out, then introduced and consolidated at the company step by step, with each small stage following the last. This reduces the size of the change and the circle of affected parties. If the pressure to act is large because of, say, the requirements of standards, such a process may in certain circumstances be difficult to mediate.

Alongside the incremental procedure, the surveyed companies named project-related introduction as a further success factor. Here, the aspects of Systems Engineering under consideration are introduced into projects where new product concepts are being developed and there is thus, as a rule, less dependence on existing systems. Some respondents emphasise that the introduction into existing or new projects must take place via previously defined stages and through focusing on certain topic areas (e.g. architecture design). The successes of an introduction can be used to motivate further stakeholders and functional units within the company. In addition, there is the option to carry out further consolidation of the required changes.

According to many respondents, the introduction of Systems Engineering can be expedient if it follows a simultaneous top-down and bottom-up approach. In a top-down approach, the introduction is carried out by management, e.g. by having goals defined in the form of a SE strategy. This legitimises the use of Systems Engineering by the corporate management and makes the case for the necessary support and changes. In a bottom-up approach, employees implement introductory Systems Engineering through active cooperation. This approach, through pioneering involvement at the operative working level, ensures suitable support at this same level. The continuous exchange and interplay of these two levels is essential.

Advanced companies indicate two other important points: the methods and approaches of Systems Engineering must be tailored to the concrete needs of the company. Taking over solutions without adapting them often does not lead to the desired results, reducing acceptance. According to some companies, the adaptation of existing processes, the methods used and tools, should be accompanied by coaching and organisational change management. In addition, generalised targets for the overall use of Systems Engineering in the company should be driven forward. If only isolated organisational units use Systems Engineering, the long-term benefit for the overall system is low.

According to the surveyed companies, it is particularly the incremental and project-related uses of Systems Engineering that are successful, above all because such introductions are accompanied by the systematic approaches of change management and organisational development. Nevertheless, there remains the additional challenge that the introduction process is a highly individual undertaking and is subject to the most varied limiting conditions (e.g. company size, sector or development goal). Against this background, research is needed into capable concepts that could support the transfer of recommended or successful methods and processes in the introduction of Systems Engineering.

The introduction of Systems Engineering: On the path towards successful Systems Engineering there are many hurdles, such as methodological deficits and low experience at demonstrating economic viability. The incremental, project-related method of introduction has clearly proven itself.

A large number of the surveyed companies is planning or introducing Systems Engineering. However, there is a lack of known methods within the accompanying change management. At the same time, companies face the challenge of ensuring developers and all management levels have the comprehensive training and motivation they need. In addition, there are significant costs associated with adapting the methods and processes of Systems Engineering to the company and the project circumstances. Important parameters such as the amortisation period across the development of several generations of the system and the long-term added value of SE introduction can barely be quantified to date.

However, some companies have implemented Systems Engineering with partial success. In this, an incremental, project-related introduction has proven effective. In addition, an introduction process can be supported by simultaneous top-down and bottom-up approaches across all management levels, with external methodological support and concurrent change management.

4.3.5 Roles in Systems Engineering

A supporting measure when introducing Systems Engineering is that of defining the role of the "systems engineer" at the company. [GENERAL ROLES IN ENGINEERING ARE SUMMARISED IN THE BELOW SECTION 4.5.2.1.] According to Ulmer, all employees taking on a role are accepting dynamically changing and alternating tasks [ULM19]. However, certain roles have the authority to carry out specific tasks and follow particular goals. In the literature, specifically tailored role profiles geared towards Systems Engineering can be found. A well-known example of roles in Systems Engineering is the Sheard approach, which describes 12 different roles in Systems Engineering (SEE FIGURE 11) [SHE96].

In principle, the highly scientific role of the systems engineer is little implemented in practice. For a large number of the respondents, the profile of a Systems Engineering role is not unambiguously defined or transferable to the company in question. Rather, the question remains open as to which concrete tasks and responsibilities the systems engineer takes on. However, many respondents have a clear view of which necessary competences and qualifications are required and which corresponding education and training pathways are suitable.

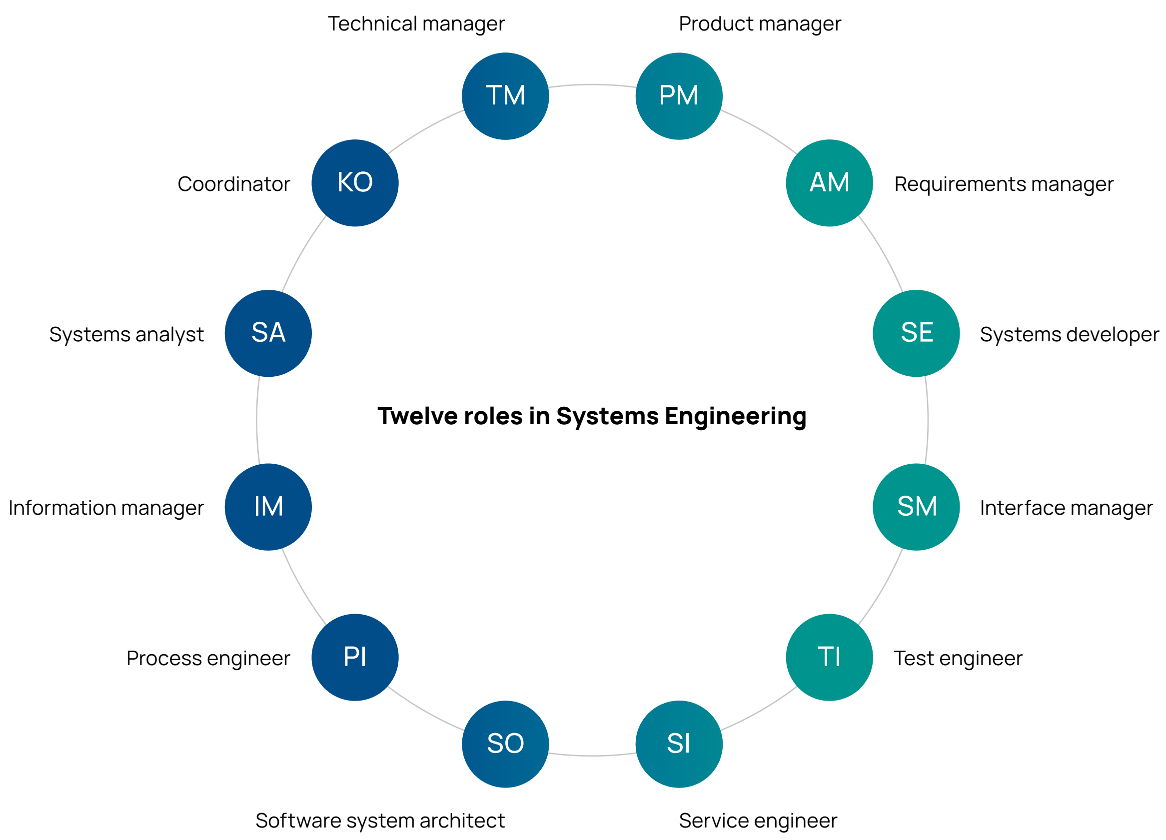


Fig. 11: Twelve roles in Systems Engineering based on [SHE96]

With regard to qualifications, there is consensus among many respondents that a fundamental understanding of the mode of thought, processes, methods and tools of Systems Engineering is essential. A systems engineer must master the processes and methods and know when which of each is to be applied. A deep technical understanding is not required by all respondents, as according to them, specialists at the company can make up for any deficits here. A large number of respondents emphasises the relevance of social competences. Knowledge of communications technologies and conflict management ensure successful interdisciplinary collaboration between various stakeholders. According to certain respondents, the role of the systems engineer also requires leadership competence and an extensive network within the organisation. Analytical capabilities and systemic thinking are further competences the respondents mention. Against this background, research must be carried out into why the existing role profiles are not yet established at companies that are already adapting their own first Systems Engineering approaches.

In the question of the right education pathways, there are two fundamentally differing opinions. On the one hand, many respondents demand well-grounded study leading to an expert qualification in an engineering discipline with subsequent career experience in the company. This is supplemented by suitable on-the-job training to become a systems engineer. On the other side, some respondents want specific training as a systems engineer to take place during study. Equally heterogeneous is the evaluation of the existing study provision. Some respondents see too strong a focus on courses to train generalists that neglect deep specialist knowledge. Others perceive a lack of sufficient courses to train systems engineers. This portion of the respondents also criticises the fact that Systems Engineering courses sometimes do not provide Systems Engineering modes of thought and methods, but simply combine several established disciplines (comparable with mechatronics). With regard to successful study for systems engineers, there is a special need for research that must be carried out in dialogue between science and industry. The first task is to identify whether or in which areas the existing training provision lives up to companies' expectations in the field of Systems Engineering. Then, research must be carried out to see which of the required qualifications and competences could be delivered by university study and which must be gained through experience. With regard to the existing training options, several respondents state that there is currently insufficient provision on offer in the field of Systems Engineering. The necessity of certification is not emphasised by respondents.

The introduction and concrete determination of the role of the systems engineer depends, according to a large number of respondents, on the company size. In small companies, the role of the systems engineer is often equated with the role of the technical project manager. To introduce a systems engineer as an independent position at a small- to medium-size enterprise would require too great an expenditure, some participants say. While the relevance of a dedicated role in SMEs is considered rather low, the surveyed companies see little need for it. In companies with greater numbers of employees, the role of the systems engineer is sometimes seen in a more differentiated way and the tasks are divided between several roles. Most often mentioned are the "system architect", who looks after the architecture of the system and its interfaces with sub-systems, and the "product owner" who, representing the customer, makes demands of the system and approves it as a whole. A further important role for large companies is the "Systems Engineering method coach". The location of the corresponding roles is also different from company to company. However, the majority of respondents agrees that not only the roles in Systems Engineering but all roles – from developers to management – need to develop a fundamental, unified understanding of the thought processes within Systems Engineering. ›

Roles in Systems Engineering: There is consensus regarding the necessity for the role of "systems engineer" and those derived from it such as "systems architect". There is some evidence that the corresponding qualifications must be "learnt by doing" and through on-the-job training measures.

A clear image of what a systems engineer is has not yet developed in industry. There exist roles derived from the systems engineer such as "systems architect" and "product owner". But there is no unified opinion regarding the profile, tasks and responsibilities of the involved roles. Thus, marked methodological and social competence is demanded of systems engineers, helping guarantee interdisciplinary work between participants. In SMEs, these competences often overlap with the role of a technical project manager. There is no unity regarding whether these competences can be transmitted through university study or must be gained in practice and through experience.

4.3.6 Model-based Systems Engineering

Many companies see Model-based Systems Engineering (MBSE) as decisive for the efficient implementation of Systems Engineering. It is also seen as a foundation for the realisation of comprehensive digital continuity. The system models should serve in the future as the central source of essential development artefacts for requirements, architecture and testing. Here, the surveyed companies see particular potential in using the system model as a communications and cooperation basis for all disciplines involved in the development process. Although there exist high expectations for the employment of MBSE, it is currently primarily used for the formal modelling of system architectures and thus strongly associated with the Systems Modeling Language (SysML). Some interview partners emphasise that MBSE can sometimes be confused with model-based engineering (MBE) (SEE INFOBOX 9).

INFO 9 Model-based engineering

The goal of model-based engineering (MBE) is to describe the relevant aspects of a product subject to development by means of models. In the context of product development, complex systems are developed, tested and improved by means of digital models. Various technologies such as CAD have become established to support structural tasks using 3D geometries. Alongside the established approaches, system modelling is taking on an increasingly big role.

The goal of Model-based Systems Engineering (MBSE) is to organise the interdisciplinary development processes and their results using a comprehensive system model.

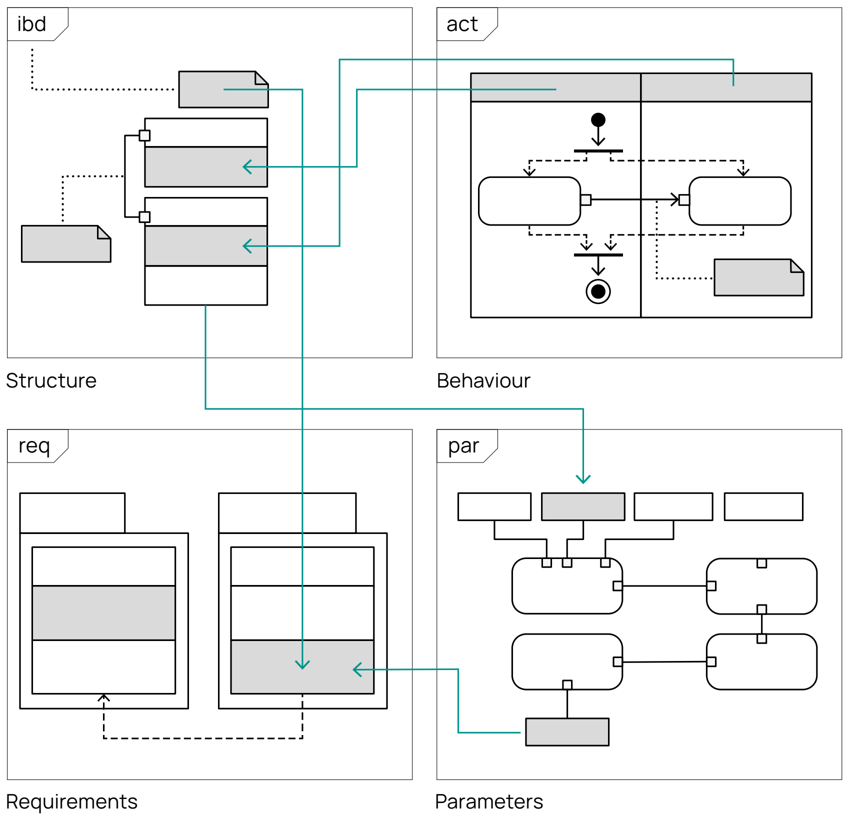


Fig. 12: The four aspects of SysML according to [FMS14]

MBSE uses the formalised application of modelling to support activities relating to system requirements, architecture, analysis, verification and validation from the start of the concept phase, through development and all the way to the later phases of the system life cycle. The system model here is an abstract representation of a real or yet-to-be-developed system which supports the development process through interdisciplinary and consistently networked sub-models. [DGS+18]

Many respondents see particular benefit in the approach of understanding systems using models. They name several advantages made possible through the introduction of MBSE. MBSE is frequently used at some of the surveyed companies to support the interpretation of system information and thus to reduce the perceived system complexity. Through visual modelling, the system specification is improved and thus the quality of the system design increased. The use of unified models creates additional transparency between various actors in the development process and allows the explicit presentation of knowledge. Through the use of a shared MBSE language, communication and collaboration within and between development teams is improved. In addition, digital continuity is supported by traceability in the form of the linking of model elements.

Comparably with Systems Engineering in general, the companies' state of ability with MBSE varies from sector to sector. At the aerospace companies surveyed and in automotive construction, a gradual migration from Systems Engineering to model-based approaches in ›

MBSE is currently taking place. This migration includes the design of own modelling methods and extensive training of employees in the use of the required modelling tools. A large number of companies emphasises the fact that employees are largely anchored in a document-based mode of thought. In this context, the respondents describe the challenge and difficulty of representing the complexity of mechatronic systems through documents like the established, mechanically oriented parts list. Against this background, there is an expectation that a large number of documents will be able to be substituted by a model-based system description, in which future goods and services can be represented together with their interdisciplinary interdependences. In this context, some companies are already using formal modelling languages that support comprehensibility for humans through various levels of abstraction and detail. The de-facto standard modelling language in the aerospace sector and in the automotive industry is the Systems Modeling Language (SysML) (SEE INFOBOX 10). At the surveyed mechanical and plant engineering, automation technology and medical technology companies, other modelling languages are widespread and are already in operative use. The reasons given for the use of other languages than SysML are predominantly related to greater ease of use, arising, say, from the smaller sizes of these languages (e.g. business process model and notation) or the use of discipline-specific elements (SEE FIGURE 12). Against this background, approaches must be researched which support companies in the selection and adaptation of existing modelling methods, languages and tools.

INFO 10 Systems Modeling Language (SysML)

The Systems Modeling Language (SysML) was developed as a modelling language for complex, interdisciplinary systems based on the Unified Modeling language (UML) which is looked after, like SysML, by the Object Management Group (OMG). In SysML, the description and specification of complex systems rest on the following four aspects:

Requirements: SysML allows the modelling of system requirements, which can be linked to further development elements and test cases. In practice, however, specialised tools without SysML are often used for requirements management.

Structure: By means of the description of structural linkages within the system, the architecture can be analysed and evaluated. This can allow consideration of requirement and development aspects and the assessment of alternatives.

Behaviour: Through the description of dynamic aspects, the behaviour and functions of the system can be reflected. In this, activities and processes, interactions and sequences can be modelled with SysML.

Parameters: SysML offers a means to represent parametric relationships between system elements. Parametric relations can be e.g. scientific laws that determine the structure and behaviour of technical systems.

One goal of SysML is to communicate the system information between different stakeholders in a unified way. To this end, SysML offers language elements and views (diagrams) supporting systematic work and the graphical modelling of complex systems. The size of the standardised language allows the development of extensive and detailed models. At the same time, there is a danger here that only a small user group of specialists is able to understand and apply the full depth of SysML. [FMS14]

Even if the use of MBSE is perceived as a sensible approach to the development of complex systems, various challenges arise for the surveyed companies in introducing it. The additional expense of modelling is considered one of the greatest barriers. Against this backdrop, there is currently no suitable amortisation concept for the increased modelling effort, meaning a quantitative assessment of economic viability is difficult to obtain.

With regard to the IT structure underlying the system, an increasing lack of integration into existing engineering IT infrastructures is often spoken of. Suitable approaches to networking the information from the formal models in the MBSE (e.g. SysML models) comprehensively with the established MBE models (e.g. simulation models) are lacking. Particularly aerospace engineering companies and automotive OEMs tend to develop a company-specific modelling method for the use of MBSE and thus adapt the modelling languages used in different ways.

Under these conditions, the intercompany exchange of models becomes problematic. Collaboration on the basis of specification sheets remains an established process. The currently available MBSE tools are, the respondents report, largely designed for experts. According to several companies, the required competence for handling MBSE tools and languages is lacking. Because of the lack of user-friendliness, there is also a failure of general acceptance, a lack of willingness to invest in the development of knowledge and experience with the tools and languages. Overall, the following areas requiring research to aid the company-wide implementation of MBSE are addressed by the respondents: on the one hand, the integration of MBSE in the existing engineering IT infrastructure is required. On the other, companies must be supported in selecting, introduction and adapting suitable MBSE approaches. The task here in particular is to increase the user-friendliness of modelling tools and languages, while retaining their performance.

Model-based Systems Engineering: MBSE is the prerequisite for the continuity of development work and is thus the key concept for the success of Systems Engineering. However, a series of deficits such as the lack of an amortisation concept for the model description is hampering the rapid spread of MBSE.

The ability to describe and master increasing systemic complexity and to organise suitable interdisciplinary development processes on the basis of a comprehensive system model is expressed in the concept of Model-based Systems Engineering (MBSE). This comes with high expectations after consistent development processes. Currently, MBSE is primarily only used for the formal modelling of system architectures. Although the Systems Modeling Language (SysML) has become established as the de-facto standard, as a rule, an adapted, company-specific modelling method needs to be introduced in order to fully comprehend the systemic context. Further hurdles to the introduction of MBSE in its modern form are the lack of amortisation concepts for the increased modelling costs, insufficient user-friendliness of the IT tools and the lack of integration into the existing engineering infrastructure.

4.4 Advanced Engineering
Rethinking engineering

Alongside interdisciplinary and holistic Systems Engineering, new technical and methodological approaches are constantly being developed in engineering. Advanced Engineering considers processes, methods, tools and work organisation in order to rethink established engineering approaches e.g. by making use of creativity, agility and digitalisation (SEE FIGURE 13).

The focus of Advanced Engineering is currently on using emerging technologies such as artificial intelligence to support development activities, promising methods and collaborative models such as agile working processes. Rapid methodological and technological progress is leading to continuous innovation in the development of goods and services. To shape the Advanced Systems Engineering guidelines, the status quo and current developments in Advanced Engineering are investigated. In order to gain a unified understanding of the important topics and developments, the status of current capabilities has been recorded using the following structure:

— Digital technologies in engineering (SEE SECTION 4.4.1)
— Innovative methods in engineering (SEE SECTION 4.4.2)

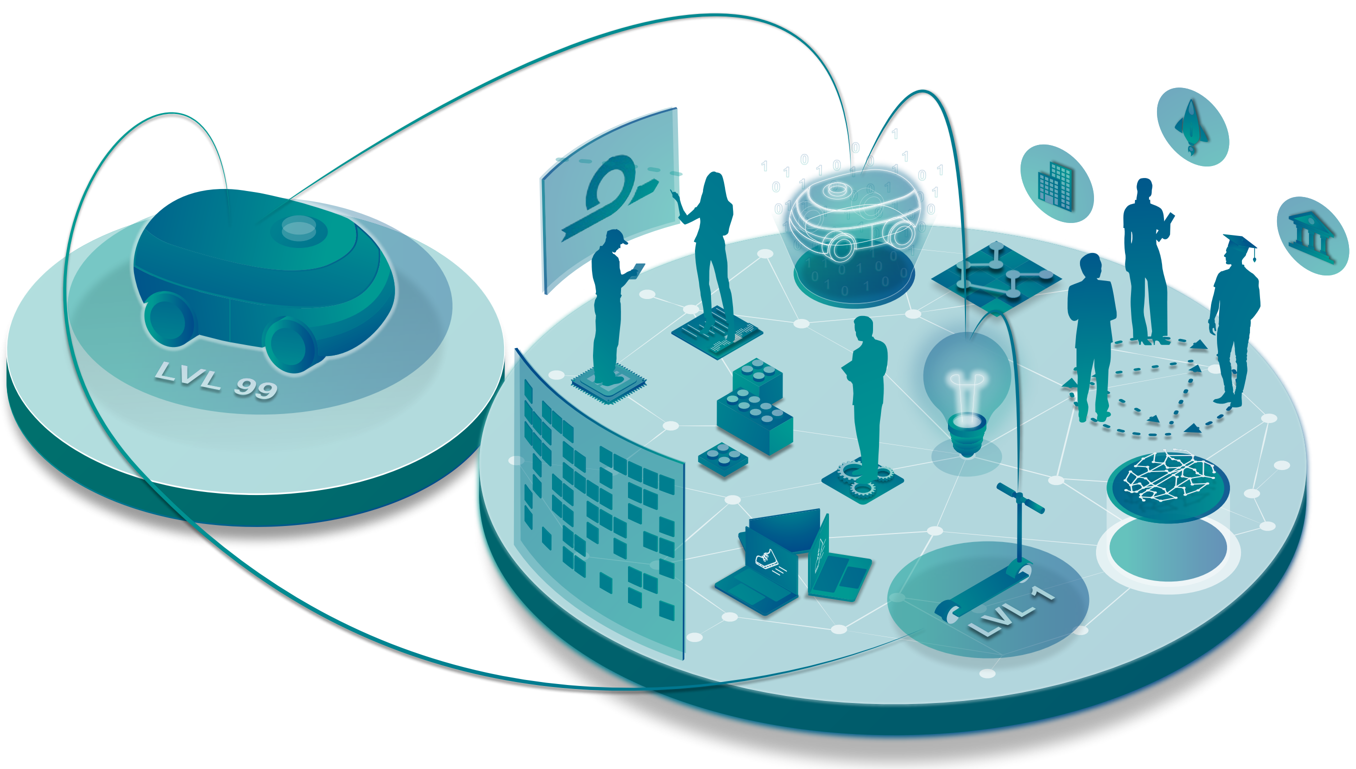


Fig. 13: Advanced Engineering: Rethinking established engineering with creativity, agility and digitisation

4.4.1 Digital technologies in engineering

"Digital technologies" covers all technologically-based support for the development process making use of digitalisation. It describes the generalised use of digital tools in product development and production processes, as well as the extensive employment of digital, automated processes. The digital technologies used for this are based, among other things, on digital continuity via networked IT tools and the increasing virtualisation of development activities. Also under investigation is the comprehensive management of product data from planning to validation and product use through the deployment of intelligent assistance systems.

In the evaluation of current capabilities, the following areas are covered:

— Digital continuity and Product Life Cycle Management (SEE SECTION 4.4.1.1)
— Digital twins and operational data usage in engineering (SEE SECTION 4.4.1.2)
— Artificial intelligence and assistance systems (SEE SECTION 4.4.1.3)

4.4.1.1 Digital continuity and Product Life Cycle Management

The vision of digital continuity describes the continuous flow of information between all value-creating activities in companies (VGL. INFOBOX 11). This flow of information requires IT system networking. The availability of this information offers the potential for individual activities within market service development to be continuously optimised. Against this background, digital continuity is seen by many companies as a decisive success factor. The surveyed companies name diverse advantages arising from the networking and traceability of data, models and information achieved through the implementation of digital continuity. Increased transparency presents efficiency advantages in the field of change management and troubleshooting. In addition, digital continuity facilitates verification and systematic working processes. Digital continuity is seen as a catalyst for the automation of processes and for transdisciplinary documentation throughout the life cycle. According to several respondents, the networking of information across several product generations and its connection with data from product use present particular potential. In this way, findings can be used to develop the next product generations. Some respondents are already using networked product data to develop new product generations. This usage is not taking place systematically, however, and is only sporadic, meaning the full potential of the use of existing product knowledge is not being exploited.

A large number of surveyed companies is currently undergoing a transformational process to achieve comprehensive continuity. The majority of respondents confirms, however, that the projects currently to be found are largely isolated solutions. Some companies are already using support systems to automate modelled work processes. At a large number of surveyed companies, the different IT systems are coupled using separate, sometimes manual interfaces. ›

INFO 11 **Digital continuity**

From the initial planning to the end of the life cycle of goods and services, a large number of artefacts arises, such as data, models and information. These artefacts arise in different disciplines, within different IT systems and increasingly across different development sites and companies [SBA+14]. During the development process, there is an increasing need for data, models and information to be networked, altered and integrated in many different ways. With regard to certifications, there are additional requirements made of documentation and of the operations carried out on the data.

The vision of digital continuity describes a continuous flow of information between all activities carried out during development and the networking of all required data and models. The networking of artefacts offers the potential to provide the right information, at the right time, to the right location, in the right quality. Both well-defined information logistics and the degree of digital continuity are decisive efficiency factors for digital technologies [SBM+13].

The seamless integration of all information is associated in the context of engineering, and particularly in product development, with Product Life Cycle Management (PLM). Some respondents understand PLM activities as the continuous management of data and models across various IT systems, alongside the linkage of methods, processes and organisational structures (SEE FIGURE 14). A large number of respondents, however, only connects PLM with the idea of an integrative IT platform for development data. Thus, PLM in many companies is for the most part limited to the narrower scope of Product Data Management (PDM). While PDM is restricted to the securing, versioning and provision of product-related data, PLM extends this concept by adding the seamless integration of all information in the life cycle of goods and services (SEE INFOBOX 12).

The essential potential uses of PLM are described by the respondents as follows: PLM that is continuous across IT systems and methodically integrated is considered the prerequisite for the development of goods and services of tomorrow. Thus, for example, it becomes easier to make evidence-based decisions, because the quantity of information available and its accessibility are increased. There is also great potential in the simplified integration of data from the use phase and across various product generations for rapid adjustment to market needs. This integration is partially also seen as enabling the company to develop new value-creation processes and new business models.

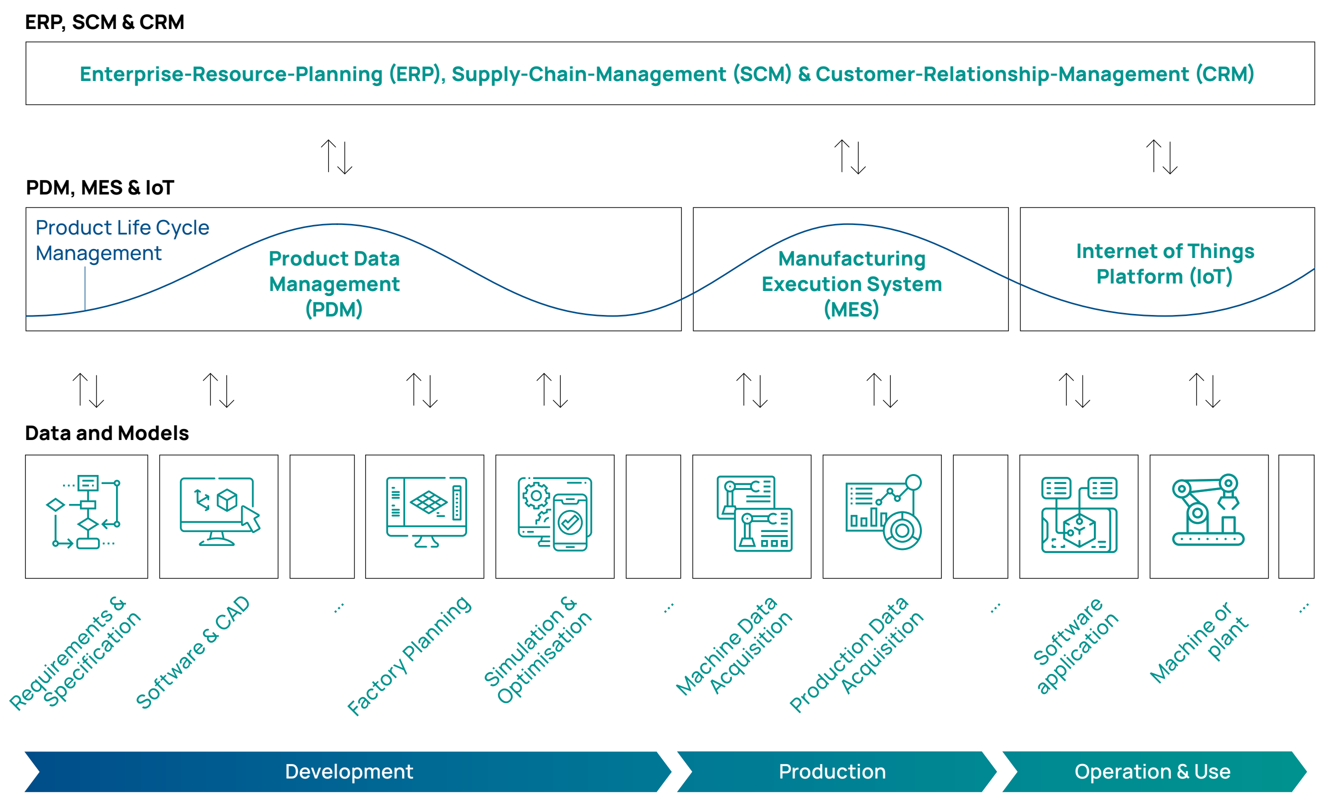


Fig. 14: PLM concept in the context of various IT systems over the life cycle of goods and services

INFO 12 **Product Data Management (PDM) and Product Life Cycle Management (PLM)**

The concept of Product Data Management (PDM) arose in the environment of the computer-supported construction of mechanical products using computer-aided design (CAD). The first PDM systems served for the technical administration of CAD documents, particularly their versioning. Relevant CAD documents are, above all, 3D models of individual parts and components and their technical drawings. Later, PDM systems and functions such as parts list management and approval and change management were added. The PDM is usually linked to a concrete IT system, thus consisting of a database, application logic and a user interface.

The concept of Product Life Cycle Management (PLM) arose from the further development of PDM and does not describe an IT system but a concept. PLM is the strategic, system-related technical management of product data and systems across their entire life cycle. A PLM solution usually consists of several IT systems such as author systems (mechanical CAD, electrical CAD, CAE simulation systems etc.) and data management systems (such as PDM systems). These are integrated via interfaces and thus allow digital continuity along the product life cycle. A PLM system does not exist as a standalone IT solution, even though these are always being promoted. ›

Although the majority of respondents recognises the advantages of a PLM solution, companies are confronted by various challenges relating to the design and care of the required IT infrastructure and systems used.

High costs of administration and orchestration of the software tools: The development of comprehensive digital continuity and the implementation of a PLM solution are connected with high financial costs. While a large number of the bigger companies surveyed is already active in this field, for SMEs balancing the expected expenditure (e.g. licensing or personnel costs) and the direct benefit is in the foreground. In this context, suitable approaches for application-oriented cost-benefit analyses must be researched.

An increasing number of IT systems: The increasing involvement of further departments in the development process of goods and services results in a large number of specialised IT systems and authoring tools. Against this background, many surveyed companies see complete continuity across all phases from planning to recycling as critical. The administration of many IT systems that lack information standards and unified data formats is the central challenge. Through cooperation with other companies in a value-creation network, the number and heterogeneity of the IT systems used rises, making seamless collaboration more difficult. Currently, there is a particular challenge for SMEs wishing to make the right decisions in shaping their system landscape. There is a conflict of goals between continuity and independence from sole IT system manufacturers. Against this background, a large number of the surveyed companies demands shared exchange and programming interface standards. There is a need for scientifically grounded approaches to the design of the engineering IT infrastructure. At the same time, both the IT system provider and the company must be supported as users in the standardisation process.

Media discontinuities and insufficient standard formats: A large portion of the respondents ascribes high importance to standard formats for internal and intercompany collaboration. However, existing standards are only partially used by the surveyed companies. One reason for this is insufficient support for these standards by the IT systems in use. A further reason named by some respondents is that media discontinuities arise in the use of standards. Through the constant change and functional extension of IT systems, the information created is often only insufficiently represented in standardised exchange formats. Against this background, research must be carried out to determine how far the conflict between the goals of the rapid development and implementation of functions from sole IT system providers and the necessary acceptance from a large community of interest can be resolved.

Designing and using suitable interfaces: Standardised exchange formats are usually unsuitable for the needs of digital continuity. Against this background, some respondents raise the increasing relevance of bidirectional interfaces. A large number of respondents complains that IT systems only partially offer open interfaces and that many providers are still promoting monolithic solutions. Many surveyed companies perceive increasing integration in the form of transdisciplinary, monolithic IT systems mostly as limiting the diversity of IT systems. Alongside the lack of a range of interfaces, many surveyed companies find insufficient documentation and definition and the management of suitable programming interfaces to be central challenges. Some respondents detect a particular need for solutions addressing the exponential relationship between the number of IT systems and required number of bidirectional interfaces. Thus, research must be carried out into how the interplay of discipline-specific standard formats and harmonised exchange formats must be designed to achieve digital continuity between increasingly heterogeneous IT systems.

Information security during intercompany cooperation: At many of the surveyed companies, the development of goods and services is not achieved through the complete in-house manufacture of all components. The greater the amount of supplier parts and outsourcing, the greater the need for special IT systems for data exchange beyond the boundaries of the company. Comprehensive continuity strengthens the previously described challenges. Some respondents see protecting intellectual property and monetising the provision of product-supporting data to suppliers and customers as a particular challenge. Some report that the required formation of digital continuity is undermined by the current business models of the company. Against this background, research must be carried out to determine how ownership relationships relating to shared information models should be designed in a value-creation network. Here it must be noted what kinds of billing and business models are needed if third parties want to have access to data and models.

User-friendly integration within the company architecture: Alongside technical challenges, some companies perceive an increasing need to integrate methodological questions and human-oriented criteria such as user-friendliness in the design of digital continuity. From the point of view of many surveyed companies, PLM must be enabled in the future to handle company-specific processes in product development. This requires the networking of the IT systems used not to stringently specify the procedures to be used, and at least partially allow adaptation to company-specific methods.

Use of synergies between PLM and Systems Engineering: A large number of companies describes both Systems Engineering and PLM as tending to address similar goals – but that the way the goals are achieved is through different means. While Systems Engineering is an approach to handling complexity by considering all departments and stakeholders across the entire life cycle, the PLM approach attempts to seamlessly integrate all information arising in the same period. Only some companies are pursuing activity linking Systems Engineering and PLM. Against this background, approaches must be investigated towards creating methodological unification and integration between Systems Engineering and PLM.

On the company side, there is often the expectation that the described challenges need to be resolved during the design of digital continuity by IT system providers. Respondents from academia are of the opinion, however, that without methodological foundations even established providers will be unable to implement digital continuity.

Digital continuity and Product Life Cycle Management (PLM): With the spread of the Product Life Cycle Management concept, virtualisation of product development and, most recently, the rise of MBSE, high diversity has arisen among IT tools and databases that need to be integrated. This uses a lot of personnel capacity in companies. This effect must be counteracted by standards e.g. for exchange formats to ensure data protection and security and allow programming interfaces.

The vision of digital continuity describes the unhindered information flow between all activities within a development project through the networking of IT systems in the company and in development partnerships. The advantages of this networking include transparency through traceability, efficiency gains thanks to process automation and quality improvement through information availability. In this way, digital continuity and networking supplement existing virtual product development approaches and Product Life Cycle Management (PLM) through the comprehensive integration of all market service development information and its usage. A large number of the surveyed companies is in a state of permanent transformation, with the goal of achieving a high level of networking. Complete networking is hindered by many challenges. Thus, for example, the design of complex interdisciplinary systems needs an increasing number of IT systems to be used. This results in high costs for the administration and orchestration of the software tools. Media discontinuities between IT systems are part of daily business, despite standardisation in exchange formats. In addition, companies are unable to include and support all the required programming interfaces. These challenges become yet more difficult in intercompany cooperation and where information has to be used communally and must live up to known security standards. Alongside the technical hurdles, company-specific processes within product development and the interrelations of IT infrastructure must be considered. Against this background, it will be necessary in future to make use in particular of the synergies between PLM, virtual product development and MBSE.

4.4.1.2 Digital twins and operational data use in engineering

The digital twin is rated by a large number of participants as a central trend in engineering (SEE INFOBOX 13). Many companies confirm that the concept of the digital twin will offer a competitive advantage in the future. Although the advantages are known, the respondents have a very heterogeneous understanding of them. Many understand digital twins to involve using the operational data of a delivered product for various applications and services. The digital representation of all product data, simulation models to safeguard product characteristics and demanding visualisations using augmented reality are also, the respondents say, covered by the concept of the digital twin.

INFO 13 Digital twin

The concept of a "digital twin" is defined as a digital representation of a clear product (e.g. a plant, service or object) or a clear Product Service System. Here, the digital representation presents all the selected characteristics, statuses and behaviours using models, information and data [SD19]. Digital twins differ from simulation models or digital prototypes by representing a real, operational product. However, they are able to use the models that arose during development. The purposes of digital twins are diverse: from simple status monitoring to solutions for autonomous systems which combine the logic within the digital representation and development models to the end of achieving self-optimisation [RLS18].

Although the respondents have no shared understanding of the digital twin, their opinions allow us to clearly demarcate how the concept differs from digital continuity (SEE FIGURE 15).
Although the respondents have no shared understanding of the digital twin, their opinions allow us to clearly demarcate how the concept differs from digital continuity (SEE FIGURE 15).
The digital twin is a digital representation of a clear market service, which records, processes and networks selected information across the entire life cycle for various purposes. For the most part, the respondents refer to the representation of physical goods and services such as technical systems (e.g. components, assemblies, products, machines or production facilities). Some respondents associate the use of digital twins with approaches within digital product development such as virtual prototyping. The majority of the surveyed companies, however, describes operational data usage by networked products as the central application of digital twins. Operational data recording has gained importance for many of the surveyed companies because of the increasing availability of communications standards, falling costs of microelectronics and the establishment of cloud infrastructures. Against this background, the digital twin is often associated with the internet of things. Alongside the various named applications in development, production and operation, as a rule, the linkage of data and models across all phases of the life cycle is in focus. ›

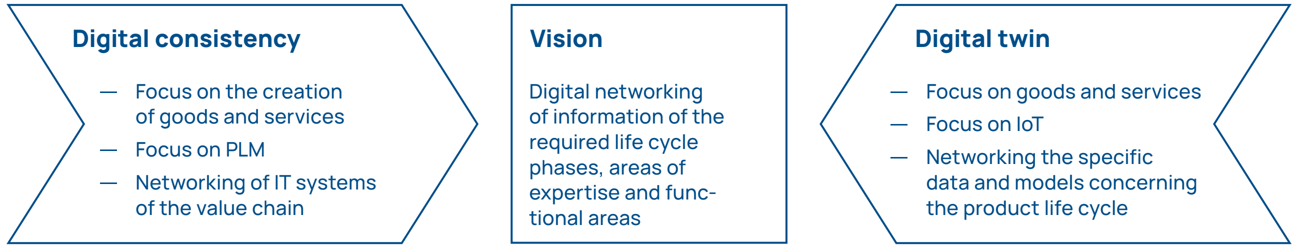


Fig. 15: Delimitation of the digital consistency and the digital twin

The surveyed companies indicate exciting potential through various applications. Many have expectations that the digital twin will form a technological basis for comprehensive data recording and use. Building on this, new forms of data-based services or business models such as predictive maintenance or data-supported decision-making will become possible. In opening up this potential, however, companies are faced by diverse challenges.

A heterogeneous understanding: Because the concept of the digital twin is used differently for different purposes in various sectors and disciplines, it has taken on different forms. Against this background, there is no unified understanding of it among the surveyed companies, scientists and IT system providers. A digital twin has diverse requirements and goals. For this reason, concepts must be researched which structure the different forms, allowing potential within the development of goods and services to be exploited.

Evaluating use cases: In the survey, the most diverse use cases were identified – from digital models that describe behaviour in product development to demanding remote data processing carried out while operating autonomous systems. The cases are differentiated by their focus on various life cycle phases, the areas of deployment addressed, model and data quality and interoperability. The majority of respondents does not yet have a systematic process for identifying and selecting relevant use cases.

Model formation and networking: Some respondents from academia describe the digital twin as a data-based model that evolves continuously throughout the development process of goods and services and is concurrently enriched with information. In practical application, the challenge arises that the required level of detail, model scope, agreement with the real structure or behaviour and reusability of model information are not defined. There is a need for more extensive research to enable closer specification of these aspects in the context of the digital twin. Without compatible and modular architectures, the expense of model formation and networking is impossible at present to estimate.

Verification and validation: The digital twin is seen by many surveyed companies as a tool to safeguard set characteristics and optimise goods and services. In this context, there exists the expectation that verification and validation will increasingly be carried out digitally. To continuously reduce the laborious development of physical prototypes, the surveyed companies increasingly use (multi-domain) simulations. In addition, many respondents are increasingly using approaches like X-in-the-loop (XiL), by which embedded systems are safeguarded by simulating their real environment. XiL offers the potential for testing to use only individual portions of systems with physical presence and to represent in simulation the interaction of the entire system via defined interfaces on the basis of real-time-capable models. At present and in the short term, however, physical prototypes cannot be fully avoided. Legal requirements and excessive deviation between the real and simulated behaviour make physical tests still necessary. In addition, some companies indicate that extremely specific and interdisciplinary interactions are difficult so far to model without significant and unviable expenditure. According to several companies, the complexity of goods and services has risen to such an extent that operational errors in many cases can no longer be traced back to a single cause. Against this background, new methods and tools are required to safeguard complex interdisciplinary systems and integrated systems, allowing them to be verified and validated at acceptable cost.

Individual pioneering companies are currently using back-coupled operational and environmental data to optimise simulations of their mechanics, mechatronics and software. Use of operational data in engineering allows simulation to approach reality even in early development stages, thus allowing earlier validation of customer desires. Here, companies analyse the data recorded in order to make robust, fitting predictions on the basis of correlations. Currently, however, a systematic process to combine analytical methods (simulation models) and empirical ones (data models) when safeguarding digital twins is lacking.

Designing IT infrastructure: The data and models required for a digital twin are, as a rule, created by independent IT systems, operating on various servers in distributed environments or on cloud platforms. According to some companies, this results in an increasing number of increasingly different data and models. At the same time, no company has identified a standardised exchange format, integrative IT platform or data structure that could address this challenge sufficiently. The problem is intensified by the increased linkage of value-creation networks, in which IT infrastructure is not designed solely by one actor. Some respondents already offer goods and services by which usage data can be transferred across company boundaries to the provider. On the part of the providers and users, there is a clear challenge in designing a suitable IT infrastructure that is capable of living up to the digital twin's future requirements for data transfer and security. Against this background, the technical and economically viable implementation of the engineering IT infrastructure for digital twins must be researched. Here, relevant conflicting goals must be identified (e.g. cloud vs. local, exchange formats vs. programming interfaces) and suitable recommendations for action, particularly for SMEs, derived.

Intercompany implementation: Through third-party supply and outsourcing, intermediate products from various companies are integrated in higher-value goods and services. Comparable with the integration of a machine module in a production line, the digital twin must also be aggregated into a single unit. Resulting from this, requirements arise of the information exchange system and compatibility of digital modellers. Some respondents name digital administration shells as a possible approach to a solution for the interoperability and integration of digital twins (SEE [PLA18]). Particularly in the intercompany design and use of digital twins there remains extensive need for research.

Use of operational data during development: Already today, some of the surveyed companies are recording and analysing increasing amounts of data from the production and usage phases. This data recording largely serves the purpose of providing data-based services, however. The surveyed companies have barely used the data so far to optimise existing or future goods and services. Only in individual cases or pilot applications are data collected from the validation process and from suppliers and systematically used in the development of the following product generation. In this context, several surveyed companies indicate that the systematic transfer of information is focused on subsequent activities. One frequently noted example of this is the use of development models in production (e.g. in the automated creation of numerical control codes for tool machines). Feeding back data into prior activities for the next product generation is only used in isolated instances by the surveyed respondents. Against this background, there is a need to investigate and validate the relevant use cases of the systematic feedback of data and models via the digital twin. ›

Digital twins and operational data use in engineering: The concept of the "digital twin" supplements MBSE by placing the focus on models of a product across its life cycle. There is general consensus on the high importance of this concept. However, its practical implementation is still nascent; only in a few cases are operational data used by product developers, say, in order to achieve product optimisation.

The concept of the digital twin is accorded central importance in engineering by many respondents. In addition to digital continuity, the focus is on the networking of specific data and models across the life cycle of goods and services. Although there is no unified understanding of the concept, diverse use potential is recognised, particularly in operational data usage and in the design of data-based services or business models. To open up this potential, use cases must first be identified, structured and assessed. In practical application, there is a particular challenge in model formation and networking across the entire life cycle. Virtual safeguarding of characteristics on the basis of networked models is only possible at the moment to an extremely limited extent. In the current state of development, only in exceptional cases are operational and environmental data used to optimise goods and services from generation to generation. Against this background, the technical and economic implementation of engineering IT infrastructure for digital twins is accorded great importance. Here, intercompany usage and the interoperability of digital twins must be ensured.

4.4.1.3 Artificial intelligence and assistance systems

Assistance systems and technologies like artificial intelligence (AI) are in no way new. Assistance systems have already achieved great success in numerous applications, helping companies and their employees through the introduction of rule-based decision-making support and automated decision-making processes to their work (SEE INFOBOX 14). Artificial intelligence describes IT solutions and methods that allow tasks that would previously have required dynamic decisions and human intelligence to be completed autonomously. The rules underlying such tasks are no longer explicitly set by human controllers. Rather, the AI uses data to learn how to complete its tasks independently (SEE FIGURE 16) [GWS+19-OL; MCK17-OL]). AI is seen by a majority of respondents as a central trend and highly relevant key technology. Some companies already use AI in their development processes and some in their products and services.

INFO 14 Neural networks

Artificial neural networks are models of machine learning. They solve problems through the use of artificial "neurons" whose switching and weighting are automatically optimised using training data to fit the task that has been set. Based on this, systems can be enabled to solve complex tasks with comparatively little programming effort, with the definition of strict decision-making rules taken over by a learning algorithm. As a rule, the reason for decisions can no longer, or only with great difficulty, be determined. For example, the training data can be used to check what percentage of correct decisions can be expected in the future. In contrast to rule-based systems, decisions are not made deterministically by neural networks. This can raise uncertainty in users and lead to conflict with regulatory authorities [ACA20].

A large number of respondents expects AI to support people in the future through assistance systems in knowledge-intensive engineering activities. Respondents suggest it has diverse potential, such as for preparing context-based knowledge from various sources, continuous analysis of CAD data or real-time cost predictions. The expected range of functions for assistance systems runs from pure data analysis and transparent, needs-based presentation to AI-supported determination of recommendations for action (INFOBOX 15). Companies do not expect that AI will replace humans in product development activities in the near future. Rather, some surveyed companies expect a paradigm shift in engineering work. In the future, they predict, developers or engineers will bear responsibility for monitoring AI-based IT systems and analysing the results. Great emphasis is placed here on the need not just to rely heavily on support services, but to critically assess the proposed decisions.

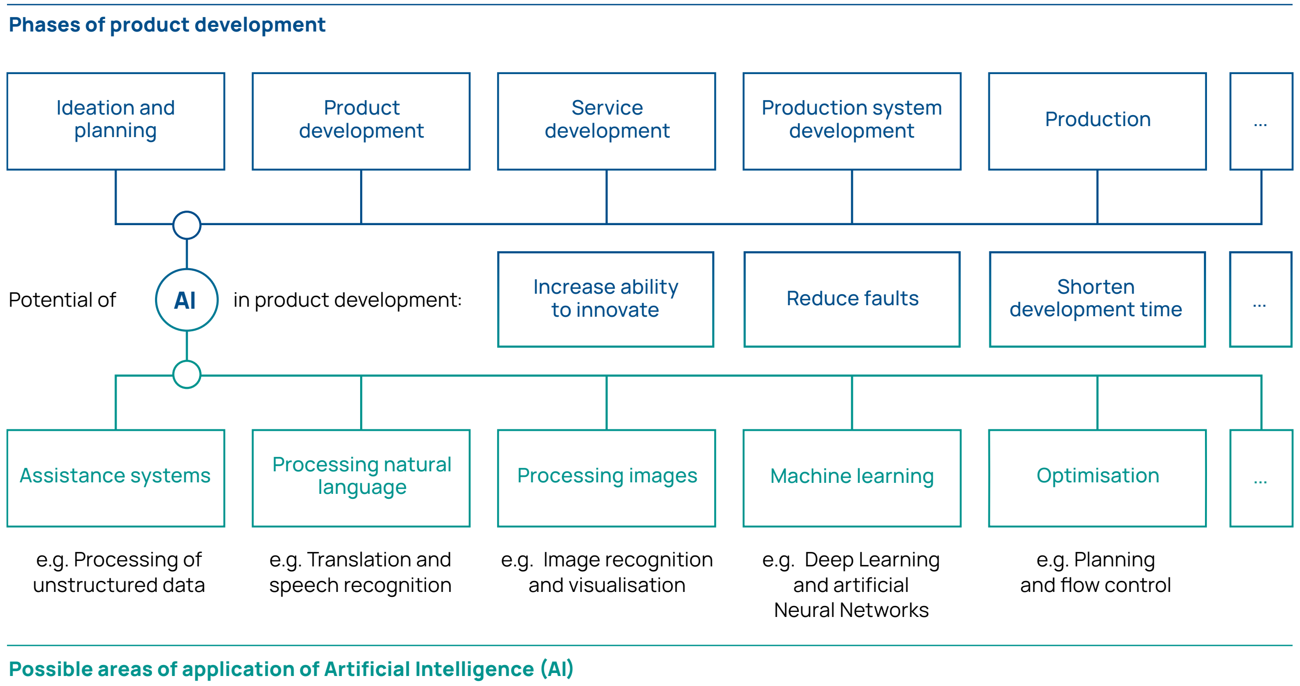


Figure 16: Potential benefits of AI in product development based on [GWS+19-OL; MCK17-OL; HNI21]

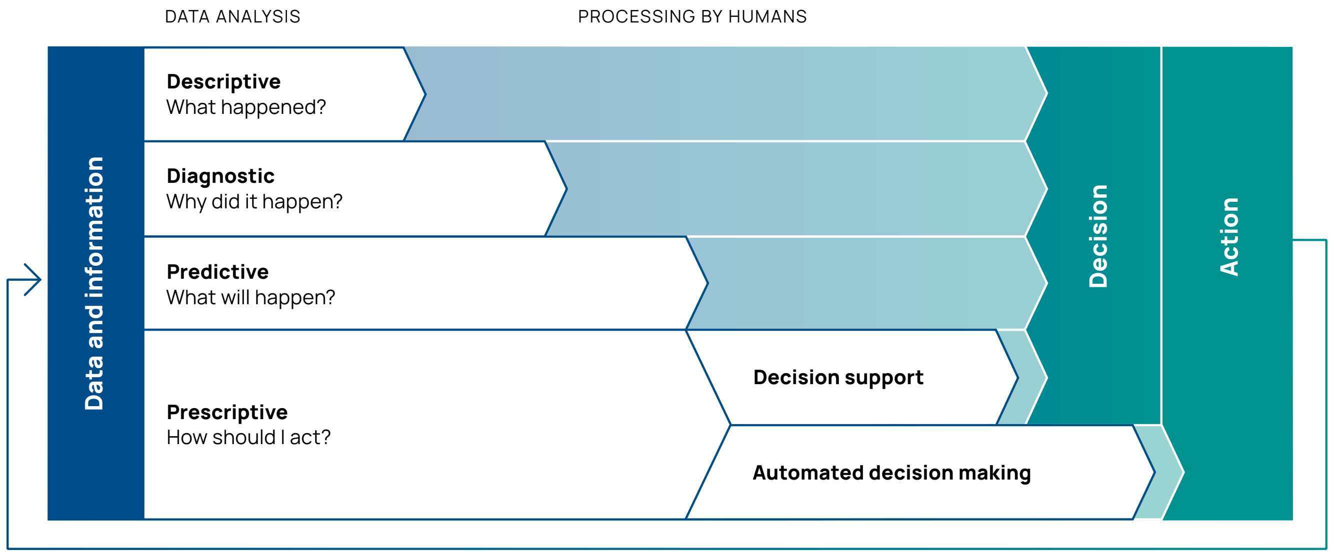


Fig. 17: Expansion stages of information processing according to [SSE+14]

INFO 15 **Assistance systems**

In context of the development and provision of goods and services, assistance systems include all types of information provided to help with work. They can be divided, depending on their capabilities and the information processing that underpins them, into four stages of development (SEE FIGURE 17). The different stages describe the level to which users are supported in their tasks by the assistance system. The stages of development are shown below using an example from the field of predictive maintenance in production [ACA20; OBE19]:

A descriptive assistance system informs the user of what has happened in the past, e.g. that a machine once broke down.

A diagnostic assistance system informs the user why something happened, e.g. what cause, or error, led to a breakdown.

A predictive assistance system forecasts what might happen in the future for the user, e.g., foretelling when a machine is likely to break down.

A prescriptive assistance system supports the user in reacting to the knowledge gained from the data, e.g. letting them know how to react to an imminent breakdown. This support can either take the form of recommendations for action or an automated decision-making process.

As a component of assistance systems, AI is a promising aid in helping engineering to become even more efficient in the future. Some respondents ascribe special potential to assistance systems through the integration of AI, which they consider able to increase productivity and efficiency in product development. The efficiency increase can be achieved e.g. by taking over repeat routine tasks, processing unstructured data and in image, language and general pattern recognition. There is also potential in the representation and provision of empirical knowledge from previous projects. Examples of this are the AI-supported optimisation of construction models or the preparation of unstructured existing data for migration into new IT environments. By taking over highly repetitive tasks and providing targeted aid and advice, the developer's burden is lightened. Whether the use of assistance systems in research-intensive development activities gives developers the opportunity to focus more strongly on creative aspects thanks to the cognitive space freed up is not answered clearly by the respondents.

In opening up these areas, however, companies are faced by the most diverse challenges.

Difficulty of entering the field: Many companies have difficulty identifying relevant use cases, forming discipline-specific AI models and dealing with sometimes insufficient specialist competence within the company. For the use of AI-supported assistance systems in product development, the first promising fields of use are emerging. However, many respondents are challenged in identifying relevant use cases, forming discipline-specific AI models and dealing with sometimes insufficient specialist competence within the company. AI is often used by employees unconsciously or indirectly (e.g. with handwriting recognition). Here, guidelines must be developed to support companies.

Use of reliable AI tools: With relation to product development, a few respondents note that the range of AI-based assistance systems is on the rise. However, these systems are largely not yet adjusted to company-specific development processes. Alongside their insufficient maturity, many companies find it challenging to have to place their trust in an IT system. Uncertainty with relation to the functioning and transparency of decision-making within neural networks is the primary barrier here. From the fact that certain types of artificial intelligence are non-deterministic and thus act without sufficient transparency for the user, there are challenges in particular with issues of liability for decisions made by such AIs. These technologically conditioned uncertainties and the frequent lack of competence leave a lot of open questions for companies with regard to the implementation of AI in product development. These open questions can prevent the use of assistance systems in product development and their integration into goods and services. Against this background, research must be carried out into how AI systems can be specified, validated, and used to generate benefits for existing IT systems and integrated into development processes.

Insufficient underlying data: Several of the interviewed companies emphasise that AI-based assistance systems both promote and require the existing approaches of model-based and digital product development. Intelligent, context-sensitive method support in MBSE systems can, say, reduce barriers to learning, especially for discipline-specific developers, and support acceptance by all users. Alongside integration in existing systems, some respondents assert particular potential in assistance systems having access to a wide range of information sources, so they can identify previously unnoticed connections. This support with handling large and somewhat unstructured datasets is currently made exceedingly difficult for the surveyed companies by very heterogeneous IT system landscapes and lack of interfaces. Particularly media discontinuities in digital continuity currently limit the extent of functions here. Against this background, research needs to be carried out to determine to what extent and under what conditions future AI systems will be able to analyse development-related knowledge from unstructured data and heterogeneous models.

The legally secure and human-centred use of AI: Many respondents currently detect an essential challenge with relation to legal limitations and unclear regulatory aspects. This includes, for example, unclear data protection regulations when using AI-based assistance systems working on cloud infrastructures with data centres outside Europe. In addition, some companies describe a potential for conflict with privacy laws in systems

that process personal user data (e.g. language assistants). At the same time, some respondents emphasise that the potential for regulatory overreach with regard to data usage could also hinder innovativeness. Various research and industry undertakings such as the pioneering GAIA-X project are attempting to address these challenges (SEE INFOBOX 16).

INFO 16 GAIA-X

GAIA-X is a European project with the goal of developing the shared requirements of a European data infrastructure. 300 organisations and representatives from politics, industry and academia in many countries are involved. To create a networked data infrastructure, data and services should be exchanged and collated in an open, transparent digital ecosystem. Here, among other aspects, data security and user-friendliness in the system should be considered, to ensure data can be made available and shared with confidence. A long-term goal of the GAIA-X project is to strengthen the competitiveness of European companies and promote collaboration across the continent. [BUN20]

Alongside the technical and legal challenges, with the increasing use of assistance systems, it is necessary to pay closer attention to maintaining and activating the user's cognitive functions. Several respondents criticise the fact that assistants to this day lead to users placing excessive trust in the system. Some see here a risk of people's cognitive abilities fading and becoming disused if a large portion of the previous work content is handled by automata. An example is given in people's lack of a sense of direction without using navigation systems.

Even if the majority of respondents cannot exclude the idea that AIs will take on a portion of the tasks of today's engineers, there is consensus that humankind will retain the central role in the engineering of tomorrow. The goal is a synergetic division of labour, in which an AI-supported assistance system helps the user while creative tasks in product development are still taken on by humans.

Artificial intelligence (AI) and assistance systems: AI has arrived in engineering; it has many successful applications, in particular in the field of assistance systems. The use of non-deterministic learning algorithms is still viewed critically.

The key technology of artificial intelligence is opening up new perspectives in engineering. Assistance systems have already been used successfully by many companies. Consequently, there is an expectation that clear potential for success in AI will soon attained. This applies in particular to the takeover of repeat tasks, the processing of unstructured data, learning from experience and the strong improvement of existing IT applications. When opening up this potential there are challenges such as the identification of relevant use cases, the formation of domain-specific AI models and insufficient competence within companies. In addition, there is great uncertainty regarding the use of non-deterministic learning algorithms, which may stand in conflict with safety-related or regulatory requirements. Comparable challenges arise with regard to data protection and the right to privacy in systems processing employee or user data.

4.4.2 Innovative methods in engineering

Innovative and forward-looking methods and processes are supporting the creation of the Advanced Systems of tomorrow. At issue here are non-technical innovations in engineering that promote the socio-technical engineering system of a company through organisational, administrative and planning abilities. Innovative methods in engineering are focused both on agile processes and creativity methods and on the systematic integration of innovation management in engineering work organisation.

At a large number of surveyed companies, there is to date no existing or only a loose connection between innovation management and engineering. The concept of innovation management is, according to many respondents, insufficiently defined, and has achieved varying levels of functionality in companies, just like Systems Engineering. Here, it is important to formalise the interface between innovation management and Systems Engineering.

In the evaluation of current capabilities, the following areas are covered more closely:

— Agility in engineering (SEE SECTION 4.4.2.1)
— Creativity in engineering (SEE SECTION 4.4.2.2)
— Production Generation Engineering in engineering (SEE SECTION 4.4.2.3)

4.4.2.1 Agility in engineering

Creating the goods and services of tomorrow is a task characterised by market dynamics and the involvement of many different disciplines. In particular in the development of networked systems and systems of systems, there exist many as-yet unknown interactions between goods and services and their environment which cannot be sufficiently anticipated during development and thus cannot be sufficiently taken into consideration during validation. High development risk results from this, demanding the early safeguarding of all concepts. At the same time, it is important to be able to react flexibly to new knowledge gained about customer and user expectations. Based on this realisation, many respondents believe that agile processes will have increased influence on companies (SEE INFOBOX 17). In the present publication, the status quo at companies, alongside potentialities and challenges, have been investigated.

The majority of respondents emphasises that agile work should not be associated with chaotic processes. In agile work, sufficient planning and adequate documentation of the process and the result of the work are highly relevant. According to many interview partners, agile methods are particularly important when a clearly defined range of tasks is being handled by a clearly defined team. The surveyed companies have tested agile work in both smaller and larger projects. Although challenges have been found with regard to the scalability of agile working methods, a large number of respondents sees potential in introducing agility to development and production projects. In safety-relevant applications (e.g. in aerospace engineering) and mechanically oriented projects (e.g. special machine construction) the use of these methods is received critically. A large number of companies confirms that the transfer of agile models without adaptation to the characteristics of mechatronic development projects does not generate the expected improvements. For this reason, often only a reduced number of adapted methods is used (e.g. a Kanban board). Some surveyed companies emphasise that the use of individual fragmentary methods does not suffice to change the employees' mentality towards greater agility. ›

INFO 17 **Agility in engineering**

Agility is a characteristic of organisations or persons able to react flexibly and proactively when change occurs. In the context of product development, agility describes the ability to implement situation- and needs-oriented adjustments to activities during an unplanned event. In this way, the benefits for the customer, user and provider are increased in a targeted fashion [AHM+19]. This is promoted by an interdisciplinary, flexible conjunction of development teams and the iterative design of incremental stages in goods and services [HOF18].

One widespread agile method is the Scrum framework that has arisen from software development. The goal of this framework is to deliver and assess partial functions (product increments) at fixed intervals (sprints). During a sprint, a tangible function is developed to have the highest possible customer value. Transparency relating to project progress, the regular inspection of results and continuous adjustment by self-organised team is intended to increase innovativeness and allow quick reactions to changes in requirements [SS11].

Currently, a large number of surveyed companies is introducing or enabling agile methods in engineering. Cross-departmental introduction has been largely excluded, except in certain individual cases. At the majority of surveyed companies, the introduction is restricted at the moment to individual departments or incipient cross-departmental projects. A few describe agile work as the central requirement for the successful creation of future goods and services. For a large number of the introduction projects, the Scrum framework, as is or in an adapted form, was used. Extreme programming is one of the more infrequently mentioned alternatives. Specialised models from industry or academia of the process for agile mechatronic system development were not named by any of the respondents. Some companies are not currently planning the use of agile methods. The reasons these companies gave was that they lacked a systematic means of introducing them and special knowledge of the suitable software support. Here, there is a need for further research activities and intensive elucidation and support work within the companies.

In the analysis of the state of current capabilities, the following potential and expectations were described by the surveyed companies:

Faster project development: Many respondents expect the introduction of agile methods to lead over the long term to faster product development structured by iterative working cycles.

Improved collaboration and communication: A large number of respondents associated work in interdisciplinary or cross-functional teams with agile processes. Against this background, it is expected that exchange between employees with different abilities and varied backgrounds should help collaboration beyond the boundaries of the department.

Improved transparency in planning, documentation and commitment: A large portion of the respondents expects transparent planning, structuring and documentation of individual work assignments within the project to be achieved by the frequently used scrum framework alongside an iterative and incremental process. Through regular approval meetings between the teams, customer representatives and project leaders, commitment should be increased.

Increased speed of reaction and continuous improvement: The respondents expect continuous improvement in work by covering successes and failures in regular feedback meetings. Through work at short intervals, there is the option to react to changed frameworks and conditions, such as the expanding of a product function, without delay. A large number of respondents expects this to lead to faster, more flexible reactions to changing customer or market conditions.

Alongside numerous potential benefits, the introduction of agility is connected with internal and external hurdles for the company. The central challenge, according to many respondents, is the comprehensive change management needed and the restructuring of existing relationships.

Selecting and adapting suitable processes and tools: A large number of companies surveyed is faced with the challenge of selecting a suitable agile method or model and adapting it to specific conditions within the company. At the same time, many respondents emphasise that introduction projects should not be limited to the implementation of new IT systems for agile working (e.g. agile task management). Against this background, approaches to selecting suitable models for action and IT systems that particularly consider the characteristics of developing complex, interdisciplinary goods and services should be researched.

Adapting the organisation to the project environment: A large portion of the surveyed companies confirms that there is no general model that can be applied without adaptation to various organisational forms and sizes, as well as to the specific project environment. For this reason, many respondents see adaptation as a decisive factor for the introduction of agility. The processes and methods have not to date, according to the respondents, been sufficiently able to transfer from theory to practice. The development of suitable approaches for systematic selection and adaptation by researchers can support the introduction work. Here, in particular, the different speeds of development and durations of life cycle must be considered. According to some companies, the determination of timeframes such as sprints leads to challenges particularly in interdisciplinary teams from hardware and software development. Prioritisation approaches for the selection of the functionalities to be supplied during a sprint have not yet reached maturity in the field of complex technical systems. Against this background, approaches must be researched enabling companies to combine dynamic method blocks to form a suitable system development approach for the required project situation.

Internal and external acceptance: With the introduction of agility, similarly to the introduction of Systems Engineering (SEE SECTION 4.3.4), changes are expected in the way work and the organisation are structured. According to a large number of the surveyed interview partners, agile collaboration is usually interdepartmental. In agile collaboration with customers and other companies in the value-creation chain, the respondents see greater barriers. Often, there is a lack of acceptance and methodological and tool support. There is a need for research to achieve a structured approach to agile collaboration within a value-creation network. A further field of research, in this context, is the development and design of agile contracts.

For successful agile work, according to many respondents, the existing corporate culture and the value-creation chains developed over decades must be considered. Acceptance for agile approaches and the connected changes in work processes must be anchored at all levels of the company. In part, markedly increased self-organisation and -discipline are expected in the methodological implementation. Also decisive are the required competences such as flexibility and communication and having an understanding for the division of roles attendant on agility. ›

Agile Systems Engineering: As agile approaches are increasingly being tested in the development of mechatronics systems and introduced in isolated cases, more and more companies are detecting synergies in a combined deployment with Systems Engineering. Here, the companies use Systems Engineering as an abstract approach to the development of complex goods and services and agile approaches in operative process design. While Systems Engineering, according to the surveyed companies, supports thought and action to handle high complexity, agile team structures and processes allow high flexibility and the continuous validation of development results at differing degrees of maturity on the basis of early prototypes. Although some respondents report initial success in the combination of methods, agile Systems Engineering is not yet widespread. Against this background, there is a need to identify and address potential contradictions, obtain synergies and determine the mutual integration of agility and Systems Engineering to a suitable level. An initial approach in this context is offered by agile systems design [AHS+19].

Agility in engineering: Agile processes demand communication and cooperation in engineering – within the company and between companies. Certainly, there is presently a lack of models allowing the large-scale adoption of agility. In addition, agile working methods still need to be adapted to Systems Engineering.

The majority of companies is currently planning or assessing the use of agile processes. This introduction is as a rule restricted to individual teams, departments or projects. At a large number of firms, the Scrum framework is being adapted and put to use. With the introduction of agility, there is an expectation born of experience that the agile work processes will promote communication and cooperation in engineering. Furthermore, the companies expect improved transparency in the planning and documentation of the procedure and the increased commitment to work results. Transparency and regular feedback should lead to continuous improvement. Finally, the agile process should enable the company to react more speedily and flexibly to changing customer and market requirements. The restructuring of existing working methods connected with this leads to a large number of challenges. The existing models and tools are reaching their limits. At the same time, there is often a lack of acceptance at all corporate levels and in intercompany projects. There is also a lack of systematic models for how to introduce agile work processes in companies in order to satisfy the requirements of the organisation (e.g. scalability across many development departments) and live up to the project environment (e.g. interdisciplinary products). Against this background, it is necessary to identity synergies with Systems Engineering and use them.

4.4.2.2 Creativity management in engineering

Creativity management is a catalyst for innovation, both supporting the creative discovery of technical solutions and allowing their economical implementation. It rests on the ability to systematically create new, original ideas by linking together existing knowledge. This knowledge, in this context, could include conceivable market developments, future technologies and business models, innovative technical solutions to problems and concrete customer functions. People are a central element in the development process here. Creativity methods give them a systematic process, recommendations for action and guidelines helping them to leave behind their habitual thought processes and development paths and further improve good ideas.

The majority of the companies surveyed shares the view that creativity as an employee skill can be promoted and that there is no contradiction between creative and analytical thought. Although a large number of the surveyed companies barely or never uses creativity technologies in daily business, it is a common expectation that giving free space for creativity when organising work improves innovative potential. In this context, and although the companies surveyed here have a different culture and history, the successful methods of pioneering companies from the innovative ecosystem of Silicon Valley are often mentioned. For example, some companies offer their employees the opportunity to work on developing their own new creative ideas at set times during work. If the outlook for success is good, these employees are sometimes given further resources to aid in implementation.

Although the relevance of having free room for creativity is recognised by many respondents, models reflecting this are not yet widespread among them. In this context, some respondents report that freeing up employees does not lead to the desired success alone, as they continue to use their free periods for operational activities. Against this backdrop it becomes clear that the transfer of creativity measures without adaptation to the given limiting conditions is in no way expedient. Research must be carried out into how the successful approaches of successful digital companies can be transferred to other fields of work with different basic preconditions and values.

With regard to the targeted use of creativity methods in engineering, opinions among the respondents differ. Some companies see no need at present for the use of special methods. Even the offer to employees to use work hours and spaces for creative work would stimulate them to find creative solutions. Other respondents suggest that an excessively systematised process in part generates a perverse effect, with creativity techniques thus better indirectly integrated within existing approaches. In some companies, the use of creativity methods is already established and employees' perception of them is incredibly positive. Named methods include e.g. brainstorming, brainwriting, method 635, mindmapping and design thinking (SEE FIGURE 18; INFOBOX 18). Particularly favoured is the method of design thinking in combination with Systems Engineering.

INFO 18 Design thinking

Design thinking is a creativity strategy used to solve complex problems in a customer-focused way and turn up original ideas. Design thinking is an iterative process with six phases and is used in many sectors. Particularly in the field of complex interdisciplinary systems, design thinking can support the handling of uncertain changes in requirements and chaotic problems, in order, say, to identify customer needs. For the development of Advanced Systems, it appears beneficial to approach solutions combining Systems Engineering with a process modified on the basis of design thinking. In this way, e.g. a development contract can be analysed for feasibility. The effects of design thinking can also be used for the targeted and continuous definition and answering of questions at varying levels of detail along the development process. With this process, the complexity of development tasks can be reduced, and their ease of handling increased. [NM19]

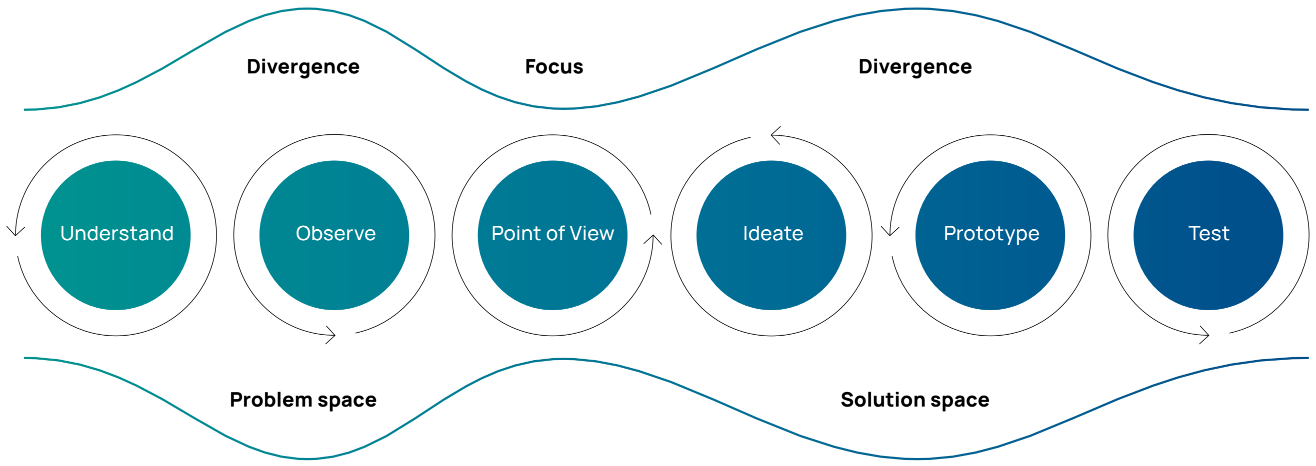


Fig. 18: The six phases of design thinking based on [NM19]

Alongside the lack of systematisation in creativity management, the successful use of creativity methods breaks down, according to many respondents, because of the lack of employee acceptance and insufficient support from management. Against this background, many respondents describe a situation where creativity methods sometimes need intensive, moderating support. An example given is the LEGO SERIOUS PLAY® method, with which discussions and problem-solving approaches are supported. Participants are encouraged through questions to approach a previously defined topic in abstract. On the basis of these questions, each participant builds a physical model using which, in the subsequent discussion round, the answers to the group's questions can be answered. According to the surveyed companies, there is a challenge in the fact that these methods fail to convince employees or overtax them if they are not given systematic instructions. Against this background there is a need to research suitable creativity methods in the development of complex interdisciplinary systems and to provide suitable approaches for educating and convincing trainers and coaches within the company. Some respondents here name the SPALTEN problem-solving model (SEE [ARB+16]).

To promote creativity in product development, many respondents say there needs to be a change of mentality among both managers and developers. The respondents in part confirm that creative thought is not inherent to employees' activities. Overcoming historically conditioned, stringent modes of thought and action is also described by some interview partners as a central challenge. To enable a change of mentality, companies are trying out creativity-promoting infrastructures. The surveyed companies expect more options for innovation design to arise outside daily operations. Against this backdrop, several companies have set up digital labs or innovation hubs alongside their existing offices. With the aid of modern equipment and validation methods, new ideas can be tried out in these environments without extensive costs. To do so 3D printers, IoT kits and building materials for prototyping are used. As a large number of the surveyed companies does not have suitable infrastructure for this, external provision is in part used. Alongside workshops, the surveyed companies are increasingly aware of events like hackathons and makeathons (SEE INFOBOX 19). These are both used within companies and organised together with universities or other companies.

INFO 19 **Makeathon**

A makeathon is a collaborative event used to generate ideas. With instruction, various teams seek to draw up the most creative solutions within a given time period towards solving a particular tasks. They can last from a few hours to several days. The teams in the workshop are interdisciplinary and work together to finding an approach to the problem. Here, techniques such as brainstorming are used. In a makeathon, not only programming tasks are dealt with, but also the general development of creative solutions for technical problems. In comparison to a hackathon, at a makeathon the focus is more strongly on the implementation of ideas and their validation through initial prototypes. [AWR+19]

Creativity management in engineering: Innovation rests on creativity. Although this is well known and there exists a wealth of creativity techniques and convincing success stories, creativity is still a side issue at many companies. This means great success potential remains unexploited.

Creativity leads to innovative goods and services. This relies on recognising the creativity potential of an organisation and systematically exploiting it. Although companies basically share this opinion, when turning to the targeted use of creativity methods in engineering, the picture is less unified. A large number of companies barely or never uses creativity techniques. Despite the known relevance of creative space, the required infrastructures and working hours models are not yet widespread. To promote creativity in product development, there needs to be a change of mentality among both managers and developers. This could raise levels of acceptance. The wide range of creativity techniques that have proven themselves in practice is a positive sign – these include, say, design thinking and creativity workshops such as makeathons. Here, the challenge is to use the best technique for the specific use case.

4.4.2.3 Product Generation Engineering

The switch to Advanced Systems promises extensive potential for innovation through the introduction of new product features or supplementary, data-based services. This results in a large number of different product versions and generations whose release must be controlled by systematic planning and development processes. The task here is to support the design of life cycle-compatible product platforms, support for models in the existing product portfolio and the development of new product generations. With the model of PGE (Product Generation Engineering), product development can be described and suitably structured (SEE [ABW15]). The development of a new product generation is based on already existing solutions that form the components of the reference system. These solutions include e.g. the company's own predecessor products and prototypes, but also systems from competitors or products from different sectors. The reference system here corresponds to the totality of elements forming the basis for the development of a new product generation. [ARS+19]

An advantage of trans-generational planning in the development of new products, according to some respondents, is risk minimisation in development and the ability to distinguish oneself from the competition. According to certain respondents from academia, a product generation with a large amount of new development involved is often followed by a generation with a lower new development content. This allows relevant differentiation characteristics to be identified, varied, reworked or transferred to the following generation. This permits validation expenses to be shared among several generations.

Approaches to MBSE can help with product development (e.g. in analysing the reference system). At the same time, the description of the previous product generations, according to some respondents, allows the comprehensive introduction and implementation of MBSE in companies. The development of a new generation of technical products requires a consistent, methodical process between strategic product planning and development. Some respondents ascribe particular potential to the integrative, strategic planning of product generations, services and production systems. In this way, the economic planning and realisation of a product range with networked product lines can take place over a space of time and several generations.

A relevant field of research named here is the interplay of trans-generational development with agile approaches. In particular during the development of complex Product Service Systems, realisable increments can be defined with the aid of PGE. A reference system made up of predecessor products can give the involved developers a starting structure and a basis upon which the agile approaches can be implemented in a targeted fashion.

Product Generation Engineering: A consistent understanding of product development as PGE – Product Generation Engineering – supports the efficient and effective design of development processes.

The increasing number of different product versions and generations and their releases can be described, structured and controlled using a systematically integrated planning and development process (e.g. the model of PGE – Product Generation Engineering). This offers advantages with regard to risk minimisation in development activities, the reduction of validation expenses and new options for competition differentiation. Although the models and potential of cross-generational development have been drawn up academically, these approaches have not yet become sufficiently established in practice.

4.5 Effects of Advanced Systems Engineering on the organisation and the people in the overall sociotechnical system

Against the backdrop of developments described here in both Systems Engineering and Advanced Engineering, product development now finds itself in a process of continuous transformation, in order that the challenges in the design of Advanced Systems can be met. The strategic orientation of the organisation and its engineering expertise play a decisive role in developing sustainable innovative goods and services and the application of technologies that benefit companies financially (SEE INFOBOX 20).

With regard to future forms of Advanced Systems, there is a need for research into suitable organisational models and their processes, roles, tasks, IT tools, powerful methods, and new forms of collaboration for digital and agile cooperation. This requires the creation of a viable engineering strategy, integrated into company management alongside existing product, technology, and innovation strategies.

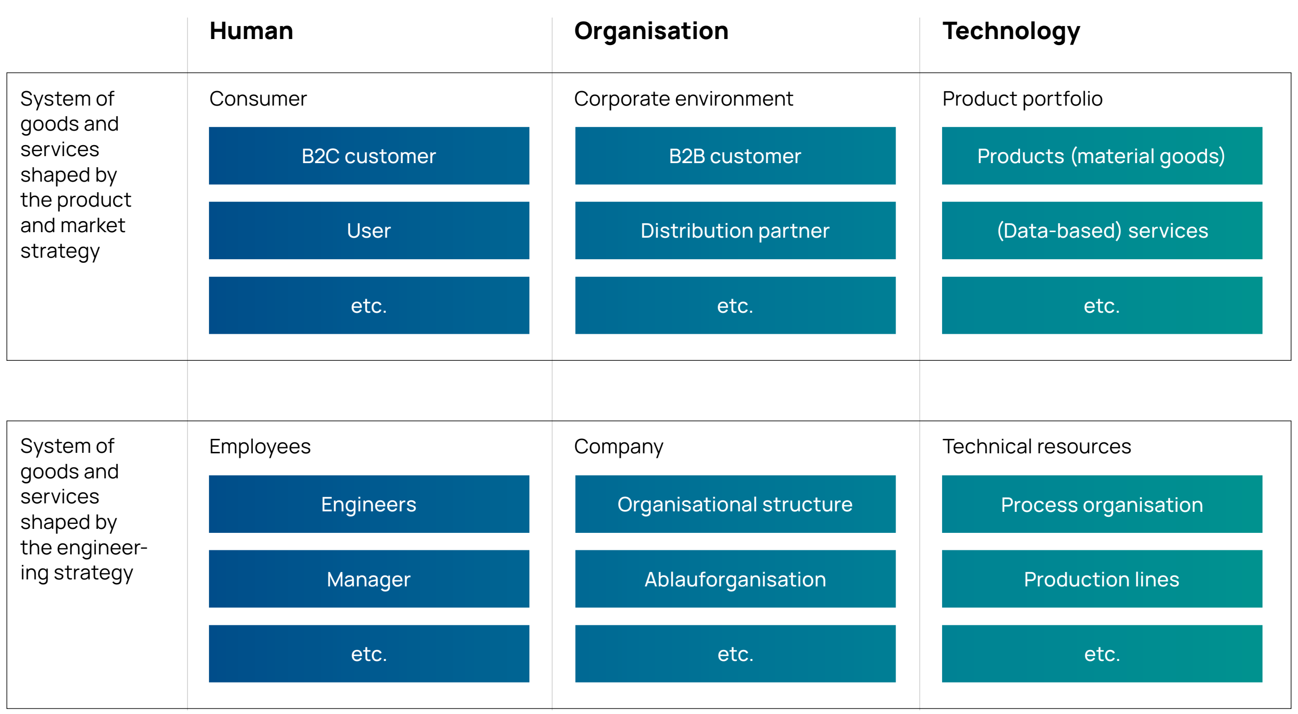


Fig. 19: Classification of goods and services and its emergence in the overall socio-technical system

INFO 20 Engineering as a sociotechnical system

A sociotechnical system refers to the interaction between an organised group of people (e.g., users and employees) and technologies (e.g., IT systems) [ROP09]. Different parties work together within and across companies to develop goods and services. A sociotechnical system can therefore be, on the one hand, the result of a development process (a market performance system) and the organisation of the development itself (market performance development system). There is a close dependency between the market performance and the organisation of the development. This can be seen, for example, in the direct relationship between the complexities of the two systems. An interdisciplinary market performance obviously also requires an interdisciplinary development process in which the mutual relationships between the components and the responsible departments or employees increase in significance.

In this context, the alignment of development processes and the associated work organisation is becoming ever more important in engineering. The investments and efforts made in the design of goods and services must be harmonised with the effects on the organisation and people in the overall sociotechnical system. This must be considered in any new services or business models (SEE FIGURE 19). Initial approaches to support this transformation process have already been described in previous sections.

The following topics were highlighted with reference to the status quo:

- Organisation in transition (SEE SECTION 4.5.1)
- The human aspects of engineering (SEE SECTION 4.5.2)

4.5.1 Organisation in transition

An organisation is usually understood to be a formal set of rules in a sociotechnical system based on the division of labour, through which people's goal-oriented work is achieved. Business administration theory traditionally distinguishes between a structural and a process organisation. Advanced Systems and their development continuously require and promote the creation of new concepts in organisational and work design.

The following subject areas were examined with reference to the performance level:

- Change in organisational structure and culture (SEE SECTION 4.5.1.1)
- Collaboration in engineering (SEE SECTION 4.5.1.2)

4.5.1.1 Change in organisational structure and culture

Looking at the change to Advanced Systems and associated requirements, companies are now operating in a market environment that is more volatile than ever before. Many of the organisational structures that remain widespread today have not yet been adapted to this environment. This is why many companies are faced with the fundamental challenge of bringing about the required reorientation of the organisation, its methods, and its processes in line with day-to-day operations.

Individual interview partners described the current organisational structure as a classic hierarchy with an isolated line organisation. A transformation of the organisation linked to the introduction of flat hierarchies and cross-functional working structures is therefore required (SEE FIGURE 20). The focus here should be on the organisation's orientation towards overall end-to-end business processes in order to coordinate the processes with each other and align them with the goal of meeting customer needs in the best possible way. An end-to-end process ranges from identifying customer needs through to the provision of services. It is usually cross-departmental.

This comprehensive transformation requires a lot of effort and presupposes a willingness to change on the part of employees and managers. Individual interviewees have described this as being critical. A fear of change and a lack of willingness to take risks generally inhibits the ability of a company to innovate. According to many respondents, it is therefore necessary to involve employees in the transformation process at an early stage, in order that they can help shape the changes. The employees affected by such changes must be given a degree of security and confidence. Furthermore, the transformation processes require strong management support and must be run holistically and in a coordinated manner. Some of those surveyed identified the greatest resistance was in middle management, as this is where the greatest changes lie ahead, due to reorganisations into a flatter hierarchy. A large number of respondents also noticed that the synchronisation of various working methods and different iteration cycles in the specialist disciplines presented additional challenges. The changeover to end-to-end processes means a departure from classic optimisation activities in individual departments, an approach which has been well established in many companies over a long period of time. Here, organisational approaches need to be developed that support and accompany the transformation of companies in working with Advanced Systems Engineering principles.

Most of the interviewees ascribed great importance to establishing an open corporate and no-blame culture with transparent communications. The increasing transparency that results from the digitisation of processes can also present a challenge for employees. It allows possible faults to be identified and assigned more quickly.

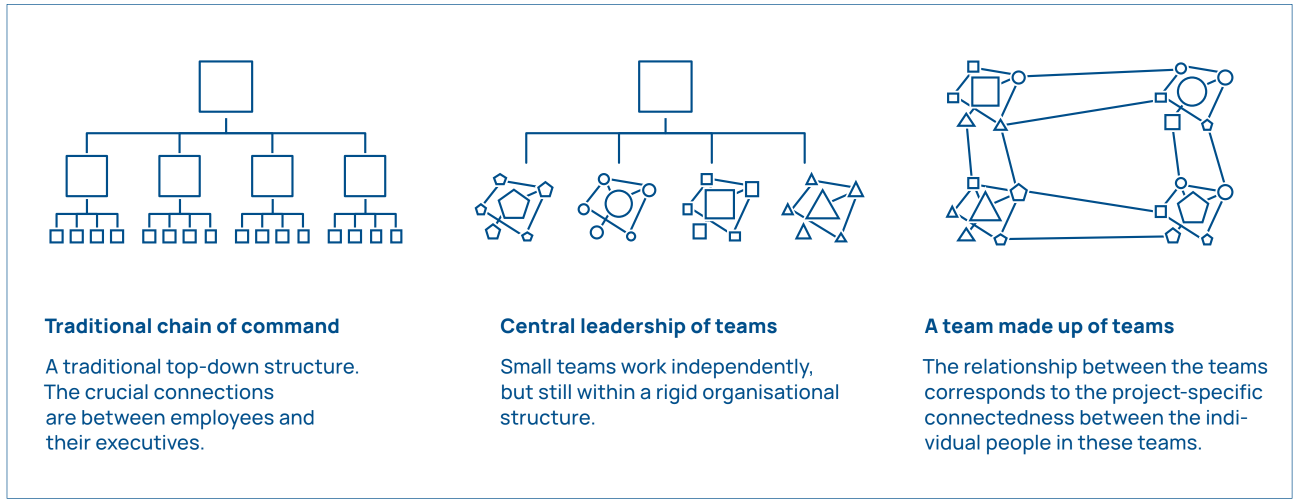


Fig. 20: Change of the established organisational structure towards cross-functional teams of teams based on [MCS+15]

The companies surveyed emphasised that, in this context, appropriate measures are needed so that the corporate culture counteracts the feeling of being monitored. The majority of those questioned consider that corporate culture plays a central role in the acceptance of change. Here, according to many interviewees surveyed, both the clear assignment of responsibilities and companies placing a high level of trust in their employees are just as important as good self-organisation and personal responsibility on the part of employees themselves. Some companies stated that engineers increasingly want to work independently of their location and be as flexible as possible in terms of working hours. At first, companies expected that a reduction in working hours could increase employee motivation with the same working performance and quality of results.

According to individual interviewees, although on the one hand ambitious young employees often place too much emphasis on their work, on the other hand there is a noticeable trend towards the merger of the worlds of work and life (work-life blending). The associated independent action and independent setting of work rhythms present globally distributed engineering organisations with new challenges. In particular, distributed teams currently use firmly defined agreements regarding the exchange of information. Furthermore, the formalisation and increasing necessity for method-supported procedures should be continuously questioned. According to several respondents, there is a fine line between being forced to use methods that hinder creativity and the required specifications that have to be considered in a company-specific design. Most employees perceive offers such as childcare, leisure, health insurance and a well-functioning infrastructure to be standard.

Change in organisational structure and culture: Dealing with engineering complexity requires forward-thinking staff, a high level of cooperation, plus thinking and acting in end-to-end processes. In most companies this also means further developments in the corporate culture. Experience has shown that this requires both time and perseverance.

Many companies find themselves in a phase of reorientation as regards the organisational structure of engineering, during which the aim is to introduce flat organisational structures and a change from function-oriented to process-oriented working structures. The establishment of an open corporate and no-blame culture with transparent communication is assigned a high level of relevance. Furthermore, there is greater focus on the role of corporate culture as a basis for promoting creativity and collaboration. The prevailing opinion is that the far-reaching changes in engineering must go hand in hand with further development of the corporate culture, encompassing all management levels and exemplified by the top executives themselves. The management must be aware that a change in corporate culture requires a lot of time and a high degree of persistence.

4.5.1.2 Collaboration in engineering

To successfully create added value, competencies and experience must be brought together within and across the company. This goes hand in hand with increasingly dissolving traditional departmental or branch boundaries. This creates new forms of partnership and organisation. The effects identified by Advanced Systems Engineering in relation to collaboration within engineering can be differentiated into 1. In-house collaboration and 2. Collaboration within value networks (SEE FIGURE 21).

Collaborative work is a central aspect of a company's economic success. In a cooperation, companies, teams or employees work asynchronously on different subtasks of a result, such as market performance. However, not all cooperation partners are involved in the end result of a project and do not necessarily pursue a common goal. In a collaboration, on the other hand, the partners work both in parallel and together on a part of the end result. At the same time, the partners in the collaboration pursue a common goal.

In-house collaboration

In view of the increasing complexity of development in particular, many respondents see an increased need to intensify their collaboration within the business. Some respondents confirmed that the mechatronic system development is currently equivalent to a cooperation with strictly separated partial results. As yet, no mandatory cooperation in the form of collaborative development has been established. In this context, the respondents emphasised that, from the customer's perspective, a global optimum is difficult to achieve with the current approach, as long as individual departments exclusively strive for the best solution in a discipline-specific manner. Against this background, several respondents see collaboration, including a common language, as a key prerequisite for the interdisciplinary development of Advanced Systems. To achieve a common understanding, employees increasingly have to communicate using common mental models (SEE INFOBOX 21).

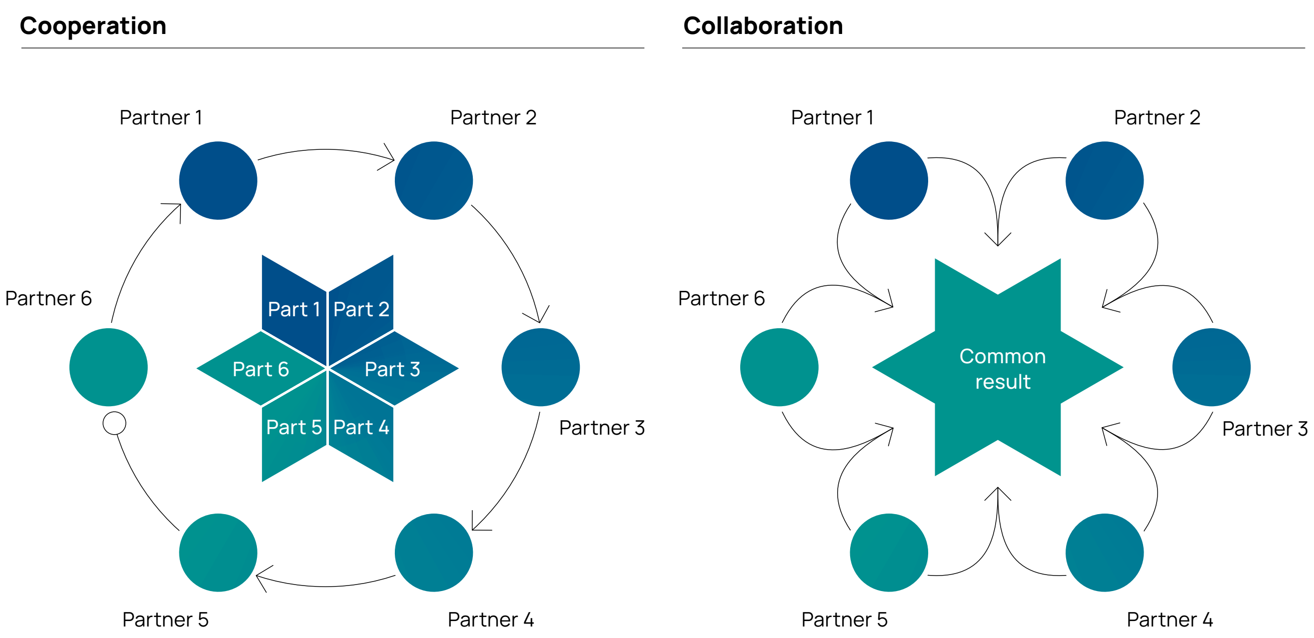


Fig. 21: Cooperation and collaboration in engineering projects

INFO 21 **Mental models**

A mental model is a representation of an object or a process, with the help of which tasks and problems can be solved by looking at the object as an analogy. Mental models are of great importance for solving problems, as they contribute significantly to the understanding of a complex system [MOS03]. Mental models are also of great importance in product development, so that increasingly complex technical systems can be understood. They build up a basic understanding of product development based on thought and description patterns and ontologies. Mental models are particularly relevant in communication. With their support, an intersubjectivity and a common language can be created, which then contributes to a common understanding of the problem [MEB08].

According to many respondents, the existing line organisations will be dismantled as a result of the requirement for interdisciplinary development work. Distributed working is also gaining popularity. Employees must be able to work together in different teams that are in different locations. Some respondents also called for a strengthening of the cooperation between the system development work for products, services and production.

These developments require increased communication across locations. A large number of the companies surveyed have already introduced communication and documentation systems with suitable IT infrastructure. Microsoft Teams has seen a big boost as a result of the COVID-19 pandemic. Knowledge management systems with wiki functionalities, communication platforms and task management systems were frequently mentioned.

Some respondents criticised the current developments in collaboration tools. The large number of communication channels that are used in parallel (e.g., chat, telephone, video conferencing, email, etc.) can make communication much more difficult and important aspects of it are not documented in a structured manner. Currently, there is a lack of methodical procedures for structuring the interfaces between collaboration options and approaches to documenting the relevant decisions. Individual companies are asking for a cloud-based collaboration system that addresses all activities within an interdisciplinary product development at the process and data level. Other individual respondents emphasised that current solutions such as “social intranet” platforms do not meet product development requirements.

Collaboration within value-adding networks

According to many interviewees, collaboration within value-adding networks is a success factor in the design of complex technical systems. In a collaboration which has the goal of a common market performance, each partner can concentrate on their core competencies and contribute their experiences to the development process. Individual respondents have already had positive experiences with merging companies together in a joint venture. Other companies surveyed emphasised that cooperation with suppliers and customers is not yet sufficient and this remains an unexploited potential.

However, similar projects may require different framework conditions. All collaboration partners must be able to adapt to rapidly changing processes, methods, IT tools and information standards. Working in collaborative value networks poses new challenges in terms of safeguarding the properties of the common market performance This is because a consensus on the further procedure for quality assurance of the partners is needed in the event of undesirable behaviour. At the same time, heterogeneous IT system landscapes, IT infrastructures and interfaces as well as a lack of standards for data exchange formats lead to increasing the effort needed for integration.

The increasing use of agile process models requires a new form of work and organisational design in value-adding networks. In the case of an internal project with agile project management, company-specific specifications such as the sprint length can be defined. However, if the agile collaboration takes place across company boundaries, the forms of cooperation and communication take on new dimensions, as does the coordination effort. Individual respondents already want agile cooperation with their suppliers and customers. However, for successful cooperation, new approaches and models, and also contracts must be developed, for example addressing an agile acceptance. In the context of agile cooperation with customers, many respondents noted that the necessary input from the customer is difficult to achieve. An agile approach is only explicitly requested by the customer in individual cases.

Because of globalisation and increasing internationalisation, the larger companies in the survey have several globally distributed development locations. English will therefore continue to increase its role as a communication language in development departments. The first major corporations in the automotive industry are already changing their corporate language to English. In addition to different languages, the time difference and a variety of cultural influences make communication and collaboration more difficult. This can lead to misunderstandings. To master these challenges, a higher level of competence is required to achieve the globally distributed cooperation that is needed. In addition to globally distributed development locations, some respondents also described international cooperation with other value-added partners as an obstacle. Clearly, what is needed here is an “untidy” and political framework for international collaborations.

Collaboration in engineering: To a large extent, innovation is based on the “learning organisation” model, a common means of expression and common practices.

Successful added value requires collaborative, collective work and the merging of internal and cross-company competencies and experience. Collaboration in the development of Advanced Systems requires a common, interdisciplinary development language as well as a common meta-model for products, services and production systems. Appropriate methods and IT systems for in-house knowledge management and communication must also be established. Furthermore, best practices for processes, methods, IT tools and information standards must be identified and communicated in order to learn from one another and enable globally distributed development locations and cross-company collaboration within value-adding networks.

4.5.1.3 Cooperation between business and science

Almost all the companies surveyed welcomed cooperation with research institutions and in general highly value the potential for collaboration between science and industry. Many respondents expect that in the future, the importance of collaboration with regard to further technological specialisation and the increasing complexity of applications will continue to increase. However, existing potential is often not used as well as it might be. Some of the companies surveyed are clearly calling for new collaboration models or exchange programs to be established. Positive examples include the Future Work Lab at the Fraunhofer Institute's IPA and IAO or the research and development cooperation projects of the leading-edge cluster known as Intelligent Technical Systems OstWestfalenLippe (OWL). In such cooperation projects, a scientist works together with the employees of a company for a limited period of time on a specific task based on previous research results. The collaboration enables implicit knowledge and best practices to be transferred. At the same time, the mixed teams of scientists and local staff promote the development of innovative problem solutions. However, some companies surveyed emphasised that there were deficits with regard to application-oriented transfer concepts for technologies and methods. One success factor is that companies should have sufficient foresight in technology planning. On the other hand, it is important to initiate the transfer of results to the company during the term of the research project. From the point of view of the respondents, the different standards and evaluation metrics of business and those of science must always be considered. Although companies must take financial success into account, for many researchers gaining knowledge and the resulting academic reputation are centre stage. In joint projects, this possible conflict of interest should be confronted with open communication of the relevant goals and motivation. From a scientific point of view, the highest priority is to not undermine the principles of basic research and teaching. To achieve this, representatives from business and science must continue establishing a common research and innovation culture. According to several respondents, this requires new forms between companies, universities, colleges and research institutions. Infrastructures in which application-oriented common technology and method development is worked on together can form an important step in creating comprehensive innovation ecosystems.

Cooperation between business and science: Successful cooperation as the key to the successful transfer of innovations must reconcile business goals with economic and scientific goals

The respondents valued the collaboration between business and science and expect it will become increasingly relevant. Alongside existing successful examples of cooperation, there are occasionally calls for new models of collaboration or exchange programmes. When working together, one must consider the conflict between the goal of a business' economic success and that of the knowledge gained from research. This conflict of goals can, for example, satisfy innovation ecosystems in which collaborative and application-oriented work is carried out on technology and method development.

4.5.2 Personnel in engineering

When designing engineering, strategic considerations must be made with regard to employees and human resources. Forward-looking questions must be considered, such as "How will the role of the engineer change in the future?" and "Which skills and qualifications are critical to the development of tomorrow's products and services?" (SEE FIGURE 22).

Respondents from across all industries and different sizes of company agree that the engineer should continue to take the central role in engineering. His or her core task is to be a creative problem solver. However, in the future, greater attention will have to be paid to creating the appropriate freedoms for this to happen.

As part of the performance level, the following topics were highlighted:

- Roles in the engineering process (SEE SECTION 4.5.2.1)
- Skills required in engineering (SEE SECTION 4.5.2.2)
- Education pathways in engineering (SEE SECTION 4.5.2.3)

4.5.2.1 Roles in the development process

The change in value added poses a multitude of different challenges for both the economy and science. At the same time, the anticipated demographic change is causing a shortage of skilled workers in development departments and especially in critical areas such as software development. Against this background, competence and knowledge management are becoming increasingly critical success factors.

According to many of the companies surveyed, their employees must be able to work flexibly on various tasks and different activities. The competence profiles and tasks of these employees must be defined, clearly demarcated and understood across all levels. Some respondents see a need for research in this area in particular, expecting clearer guidelines for the individual role profiles (SEE INFOBOX 22; FIG. 23). The concept of roles is misinterpreted by several respondents. ›

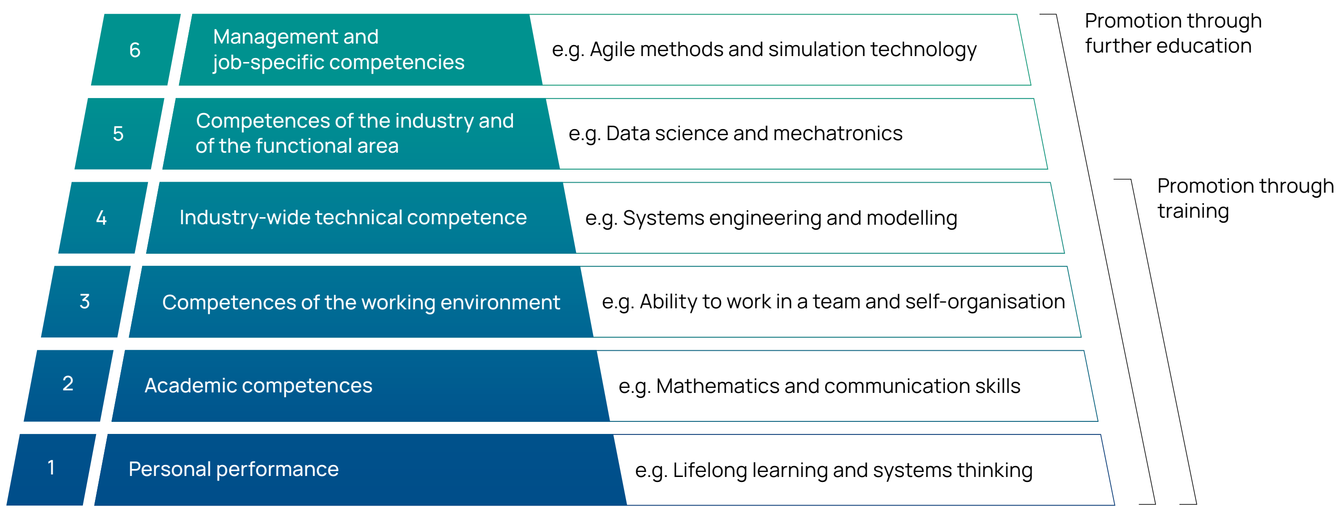


Fig. 22: Competencies in engineering based on [AYM18]

INFO 22 **Role**

Role is a frequently used term in everyday or professional life. It is defined differently when viewed from a social science perspective [ST14]. According to Broy et al., in the engineering environment the term role describes a specific function that a person performs in an organisation. A specific task and skill profile is defined for each role. Roles can also be exercised by individuals, teams and organisational units [BK13]. According to Schmidt et al. the role profile includes tasks, role expectations, responsibility, personality structure as well as competencies and skills [SJ20].

In the course of these phases, new role profiles will develop in addition to the existing ones. For example, they are responsible for an organisational interface function in order to coordinate the various disciplines or focus on the management of processes, methods, and tools (PMT roles). This will be particularly pronounced among OEMs in the automotive industry in their role as system integrators, as the trend towards outsourcing the development of subsystems to suppliers creates special requirements. Other new role profiles mentioned included the engineering IT manager, the engineering method coach and someone responsible for emergent properties at the overall system level. In addition, some interview partners are of the opinion that in the future, experts will also be required to have more expertise with regard to cross-system tasks.

The main problem is that there is a discrepancy between the defined and lived roles in a company and their actual range of tasks. Many respondents now no longer structure roles based on individual activities, but rather in a function-oriented manner. This has an influence on the competence profiles required. In addition, staff planning, the composition of the project team and the organisational framework must be adjusted accordingly.

The clarification of a role profile is particularly important when introducing new ones. By way of an example, the roles mentioned are those of product manager, innovation manager, scrum master or system architect. According to individual respondents, companies remain sustainable and competitive if they look at the tasks, roles and responsibilities and redistribute them. Even if there is openness, the necessary changes must be recognised and responded to in a timely manner. Due to the change in value added, the content of the role profiles is shifting, and new skills are required. Agile methods in particular require a completely new understanding of roles. With regard to these new roles, many of the companies surveyed are currently in a phase of definition or transformation.

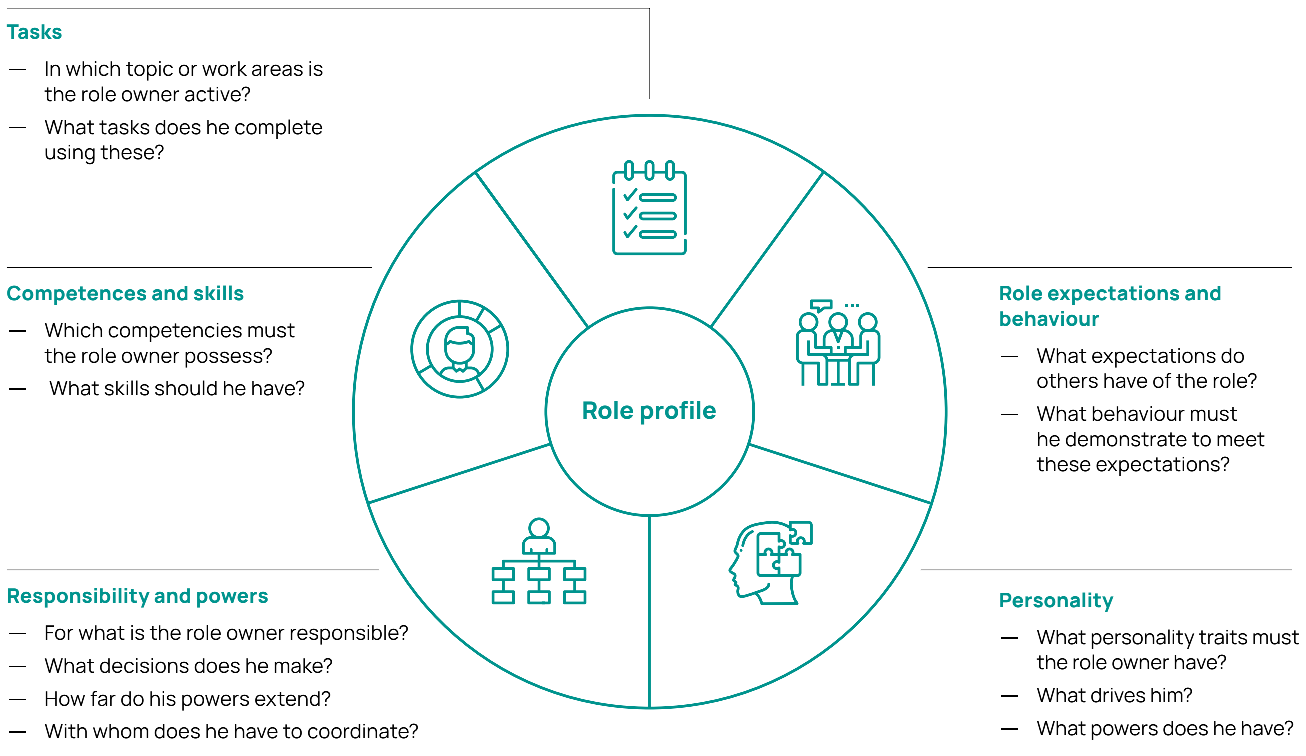


Fig. 23: Components of a role profile based on [SJ20]

Roles in the development process: The engineering environment is constantly changing. This requires regular readjustment of roles in the engineering process, which must be accompanied by situation-compliant personnel deployment planning and team nominations as well as forward-looking qualification planning.

In the future, the players in the development process will be employed in areas of activity that are increasingly changing and sometimes completely new. On the one hand, this requires a high degree of flexibility and willingness to learn on the part of the developers. On the other, it is necessary for the company to continuously introduce and consolidate the further development of new role profiles in engineering and the associated responsibilities. In this context, particular relevance is attributed to organisational interface functions in engineering and supporting staff units such as a coach for the management of processes, methods, and tools. In order to avoid a discrepancy between defined and lived roles, the personnel deployment planning, project team composition and qualification planning must be suitably adapted during the development process.

4.5.2.2 Skills required in Engineering

As a result of advancing digitisation and a change towards highly networked socio-technical systems, the requirements for the competence profiles of employees are changing too. Due to the complexity of Advanced Systems and increasing interdisciplinarity, a large number of those surveyed saw a greater need for staff with T-shaped competence profiles in the future (SEE FIGURE 24). In the future, engineers will more and more have to master the trade-off between having a deep technical expertise in a specialist discipline and an abstract understanding of the overall system. At the same time, several companies surveyed are calling for generalists who support model-based communication between the specialist disciplines in complex development projects, taking on a coordinating role. According to many interviewees from a science background, subject specialists with a pronounced competence in interdisciplinary communication using models form an increasingly central role in engineering.

In addition to the change in profiles, other skills are also increasingly required. A competence might involve the ability to solve problems whilst also being willing to do exactly that. The required competencies can be structured in technical, methodological, personal, and social competencies.

Technical and methodological competence: The companies surveyed will require their future employees to be technically savvy but with a solution-neutral understanding of the overall context. Discipline-specific and interdisciplinary knowledge is expected, particularly in the disciplines of mathematics, statistics, and software development. According to several respondents, the interplay of these competencies supports the ability to think analytically. Analytical thinking and systems thinking include, in particular, the ability to recognise, analyse and model a complex relationship with its structures and behaviour. According to some respondents, these are core competencies for problem detection and solution development.

In addition to knowledge in the area of software development, tomorrow's engineers should, according to many respondents, have additional IT-specific knowledge. Sub-areas of computer science such as a knowledge of algorithms, methods and procedures in data science are becoming more and more relevant. The specialist knowledge required relates to a basic understanding of the application, which results in particular added value with subject-specific knowledge. There is also an increasing demand for knowledge of simulation-based validation, agile procedures, and development methods as well as Systems Engineering and model-based development.

Many respondents demand an increasing understanding of the product, customer, and company context. In addition to an understanding of market performance, the empirical knowledge of the company's internal activities in the development process is relevant. Working as a technical expert in interdisciplinary teams requires systematic thinking and an understanding of context (SEE INFOBOX 23). With regard to interdisciplinary model-based development, skills are required with which, in particular, the interfaces between the disciplines can be clearly defined and described using overarching models. ›

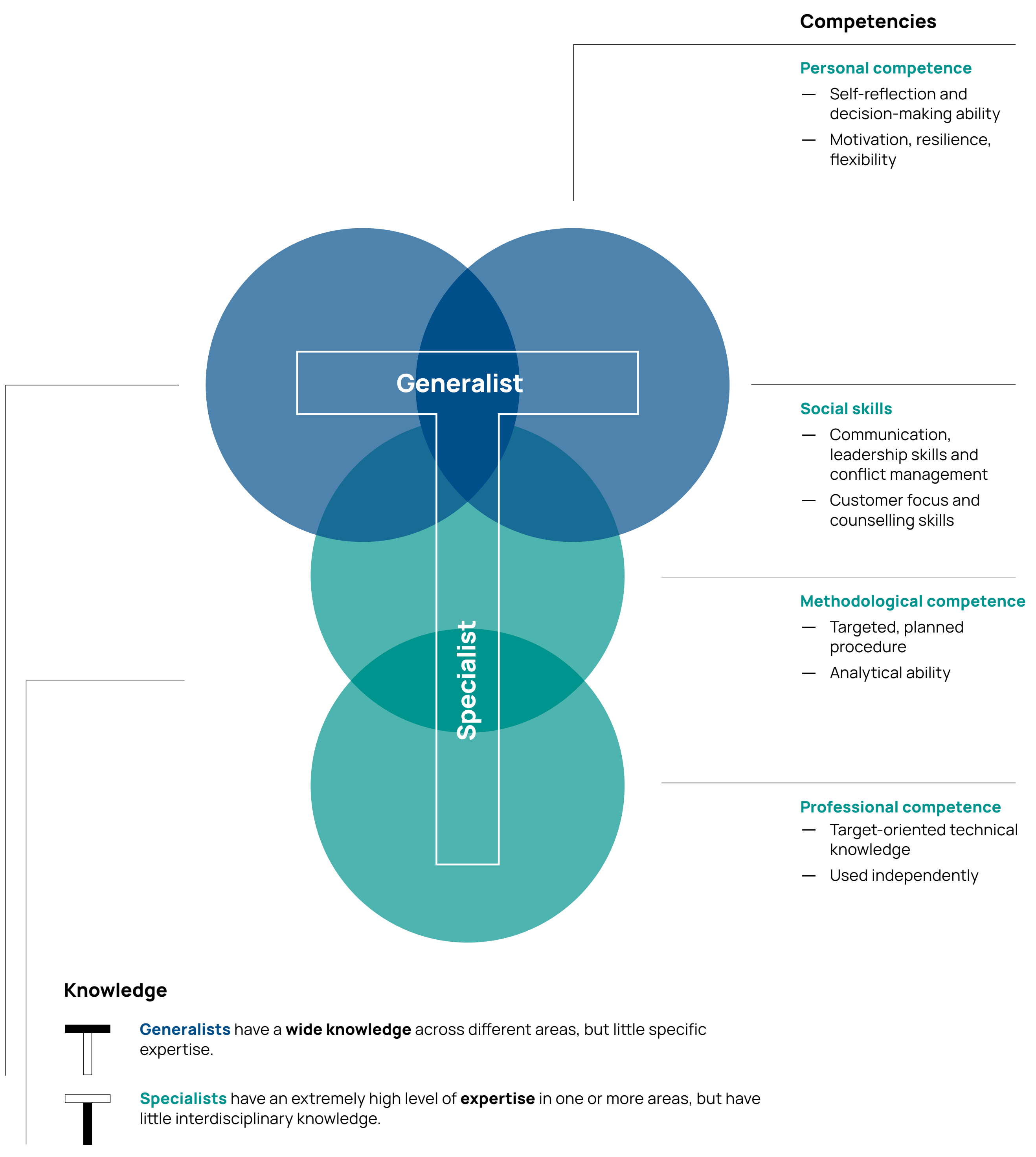


Fig. 24: Required knowledge and competence profiles in engineering based on [EHM+07; PB96; KAU06; HK07]

INFO 23 **Systems thinking - the holistic view of the system**

The aim of systems thinking is to visualise the complex internal relationships and interactions with the environment by using model-like illustrations. All relevant functions and sub-components are included by taking a holistic view of the system. Depending on the problem and the situation, different levels of abstraction are selected, depending on the usefulness and relevance of the problem [GDE+18].

Personnel and technical competence: In the opinion of many respondents, in addition to communication skills, employees should above all demonstrate good self-organisation and a high level of intrinsic motivation. Furthermore, according to some, companies require every employee to familiarise themselves quickly and constantly with any new specialist topics. They are also expected to be willing and open-minded to act as specialists within an interdisciplinary team. Although interdisciplinary cooperation is already taking place in many parts of the company, many respondents believe this will increase in the future. Due to the close interlocking of hardware and software functions in products, development teams must be set up in a more interdisciplinary manner in order to be able to map the knowledge required for the provision of a product function in a team.

Against this background, there is an increasing need to research future competency needs and further develop the competency models so that they can then be transferred to training and further education.

Required competencies: Players in the development processes for innovations will be challenged more than ever to master the conflict between, on the one hand, well-founded specialist knowledge in the subject area in question and holistic systematic thinking on the other.

The balanced triad of technical, methodological, and social skills is important more than ever before. In addition, the parties in future development processes will be required to master the conflict between being deeply technically adept in a particular discipline whilst also having a holistic understanding of the overall system. Systems thinking is becoming an outstanding key competence. The basis for this is to have a good understanding of the respective application context as well as the principle systemic solution approaches. Although the specialist disciplines involved are, in principle, of equal relevance, in the age of digitisation IT skills form a particularly critical role, especially in integrating cross-sector competence. Last but not least, social skills are of ever-increasing importance, including in particular communication skills and the ability to cooperate. Despite this breadth of new, and sometimes soft, competencies, it would be a fallacy to conclude that well-founded specialist competencies are anything other than vital in the establishment of a complex system. “Soft” competencies do not replace “hard” competencies. This means that players in the development process will be challenged more than ever to buttress their strengths in well-founded specialist and methodological knowledge with “soft” skills.

4.5.2.3 Education pathways in engineering

Targeted measures need to be implemented in both training and further education in order that staff have the necessary skills for future development processes. For this reason, as regards performance status, the question of whether the current education system and professional training meet emerging requirements has been raised.

Education

Looking at the technical and methodological skills required, many of the companies surveyed saw a potential for improvement in university graduates. According to the interviewees that came from academia, engineers of the future should develop a broad understanding of interdisciplinary communication during their studies. Individual respondents wanted the courses to be more practical. The respondents rarely considered the fact that teaching at universities follows different goals to those at technical colleges. There is a broad spectrum that runs from a scientific education to an education which aims to directly provide students with employment in businesses. Furthermore, many interviewees emphasised the ever-growing importance of social skills such as communication skills within teams or interdisciplinary environments. Here many of the respondents found deficits among graduates.

The number of graduates available is also a challenge for business. Some of those surveyed who came from the world of science also described the increasing challenge of the downward trend in new students in technical courses . But while the number of mechanical engineering students in Germany is on a declining path, the number of students in courses with a high proportion of computer science is increasing. This is an important finding as it may, in due course, show up as a shortage of trained engineers in business and science (SEE INFOBOX 24).

INFO 24 **STEM Young Talent Barometer 2020**

The 2020 STEM Young Talent Barometer from acatech (the German Academy of Science and Engineering) and the Körber Foundation shows that efforts in Germany to improve STEM education and encourage more young people to study the natural sciences and technical subjects are not working well enough. The interest and performance of students in these subjects is decreasing; a third of the young people surveyed lack basic computer-related knowledge and skills. The recommendations for action in the survey included, among other things, an increase in the quality of both teaching and the teachers themselves. Digital education must be systematically embedded across different disciplines. Further recommendations for action can be found in the detailed report from the STEM Young Talent Barometer 2020 [AK20].

Several respondents agreed that to counter this trend the public perception of engineering sciences must be improved. To achieve this, schools should encourage an interest in technology at an early stage. Supposed stereotypes would limit interest in STEM subjects. In the opinion of individual interview participants from the world of science, imparting the basics of STEM at an early stage is a good opportunity to arouse student's interest in technology. The content should be supplemented by aspects such as systemic thinking and problem-solving skills. For this purpose, new competency models are to be developed on the research side and transferred into teaching.

The increasing number of courses with non-transparent or ambiguous names (e.g., data scientist, data analyst, data engineer) is a challenge for several of the companies surveyed, as in some cases the expectations raised by these new courses are not met. This increases the efforts made by the companies to find suitable employees and harbours the risk of vacancies being filled by unsuitable individuals. According to several respondents, the focus should be less on the development of new courses but rather on further developing existing, › established courses. Both from the point of view of both business and science, it is important to create a good and up-to-date combination of technical, methodological, personal, and social skills. The limited absorption capacity of students and the capacity of universities and colleges over a limited study period must be considered here. It is becoming apparent that teaching social skills may require new, capacity-intensive teaching formats. This needs to be researched.

A large number of the companies surveyed see the need for a significant increase in interdisciplinary activities during the period of study, such as a combination of thermodynamics and computer science. This might make it possible to create competencies in interdisciplinary cooperation at an early stage. This should also be combined with disseminating a distinct systematic approach. However, it should be noted that, according to respondents, students must continue to possess extensive specialist core competencies. As a rule, the respondents were unable to show how this conflict of goals could be resolved within the same study period. Some individuals demanded that students from different disciplines should work on joint projects a number of times. At the same time, individual respondents insisted that the faculty boundaries should take a back seat in order to facilitate interdisciplinary training.

According to statements by some interview partners from the world of teaching, universities and their faculties are very well positioned to impart specialist and systemic knowledge. The challenge, however, is to enable these specialists to work together successfully at the system level of the overall system and without major obstacles to communication. Integrating the teaching of this system competence into the basic course is needed. Other voices from large corporations continue to support the classic undergraduate routes of mechanical engineering, electrical engineering, and computer science courses. The employees would then build up the necessary specialist knowledge from other specialist disciplines in their first year of work in the company.

In the opinion of many respondents, important social skills can be gathered through teamwork and project work in semester-long periods. The focus here is on interdisciplinary communication, experience in project management or the learning of presentation techniques. Competencies in self-organisation for dealing with complex topics should continue to be shaped as well as systematic thinking and a sense of responsibility for the overall results of the team. Imparting these competencies can be achieved through, for example, case studies and project work in which different specialist disciplines are able to work together. Here, the previous schemes on offer at technical colleges and universities need to be expanded. Seen from the point of view of several companies that were surveyed, there is an expectation that universities will be establishing new formats in the curriculum. At the same time, they see the need as a company to get involved in collaborative formats, for example by offering exciting tasks or acting as partners during the processing. Voices from the world of research described the demand for a stronger focus on interdisciplinary training being plausible and understandable. Many business respondents sometimes see the university structures as being too conservative and insufficiently flexible.

The companies surveyed see a higher proportion of practical work during their studies as a lever to making it easier to get started in a working career. In their opinion, the exercises that accompany the lectures are not designed in to be sufficiently practical. A large number of the businesses surveyed recommended that students should do at least one half-year internship during their studies. This should also be provided for in the study regulations issued by the universities and be clearly structured. Likewise, theses and doctorates that address the problems within industry should be endorsed by industry more often. These demands from the interviewees in the business world cannot be readily met. Students of engineering disciplines who want to gain practical experience alongside their theses are sometimes held back by a lack of supervision on the part of the professorships. According to individual science interviewees however, it is exceedingly difficult for these professors to expand the range of supervision beyond its current status, since such collaborative work often does not offer the conditions required by scientific qualification work. In particular, economic added value must not be a condition of the work carried out.

Further education

Taking account of the fact that not all skills required for future development can be imparted solely through courses, it is important that suitable further training measures are implemented. When imparting new skills to employees and managers, the arrival of digitisation enables the formats and communication channels themselves to be redesigned. There has been a significant increase in digital offerings. The facilities for imparting knowledge are increasingly individual and also can made available at any time, so that the need for a merging of skills development and application can be met in everyday work. As a result of the increasing number of technologies and IT tools, many interviewees emphasised that it would be essential to adjust the competence profiles with their associated qualification measures on an ongoing basis. The progress of digitisation means that the need for such competencies is developing rapidly and in a highly individual manner. Situation and workplace-related measures are needed, ideally ones that can be seamlessly integrated into everyday work. The concept of on-the-job training is ideal for this. Staff can directly apply methods in everyday life that they have learned in training. Another concept is the formation of pairings of experienced employees with young staff, who are well versed in new technologies and who complement each other and can exchange their experiences.

Some interviewees from the science sector emphasised that the dynamic state of digital competencies in engineering represent a challenge for transferring knowledge successfully. As these competencies can only be imparted to a limited extent, using specific specialisations during education, further training must continue immediately after the degree course. This science-oriented lifelong knowledge transfer at the academic level can be offered and supported by the universities. To achieve this, however, there must be new ways to transfer knowledge at the universities after the degree.

External training providers are currently experiencing a great demand for their services, especially in the areas of project management, agility, and Systems Engineering. Several respondents did not see the need for certification in certain subject areas, such as Systems Engineering. Training concepts developed by and with suppliers, customers or IT system providers are also being used to an increasing degree. As regards the ways in which the learning content is being conveyed, both on-site training and e-learning platforms are in use. Large companies have established extensive internal training programs and monitor their staff's learning progress. Here, there is an emphasis on the balanced build-up of specialist, methodological and social skills.

Individual companies criticised the lack of success with existing qualifications. In some cases, the transfer of training content into everyday work is not possible. The respondents cite insufficient training content, or training content that is not tailored to the specific company, as the cause of this. Other respondents reported that companies often have the wrong expectations with regard to qualification measures in Systems Engineering methods and processes. The change in the organisation requires more extensive programmes, which can only be supported by further training measures. Individual learning paths must be defined in order to impart relevant skills to the staff. On the research side, the existing training concepts need to be analysed and optimised. In addition to further training courses organised and carried out according to plans set out by the HR department, a large number of companies surveyed also saw the employees themselves as having an obligation to develop their skills. There is therefore an increasing demand for employees who react proactively to new topics and spread the knowledge gained across the company.

Education pathways in engineering: In the field of university teaching, project work involving practical tasks that are worked on in interdisciplinary teams appears to be an effective means of using and deepening specialist, methodological and social skills. In addition, new offers could be used to create effective emphases in in-service training.

Training engineers requires the establishment of a comprehensive understanding of the importance of interdisciplinary cooperation and communication. For this purpose, teaching at universities should be continuously updated within an established specialist discipline using new teaching formats such as cross-disciplinary project work in teams where business problems can be further developed. Such formats aim to apply methodological skills to specific tasks and train social skills. At the same time, it is important to get more young people interested in technical sciences in order to counteract the emerging shortage of skilled workers at an early stage. Here new ways must be found that lead to the system design becoming more attractive.

Not all of the competencies needed can be imparted at the required level of maturity by studying alone. Practical knowledge and skills must therefore be imparted and tested in professional training. The training programmes must do justice to the dynamics of new technologies and methods as well as making the sustainable transfer of experience possible.

5 Engineering in an international comparison

The engineering of innovative goods and services in complex socio-technical systems plays a decisive role in future value added. The results of the qualitative survey (SEE CHAPTER 4) show the current level of engineering performance in Germany and the associated challenges. At the same time, the qualitative survey confirms that future products, services and systems and their development will be subject to major changes. The existing successes in innovation can only be sustained in the long term if companies are empowered to successfully shape future goods and services and successfully bring them to market. Against this background, it was found that the holistic design of future goods and services requires new approaches in the context of Advanced Systems Engineering.

When it comes to relevant future topics such as Advanced Systems Engineering, the question arises as to how well Germany is positioned compared to the global competition. International comparisons offer a guide, showing how ASE's areas of activity, and Systems Engineering in particular, have developed in recent years (SEE INFOBOX 25, FIG. 25).

INFO 25 Germany's position in innovation indices

Countries' innovative capacity in different categories is compared annually in different studies. According to the Bloomberg Innovation Index 2020, Germany is the most innovative country in the world. The Bloomberg Innovation Index analyses dozens of criteria based on seven metrics. Among other things, the level of expenditure on research and development, production capacity and the concentration of listed high-tech companies are assessed [JL20].

According to the innovation indicator from the Federation of German Industries, in 2020 Germany ranks fourth after Switzerland, Singapore and Belgium [FSF+20]. The evaluations included the five sub-indicators of economy (7th place), science (12th place), education (11th place), state (9th place) and society (12th place). Taking the average of various reports covering innovation indices, Germany has been in the Top 10 over the last 20 years. ›

Research and development activities in Germany form the essential basis of its innovative strength. Its position as innovation leader clearly shows that in Germany the process covering the steps from idea to market penetration of current products and systems has been mastered. In recent years, however, the global environment in which the innovation nations and science locations find themselves has undergone a noticeable change. Emerging countries like South Korea or Singapore are developing into becoming strong competitors. This is becoming increasingly clear by looking at the successes of these nations in knowledge-intensive topics such as electro mobility or artificial intelligence.

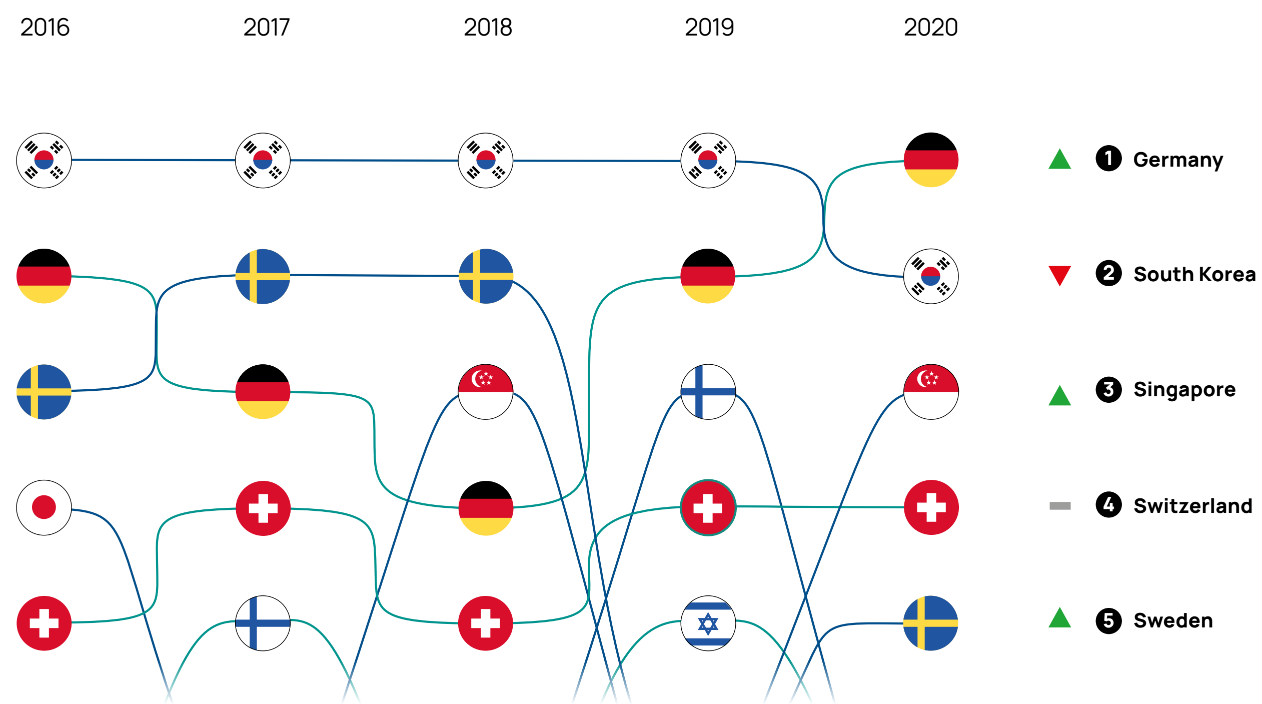


Fig. 25: Germany tops the list of the most innovative countries in a five-year comparison [JL20]

The basis of the quantitative key data collection is a multi-stage approach in a systematic literature search (SEE FIG. 26). In the first step, the distribution and penetration of Systems Engineering in research (e.g., by the number of SE publications) and teaching (e.g., by the number of SE lectures) in Germany and in those countries previously defined was surveyed and analysed in detail. In addition to this, the international performance level of Advanced Engineering in research was investigated based on topics identified in Section 4.4, such as artificial intelligence or agility. A final evaluation addresses the joint consideration of the two fields of action Systems Engineering and Advanced Engineering and offers a perspective on the need for action.

Methodical procedure: Engineering in an international overview

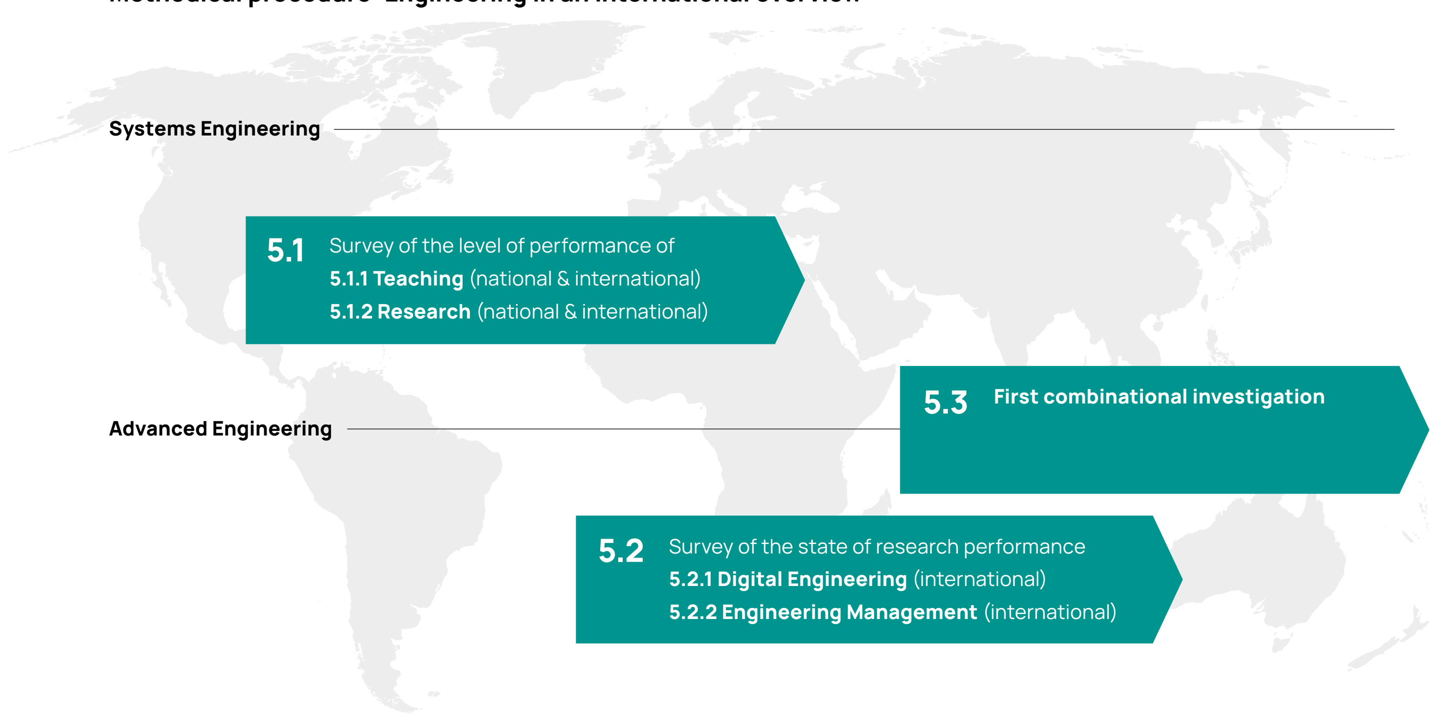


Fig. 26: Methodical approach of the quantitative survey of engineering in an international comparison

5.1 Systems Engineering

The qualitative survey underlines the importance of Systems Engineering in the development of complex goods and services. In addition to the interviews conducted in industrial practice and the academic environment, quantitative findings from research and teaching were derived by means of collecting key data. Using this survey, the current penetration of Systems Engineering in research and teaching at universities is examined both nationally and internationally.

To ensure comparability, a series of key figures was initially defined for the differentiated description of the penetration of research and teaching by Systems Engineering. These key figures were collected in various forms, both nationally and internationally (SEE TABLE 1).

Title	Description	National	Intern.
Teaching			
Number of universities	Number of universities with courses in which SE is a topic	X	X
Number of courses	Number of courses in which SE is a topic	X	X
Number of professorships	Number of chairs where SE is a topic	X	–
Number of lectures	Number of universities with lectures in which SE is a topic	X	X
Number of students	Number of students in courses in which SE is a topic	X	–
Research			
Number of publications	Number of SE-related publications p.a..	X	X
Number of citations	Number of citations of publications related to SE p.a.	X	X
Number of authors	Number of authors who publish on SE p.a.	X	X
Publications per author	Number of SE-related publications / number of authors involved p.a.	X	X
Number of conferences	Number of scientific conferences with SE relevance p.a.	X	–
Number of research projects	Number of publicly funded research projects with SE relevance p.a.	X	–
Conference contributions per conference	Number of SE-related conference papers per SE-related conference p.a.	X	–
Number of dissertations	Number of dissertations with SE reference p.a.	X	–

Table 1: Key figures for describing the penetration of Systems Engineering in research and teaching

5.1.1 Systems Engineering in teaching

Methodical approach to collecting key figures in teaching

National and international data sources were used to assemble the database needed to determine the key figures. For the key figures taken from the teaching sector, student statistics and module manuals from individual courses were used. The penetration of Systems Engineering in university teaching in Germany was initially investigated for the leading technical universities in the TU9 consortium. Here the data was from 2019. The dissemination of Systems Engineering at the level of courses, professorships and lectures was investigated. A lecture was always rated as an event relevant to Systems Engineering where the description of the lecture in the module handbook contains the expression "Systems Engineering". Courses of study and professorships were recognised as being related to Systems Engineering if they contained or offered at least one lecture with a reference to SE. Both the absolute numbers of degree courses, professorships and lectures related to SE and the relative number per 10,000 students were evaluated.

Systems Engineering in teaching in Germany

The evaluation shows that in 2019, courses of study and professorships related to Systems Engineering can be found at all universities in the TU9 group (SEE FIGURE 27). However, in absolute numbers, both the penetration of such courses, and when seen in relation to the number of students, varies greatly among the nine universities. The technical universities of Berlin, Braunschweig, and Munich as well as the University of Stuttgart have a particularly high number of SE-related courses, lectures, and professorships . These universities offer between 13 and 15 SE-related courses for every 10,000 students.

A similar picture emerges when looking at the relative numbers. Here too, the technical universities of Berlin, Braunschweig, and Munich as well as the University of Stuttgart have the highest relative proportion of courses with SE-related subjects among the TU9. At all four universities, this proportion is over 20% when measured against all courses offered at the respective university. When looking at the relative proportions of professorships and lectures related to SE, it is noticeable that these are relatively low. There is a maximum of 4% at almost all other universities in the TU9, which may be attributable to how they have positioned themselves with a broad content. The only exception here is the Technical University of Braunschweig with a share of 15% of all professorships being related to SE.

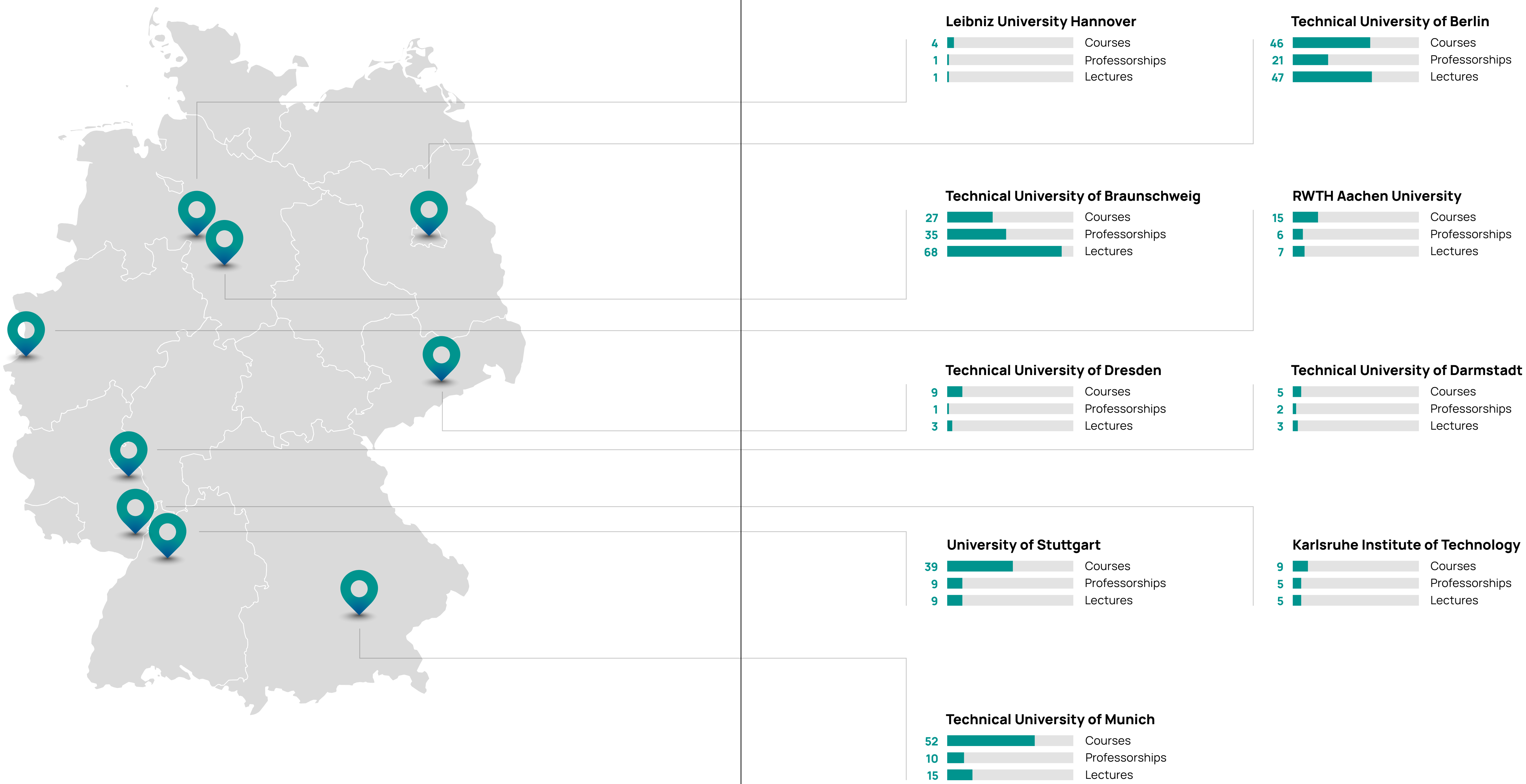


Fig. 27: Penetration of Systems Engineering in university teaching at the TU9 group in 2019

A total of 206 SE-related courses were identified at these nine technical universities in Germany. 50% of these courses can be assigned to the faculties of computer science and mechanical engineering (including mechanical engineering and transport systems) at 25% each.

At 16%, the faculties of natural sciences / mathematics at the TU9 universities have the third highest reference to SE topics. Another 13% of the courses identified belong to the faculty of electrical engineering. The remaining courses are divided between the faculties of economics (10%), construction (7%) and teaching / humanities (3%).

Systems Engineering in international teaching

In order to evaluate the level of performance of teaching in Germany on an international basis, the courses offered in the following countries were analysed:

— United States
— China
— United Kingdom
— Netherlands
— Japan
— Scandinavia
— France
— Switzerland

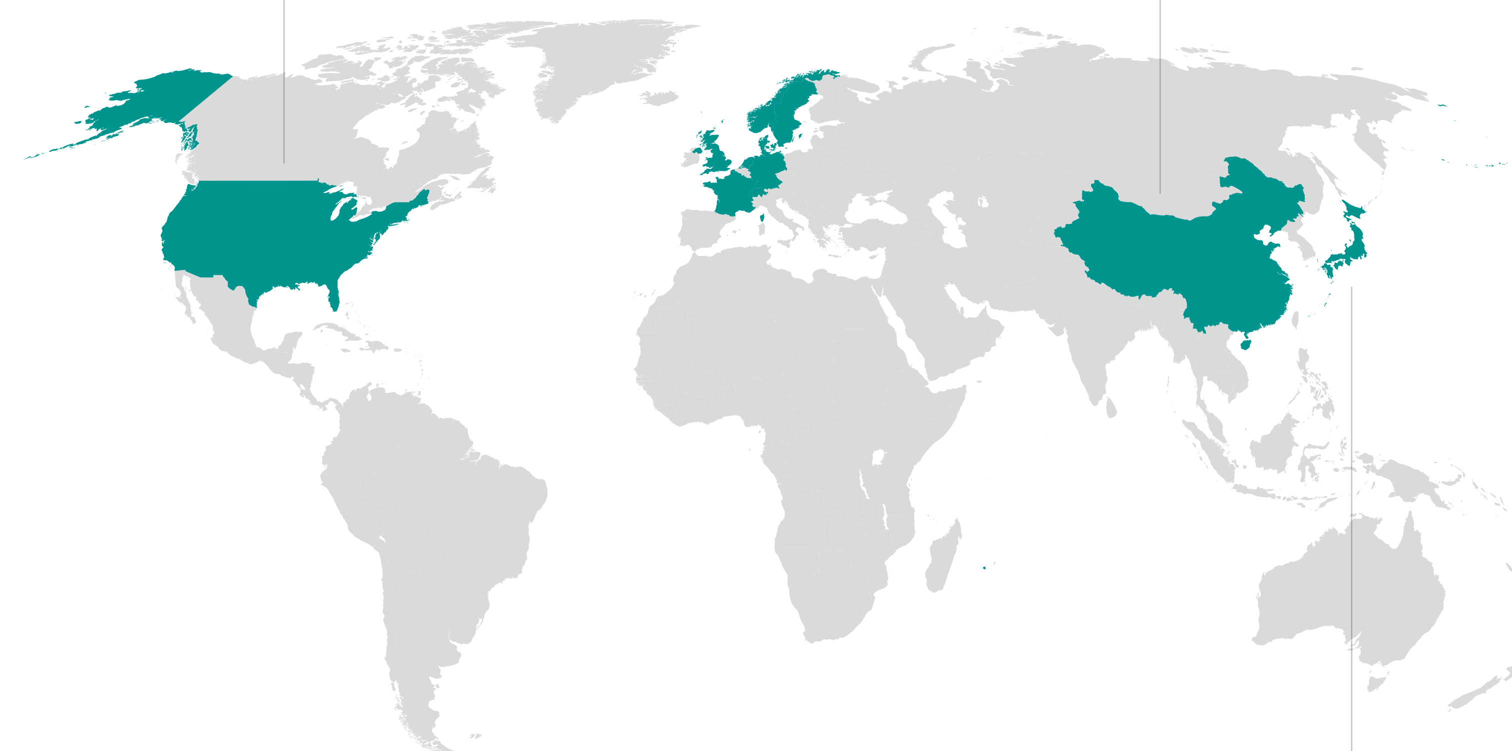
Similar to the analysis in Germany, the penetration of Systems Engineering in university teaching was investigated at the level of degree courses, professorships, and lectures. Since there is no general consensus on what constitutes a reference to SE, this summary only lists those universities which clearly have a degree, a lecture, a professorship, or a faculty with the designation "Systems Engineering". Due to linguistic barriers in the databases or the lack of access to the teaching program, systematic overviews and secondary literature were used in some cases. In such cases, the work used was checked for applicability and the literature reviews available were critically assessed. Technical universities were primarily examined where it was not possible to fall back on existing data sets. The survey of the key figures does not allow a comparison between the countries but offers an initial overview of the available courses in an international comparison. ›

111

USA
In 2017, more than 111 universities in the United States offered undergraduate and graduate degrees in Systems Engineering. This means that in an international comparison, SE is a common course of study and can be taken at many different colleges and universities. Many universities offer specialised Systems Engineering programmes. The survey was based on data from the Systems Engineering Research Center (SERC) of the Stevens Institute of Technology, the International Council on Systems Engineering (INCOSE) and the Data USA platform.

43 **83 universities**

China
According to the classification criteria set out by the Chinese Ministry of Education, Systems Engineering is a sub-discipline of engineering and, in particular, of control technology. In this context, control technology refers to a wide variety of technical systems (energy systems, supply systems, industrial processes, production management systems, etc.) In 2012, 83 Chinese universities with and without doctoral degrees took part in an evaluation of training in engineering. In fact, 43 of 83 universities have classified Systems Engineering as a research focus and offered it as part of their teaching programme.



50 **792 universities**

Japan
According to the study carried out by the "Japan Student Services Organization", three out of seven universities in the "National Seven" group of top institutions are SE-related. A total of 50 out of 729 university institutions in Japan related to the topic of Systems Engineering.

Fig. 28: Overview of international courses in Systems Engineering

4 13 universities

Netherlands
In the Netherlands, Systems Engineering is of particularly importance at the Delft University of Technology. Students are offered ten courses related to SE. A total of 4 out of 13 Dutch universities that were looked at offer teaching related to SE in the form of corresponding courses, lectures or professorships that deal with the topic. Systems Engineering is particularly well represented in technical universities.

20 41 universities

United Kingdom
In the UK, 41 universities were investigated as part of this analysis. Twenty of these universities are SE-related, ten of which belong to the Russell Group (British public research universities with academic excellence status). The University of Nottingham, University College London and the University of Birmingham are the largest universities with work related to SE. The University of Nottingham, for example, offers its students 12 different courses of study related to SE and has four professorships in Systems Engineering.

11 22 universities

France
Most of the courses related to the topic of Systems Engineering are also offered by the smallest of the universities studied, the Université Central Nantes. A total of 11 of the 22 universities examined offer courses in SE.

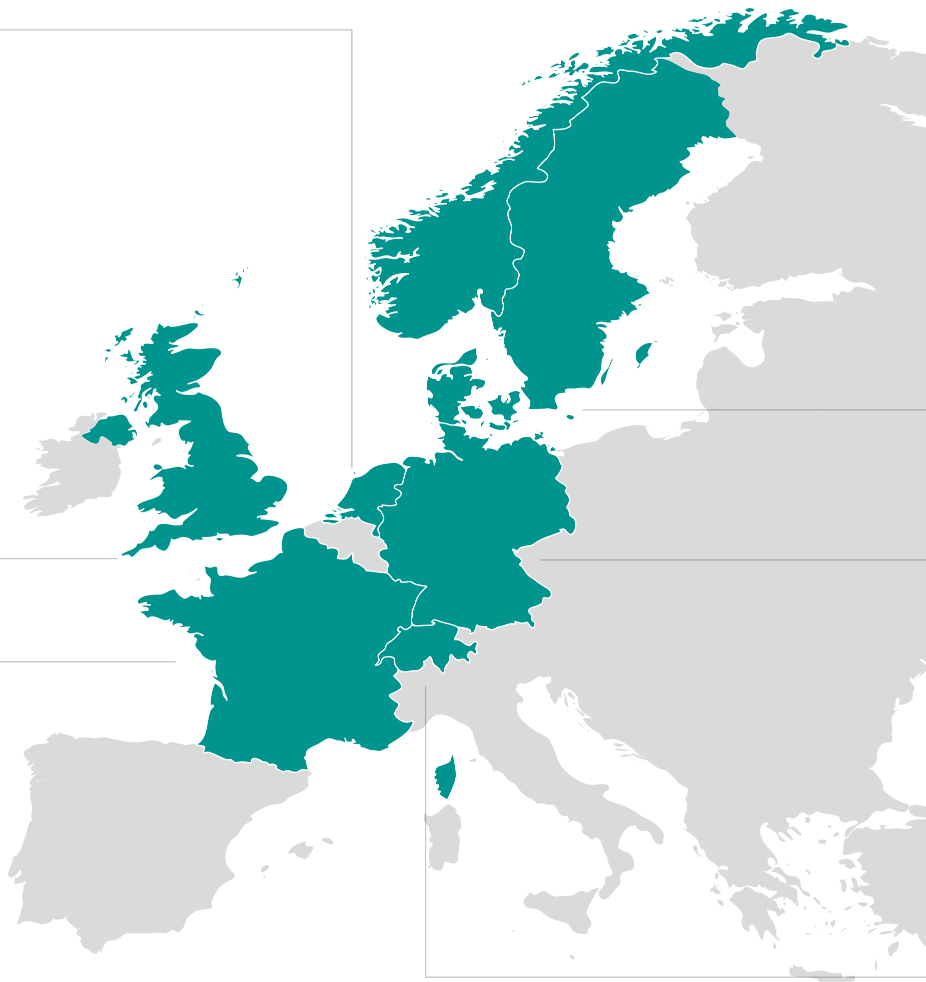


Fig. 28: Overview of international courses in Systems Engineering

11 19 universities

Scandinavia
Systems Engineering is offered in university teaching in Sweden, particularly at the KTH Royal Institute of Technology. Here students can choose from seven SE-related courses of study and are supervised by five professorships in the field of SE.

In **Norway**, the Norwegian University of Science and Technology offers 15 courses in the field of Systems Engineering. Three professorships at the university use the term “Systems Engineering” in their description. Courses with an SE-related aspect are taught at three of the Norwegian universities investigated.

In **Denmark**, teaching in the field of Systems Engineering is concentrated in the three professorships at the University of Copenhagen and one at the Technical University of Denmark in the capital city of Copenhagen. In addition, Aarhus University offers two courses of study that can be identified as having SE content.

In **Finland** it was not possible to identify any study programmes, lectures or professorships that met the direct analysis criteria.

16 17 universities

Germany
In Germany, almost all technical universities offer lectures related to SE. The penetration is very heterogeneous, especially outside the TU9.

2 2 universities

Switzerland
Both of the universities investigated in Switzerland offer courses in Systems Engineering. In addition, the École Polytechnique Fédérale de Lausanne offers students Systems Engineering as a specialisation or a minor in the “Management, Technology and Entrepreneurship” course.

In comparison: According to the international survey, in absolute terms the United States has the largest number of higher education institutions that award degrees in Systems Engineering. This number can be attributed to the high availability of information as well as the widespread use and popularity of the topic. There are also a large number of Systems Engineering courses on offer in both China and Japan. The number of universities identified is comparable to the cumulative range of courses in Europe. The technical universities in Germany have a larger absolute and relative proportion of courses and professorships related to Systems Engineering compared to the leading technical universities in the United Kingdom, France, the Netherlands, and Scandinavia. Nevertheless, the survey showed that Systems Engineering is taught in those European countries investigated. However, the analysis has also shown that the understanding of the specific content, research priorities and characteristics can be interpreted in a variety of ways and therefore the comparability, in particular of the courses and degrees, is only possible to a limited extent.

5.1.2 Systems Engineering in research

Methodical approach to collecting key figures in research

The penetration of by Systems Engineering into the world of research was investigated, based on the number of publications which have a corresponding thematic reference to Systems Engineering over the period between 2010 and 2018. A publication was considered to be related to SE if the title, abstract or keywords contained the term "Systems Engineering" The Scopus abstract and citation database was used for data collection. In addition, the number of citations and the number of authors involved were determined for publications identified as having reference to SE.

Systems Engineering in research in Germany

Looking at the numbers of SE related publications in the period under review, from 2010 to 2018, the analysis showed an average increase of 8% per year (SEE FIGURE 29). Since the number of publications per author remained more or less constant during this period, the number of authors who publish on the subject of Systems Engineering was also rising at an average of 7% per year. The figures indicate the increasing relevance of Systems Engineering in the German research landscape, especially since more authors deal with the topic every year and accordingly there are more publications covering this topic. The same also applies to the dissertations related to SE, where an increase can also be observed in the period from 2010 to 2018. However, such an increase cannot be ascertained when it comes to the associated citations.

The penetration of Systems Engineering into research in Germany can not only be seen in the number of publications but also in the presence of this topic at German-language specialist conferences: In addition to "Systems Engineering Day (TdSE)", the Stuttgart Symposium for Product Development and the DfX Symposium focussed on the topic of Systems Engineering as well (SEE INFOBOX 26). The TdSE is a specialist conference established in the German-speaking research world that is specifically dedicated to the topic of Systems Engineering. This is reflected in a correspondingly high number of articles related to SE.

INFO 26 **Systems Engineering Day (TdSE)**

"Systems Engineering Day" (TdSE) is a Systems Engineering conference, serving as a central meeting point for interested parties, decision-makers and Systems Engineering experts. The topic of Systems Engineering is deepened with the help of workshops, lectures, and discussions on specific issues. The conference is organized by the Systems Engineering Society (GfSE), the German section of the International Council on Systems Engineering (INCOSE).

That Systems Engineering is considered in publicly funded research projects in Germany is a sign of the importance of the topic in German research. This was where the number of SE-related research projects funded by the German federal government and the German Research Foundation (DFG) was determined. Projects with an SE reference were counted where the description included the words "Systems Engineering". However, the analysis, which was created using the German federal government's funding catalogue and the DFG's project database, shows that the topic was not given constant attention over the period from 2010 to 2019. Both the number of SE-related projects funded, and the associated funding amounts varied greatly.

Systems Engineering in international research

Looking beyond Germany at the research activities involving Systems Engineering, the penetration of Systems Engineering in research in the following countries was investigated:

- United States
- China
- United Kingdom
- Netherlands
- Japan
- Scandinavia
- France
- Switzerland

Similar to the analysis in Germany, the objects considered in the analysis were the number of publications with reference to SE, the number of citations and the number of authors involved. The analysis produced the following findings:

United States: Since 2010, the number of SE-related publications in the USA has increased slightly by around 4% p.a. The number of publications is usually 850 per year. Of note are the number of citations (e.g., 9202 in 2012), suggesting the high relevance of the research work. The number of publications per author is relatively constant at between 0.3 and 0.4. Accordingly, the absolute number of authors increases only marginally at 4% p.a.

China: The number of SE-related publications increased eight-fold between 2010 (295) and 2017 (2237). This is also reflected in the average annual growth rate of around 33% p.a. At the same time, the number of citations doubled from 2010 (2036) to 2017 (4696). The high number of publications and the continuous increase in citations illustrate China's considerable dynamism in the field of SE research. The number of publications per author is constant at between 0.3 and 0.4. As a result, the number of authors increased by 30% pa from 2010 to 2018.

United Kingdom: In the UK, the number of publications in the field of Systems Engineering increased from 2010 (159 publications) to 2017 with slight fluctuations. The Scopus database shows that 2017 stands out, with 291 publications listed. In 2017, 1144 authors were involved in publications referring to SE. In 2018 the number reduced to 163 publications. Overall, the number of authors who wrote publications in the field of SE increased by an average of 3% p.a. between 2010 and 2018.

Netherlands: The increase in scientific publications per year from 80 (2010) to 95 (2018) underlines the increasing relevance of the SE in scientific discussion. While there were 467 authors of SE context in 2014, the number of participating authors fell to 375 in 2018.

Japan: In Japan, the number of publications addressing the topic of SE decreased from 85 (2010) to 61 in 2012 since 2010. There has been a trend reversal since 2013 and the number of publications has almost doubled to 111 in 2016. This year, 344 authors contributed to the publications listed in Scopus. The number of publications has been falling again since 2017. In 2018, the Scopus literature database included 78 publications in the field of Systems Engineering in Japan.

Scandinavia: The number of SE-related publications in Scandinavian countries increased significantly between 2010 and 2018 by 14% p.a. This is due to the steady increase in the number of authors, up 22% p.a. between 2010 and 2018. The increase clearly shows that Systems Engineering has massively gained in importance in Scandinavian research.

France: The number of SE-related publications published in France and included in the Scopus database each year more than doubled compared to 2010 (99) and 2018 (235). This means an annual increase of 15%. An even greater increase can be found in the number of authors. In 2010 there were 135 authors with publications in the field of SE, in 2018 528 authors wrote about the subject.

Switzerland: The number of scientific publications related to SE increased by an average of 7.4% p.a. between 2010 and 2018, with 2016 recording 54 papers, an above-average number. It is similar with the number of authors. Here an average increase of 23% p.a was observed between 2010 and 2018. In general, it can be said that Systems Engineering is becoming increasingly important.

Fig. 29: Development of publications, citations and dissertations on the subject of Systems Engineering in Germany

Compared: China and the USA lead in the absolute number of SE-related publications; In an international comparison, China has the highest annual growth rate. This confirms the general trend, with China rapidly catching up in scientific competition. Compared to Germany, there are lower increases in publications covering SE-related issues in Japan, the United Kingdom, and the Netherlands. The absolute number of publications in Germany and the UK is comparable - the number of citations of publications coming from Britain is higher, however. The reasons for this could be the languages used. A look at the authors involved in these publications shows that the number of authors is increasing at the same rate in all the countries looked at; the number of publications per author is between 0.3 and 0.4.

INFO 27 Study: The rise of Systems Engineering in China

The 2016 brochure sponsored by the China Aerospace Laboratory of Social System Engineering entitled "The rise of Systems Engineering in China" illustrates the great importance of Systems Engineering in that country. The comprehensive publication describes China's activities in the area of research into Systems Engineering. In addition to explaining Systems Engineering, there is a presentation of the beginnings of research activities in China. Furthermore, the development of Systems Engineering theories in China and their increasing importance are explained. In addition to the historical perspective, the authors take a look at the future of SE in China. The report also introduces the key research partners in Systems Engineering. According to the brochure, the Systems Engineering Society of China (SESC) has 21 recognised committees. In addition, there is a list of 15 selected research facilities operating in the SE sector are listed, with over 40 universities offering training in Systems Engineering being named. ›

USA

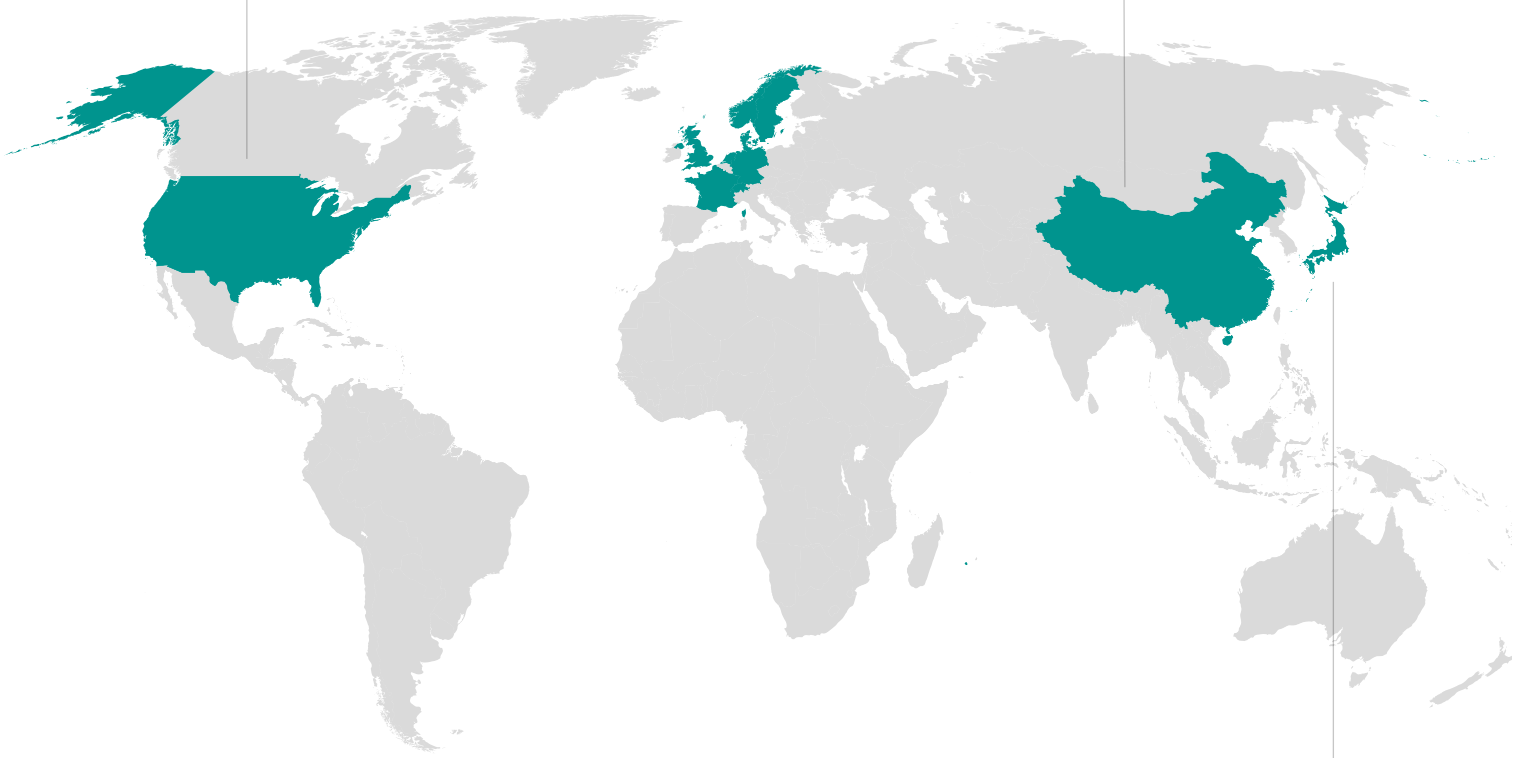
7.455 Publications | **56.064** Citations

4 % p.a. ↗
Growth rate in publications

China

8.906 Publications | **29.756** Citations

33 % p.a. ↑
Growth rate in publications



Japan

735 Publications | **2.866** Citations

0,5 % p.a. →
Growth rate in publications

Publications
Absolute number of publications between 2010 and 2018

Citations
Absolute number of citations between 2010 and 2018

Growth rate in publications
Average annual growth rate of publications between 2010 and 2018

Fig. 30: Overview of international research in the field of Systems Engineering

Netherlands

751 Publications | **5.486** Citations

5 % p.a. →
Growth rate in publications

Scandinavia

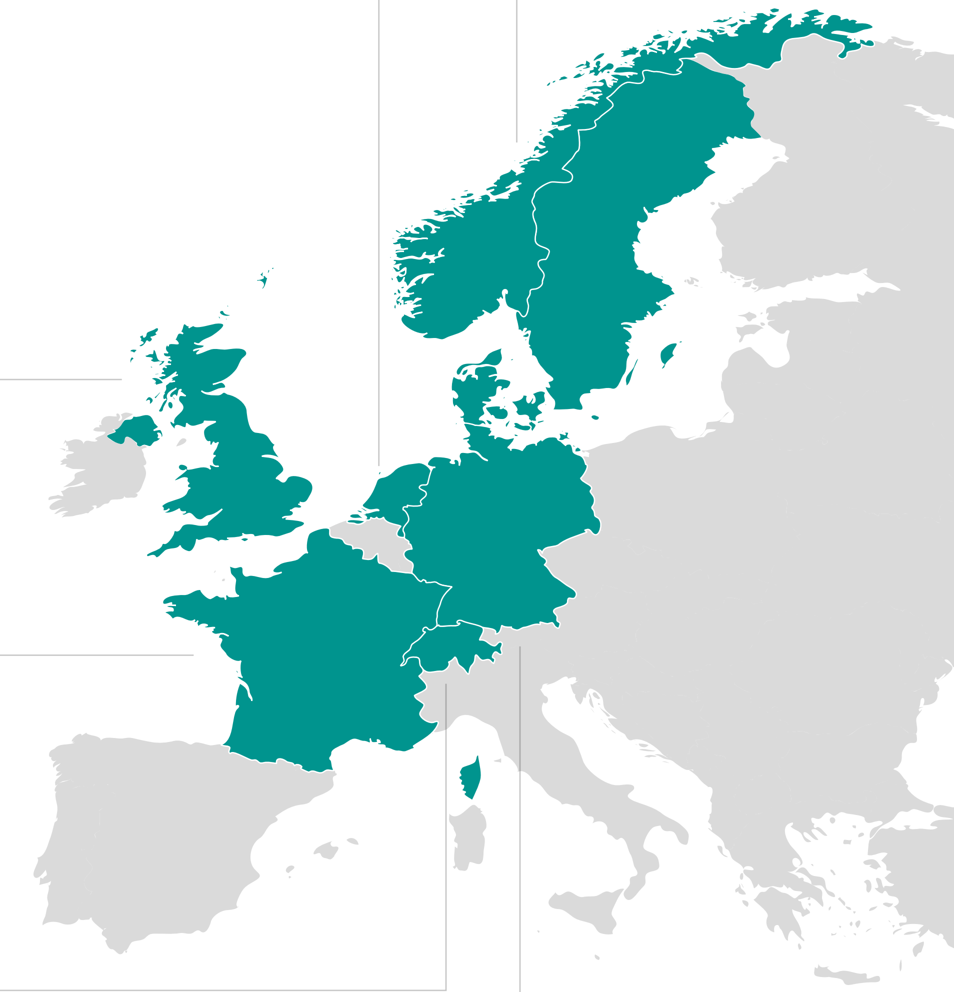
1.005 Publications | **6.712** Citations

14 % p.a. ↗
Growth rate in publications

United Kingdom

1.786 Publications | **14.740** Citations

3 % p.a. ↑
Growth rate in publications



France

1.569 Publications | **13.262** Citations

15 % p.a. ↗
Growth rate in publications

Switzerland

269 Publications | **2.553** Citations

7,4 % p.a. →
Growth rate in publications

Germany

2.134 Publications | **10.884** Citations

7 % p.a. →
Growth rate in publications

China and the USA lead in the absolute number of SE-related publications; in an international comparison, China has the highest annual growth rate. This confirms the general trend, with China rapidly catching up in scientific competition. Compared to Germany, there are lower increases in publications covering SE-related issues in Japan, the United Kingdom, and the Netherlands. The absolute number of publications in Germany and the UK is comparable - the number of citations of publications coming from Britain is higher, however. The reasons for this could be the languages used. A look at the authors involved in these publications shows that the number of authors is increasing at the same rate in all the countries looked at; the number of publications per author is between 0.3 and 0.4.

Systems Engineering in research and teaching in an international comparison: The leading industrial nations have recognised that Systems Engineering as a key competence in the race for the future and are acting accordingly. China and the USA clearly lead in terms of graduates and publications, which can be taken as an indication of the intensity of research. Germany follows, but is not keeping pace with the leaders.

Seen as part of a European comparison, Germany has a pioneering role in Systems Engineering. Systems Engineering is becoming increasingly important right across the world, both in teaching and research. The penetration of Systems Engineering into teaching programmes at the nine German technical universities (TU9) is very heterogeneous, but it can nevertheless already be found in a range of faculties. Internationally, most Systems Engineering graduates are educated in the United States, China, and Japan. No comparability of the educational landscapes can be given due to the diverse ways in which the teaching content can be interpreted.

With an annual increase in scientific publications of 8%, Systems Engineering is becoming an increasingly relevant part of the German research sector. In an international comparison, the USA and China both have the highest number and highest quality of publications, as measured by the number of citations. China has the highest annual growth rate at around 30%.

5.2 Advanced Engineering

In addition to the increasing relevance of a holistic development methodology in terms of Systems Engineering, the interviews confirmed a variety of developments and trends in engineering: Model-based Systems Engineering, artificial intelligence and assistance systems, cloud-based collaboration, Product Life Cycle Management and the digital twins will shape the development of innovative goods and services in the future. The engineering of the future will not only include optimised IT tools but will also have to consider processes, methods and work organisations within the framework of Advanced Engineering in order to guarantee the ability to innovate through creativity and agility.

Against the background of these developments, it is important to identify Germany's position with regard to development trends in Advanced Engineering. For this reason, relevant topics in the complex of topics of Advanced Engineering were derived, based on the interview results. Using the survey, the current penetration of the following developments has been investigated as part of an international comparison:

- Digital technologies in engineering - Artificial intelligence, digital twins and Product Life Cycle Management in engineering
- Innovative methods in engineering - Creativity and agility in engineering

Due to the high novelty status and a broad anchoring of the subject in teaching programmes at universities, the key figures collected are limited to research. In contrast to considering the country-specific aspects of Systems Engineering, the investigation was structured according to the subject areas described.

Methodical approach to collecting key figures in research

The Scopus literature database was used to systematically collect key figures in Advanced Engineering. The intensity of the research is analysed based on the number of publications that have a thematic reference to the individual subject areas.

When defining the search terms, the relevant technical terms for the subject areas were defined on the basis of the qualitative survey. As regards the subject of Advanced Engineering, the terms agility, creativity, artificial intelligence, digital twins, and Product Life Cycle Management (PLM) were used. The terms have only been investigated in the context of the subject "engineering".

The key figure is the absolute number of times the expressions are mentioned in the title, the summary or in keywords of a publication. In the main, English-language publications were considered on the basis of translated terms. The publication numbers examined coved the period from 2010 to 2018.

5.2.1 Digital technologies in engineering: Artificial intelligence, digital twins, and Product Life Cycle Management in engineering

The investigation into the international level of performance of digital technologies in engineering is based on the number of publications relating to the following subject areas in engineering (SEE FIGURE 31):

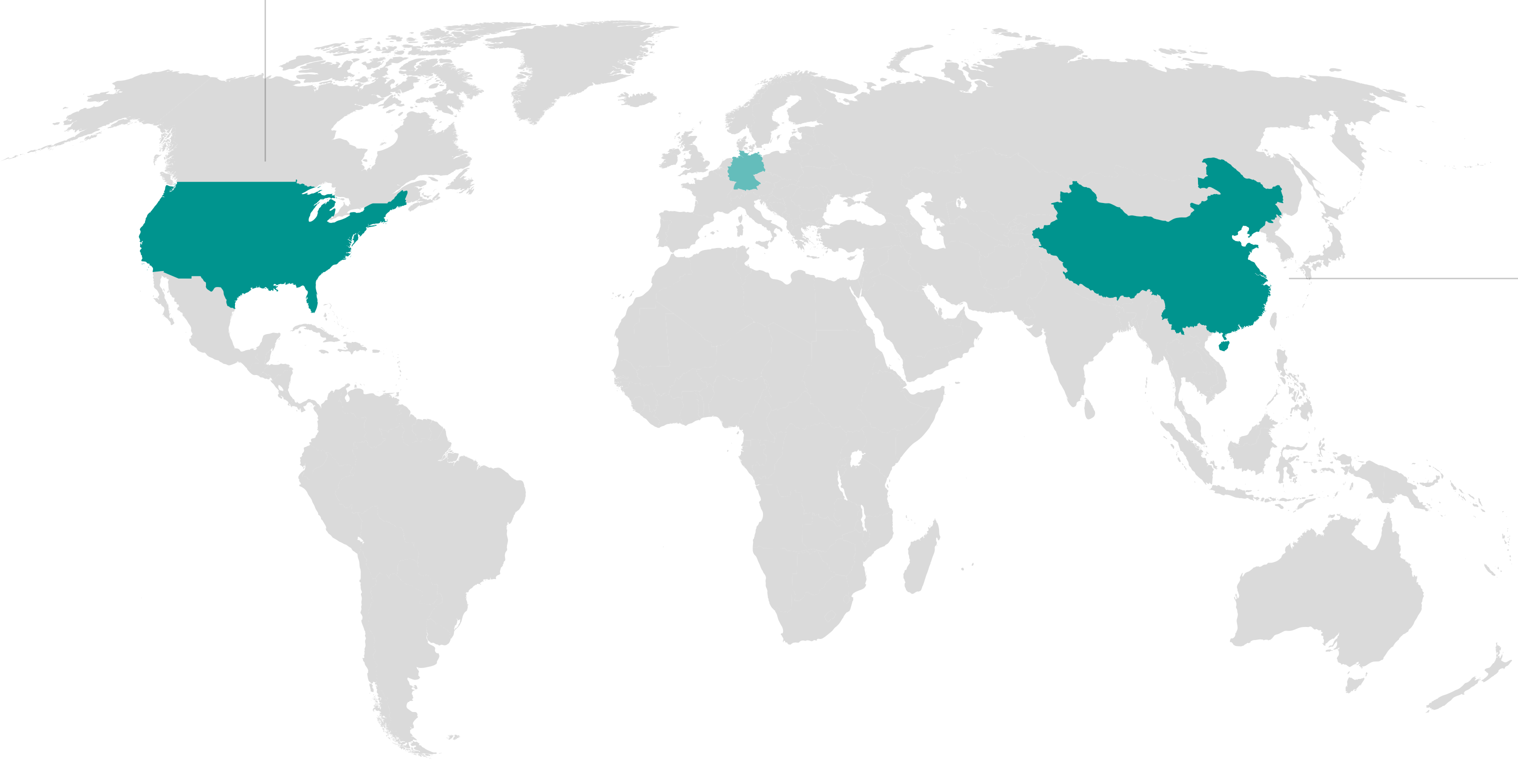
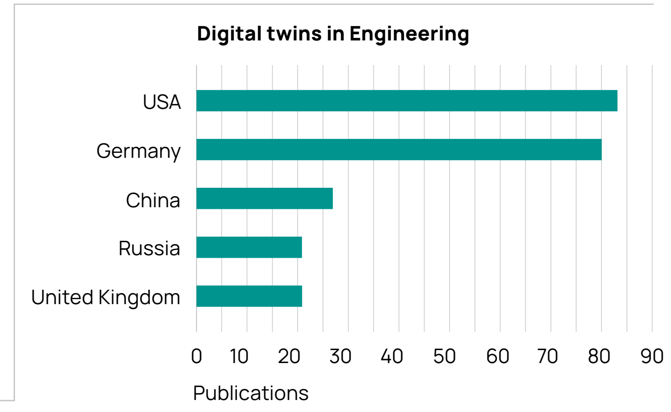
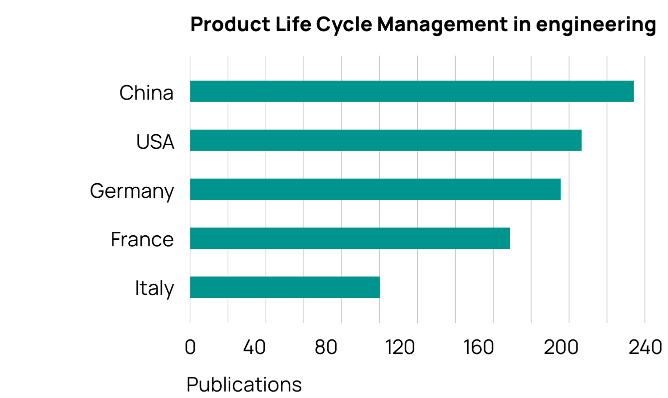
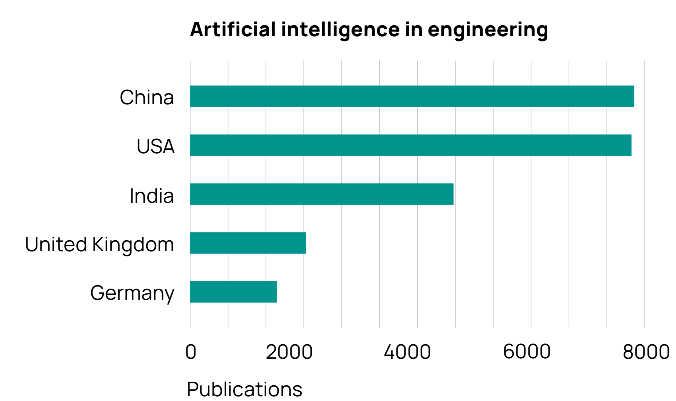


Fig. 31: Selected digital technologies in engineering in an international comparison

Leading research in the field







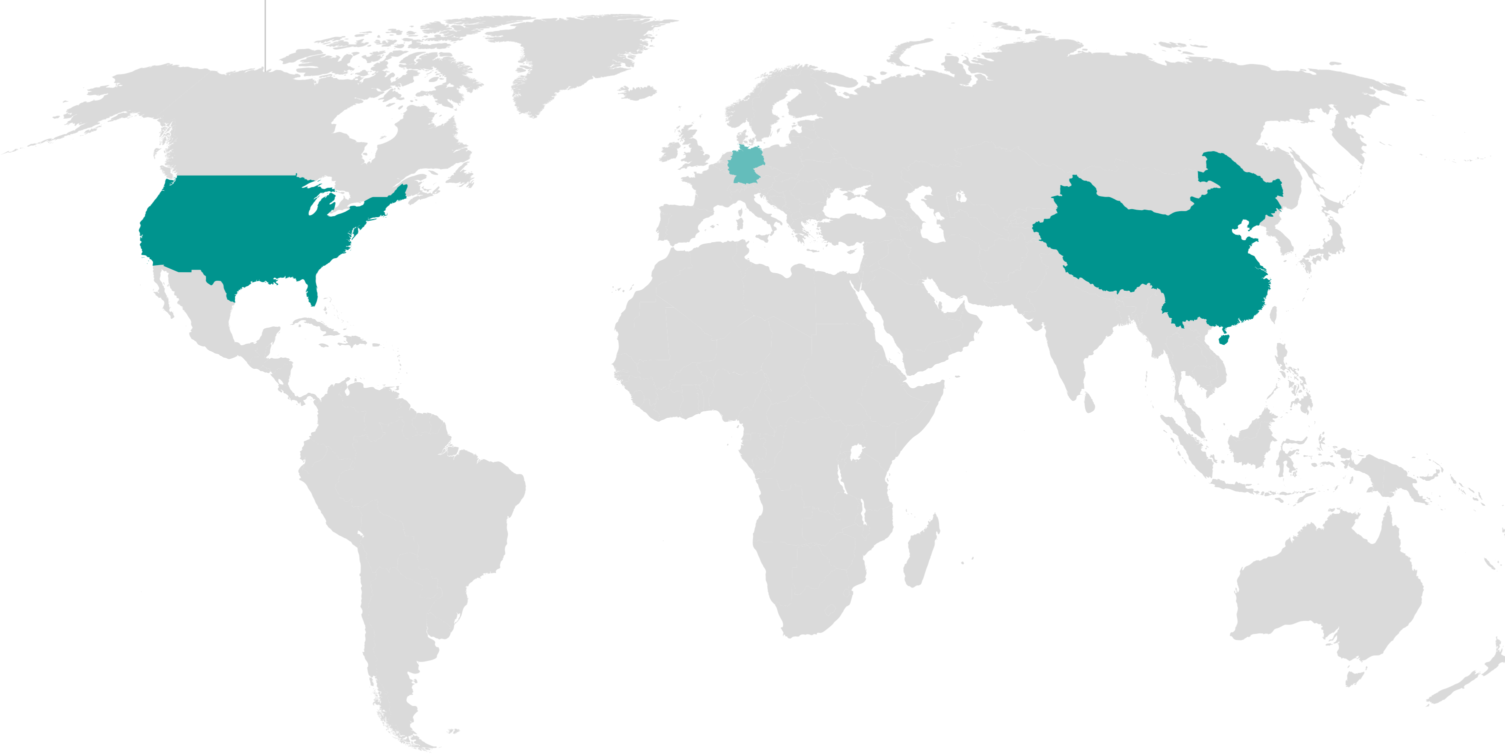
Artificial intelligence in engineering: The use of AI is a global trend that results in an increasing relevance of AI approaches in engineering. This is reflected in the increasing number of publications related to artificial intelligence in engineering. Publications across the world show a strong increase from 2015 onwards. With a cumulative number of 56 publications in the period 2010 to 2018, Germany is far behind China (299), the USA (213) and India (193).

Digital twins in engineering: A comparable increase can also be observed in publications covering the field of digital twins. The low number of publications from 2010 to 2016 and the subsequent sharp increase in 2017 and 2018 suggest that the subject of digital twins will have a high level of relevance in future research. In a global comparison, the USA (38) leads first, followed by Germany (34) and China (21).

Product Life Cycle Management: The number of publications in the field of PLM has remained relatively constant when compared to publications on AI and digital twins over the period from 2010 to 2018. With 235 publications in the years from 2010 to 2018, China is just ahead of the USA (221). At 192 publications, Germany is also one of the leading nations in the field of PLM. In addition, it can be said that the country-specific distribution of publications on the subject of PLM is significantly more homogeneous than on other topics.

5.2.2 Innovative methods in engineering: Creativity and agility in engineering

The research relevance of creativity and agility in engineering was also investigated, based on publications in the above-mentioned subject areas (SEE FIGURE 32):



Leading research in the field

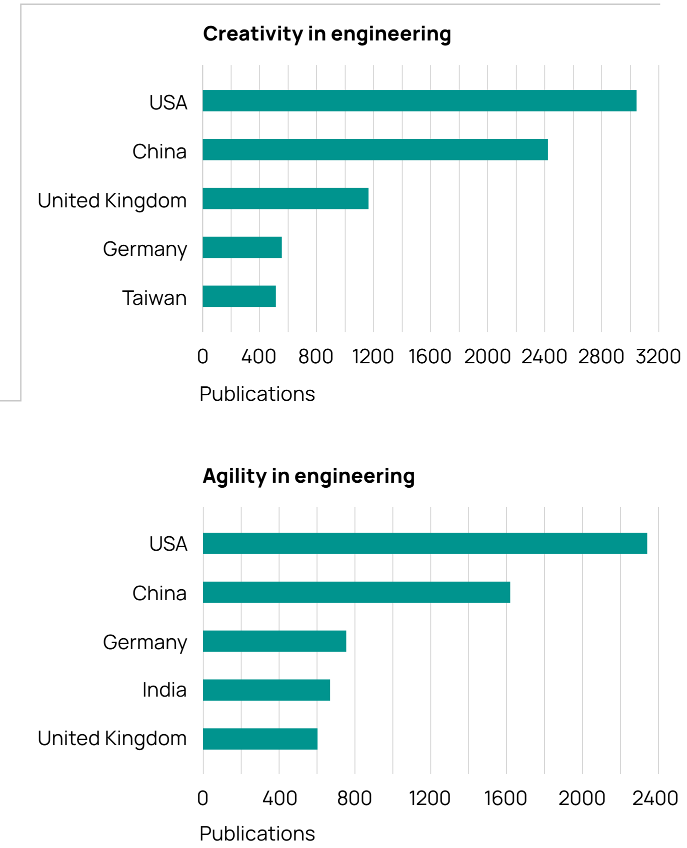


Fig. 32: Selected innovative methods in engineering in an international comparison

Agility: A survey of the number of publications on agility in the context of engineering suggests that it is of increasing relevance. The number of publications has been increasing steadily since 2010. The survey found 442 publications related to agility in 2018, compared to only 243 in 2010. Most of the research results on agility are published in the USA, with 576 publications between 2010 and 2018. China (383) and Germany (252) follow in second and third place on the list of publications.

Creativity: The number of publications in the field of creativity in engineering has been rising steadily since 2010, increasing from 217 publications in 2010 to 345 in 2018. Similar to the results in the area of agility, in a global comparison the USA also leads the field in creativity with 480 publications, followed by China at 291 and the United Kingdom at 234. Germany (86) lags behind with a comparatively low number of publications covering the subject of creativity.

Advanced Engineering in international comparison: Germany is falling behind the USA and China. Significant strengths can still be seen in the areas of PLM and digital twins.

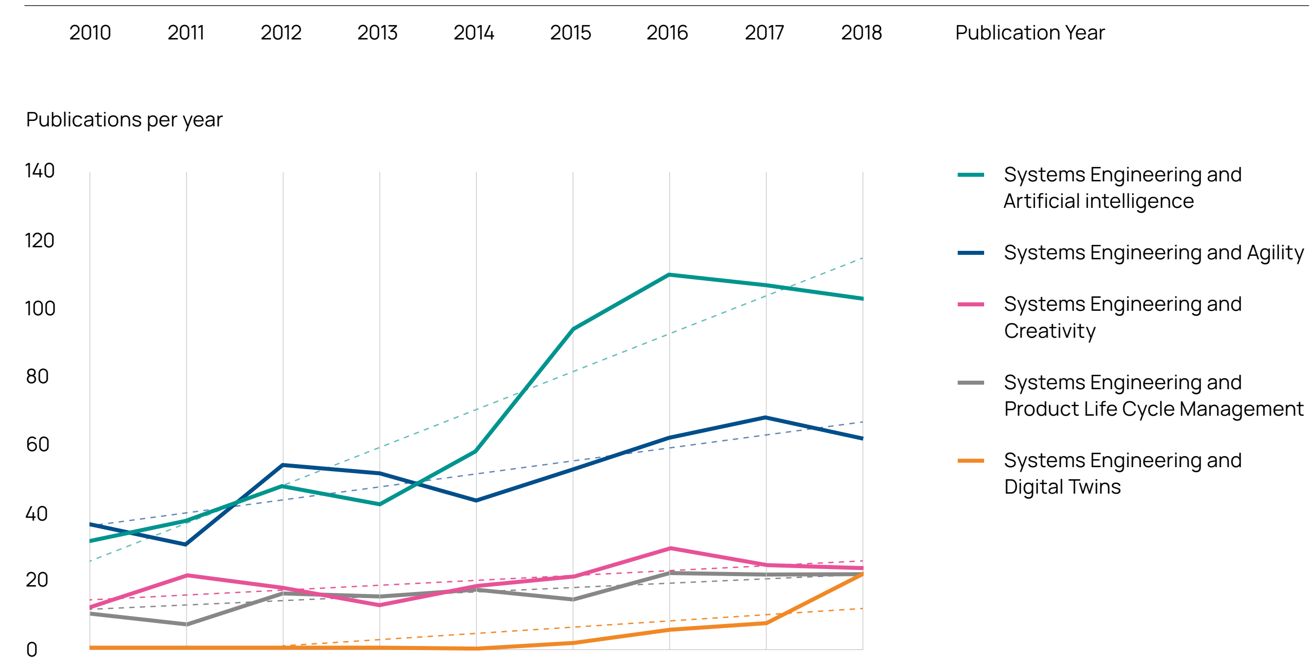
The survey of key research figures in the area of Advanced Engineering underlines the supremacy of the USA and China. The US leads the number of publications in the fields of creativity and agility in engineering. China dominates digitisation in engineering. Germany lags far behind in terms of the number of publications in the areas of AI and creativity but has a leading position in PLM and digital twins.

5.3 First approaches to Advanced Systems Engineering

The quantitative survey of the level of performance in the areas of Systems Engineering and Advanced Engineering illustrates the dominance of the USA and the increasing technological leadership of China. Germany takes a leading position in terms of the number of publications in engineering, particularly when compared to the rest of Europe. When it comes to the development of future Advanced Systems, a systematic linkage and integration of the subjects of Systems Engineering and Advanced Engineering are opening up a special opportunity to make product development more efficient and effective. Against this background, finally an investigation was carried out into those publications that relate to Systems Engineering as well as to the sub-aspects of Advanced Engineering mentioned above (SEE FIGURE 33).

This survey showed that a combination of Systems Engineering and agility together with Systems Engineering and artificial intelligence is attracting increasing interest. The number of publications in these subject areas is significantly higher than the number in Systems Engineering and creativity, Systems Engineering and digital twins, or Systems Engineering and PLM.

At the time of the investigation, the USA led in terms of the number of publications in all combinations mentioned, with the sole exception of Systems Engineering and PLM. Here, too, the number of publications illustrates the increasing relevance of China in scientific competition. China ranks among the top three research nations in four of the five surveys. Germany leads in the cumulative number of publications in the field of Systems Engineering and PLM. In addition, at 17 publications in the field of Systems Engineering and digital twins, Germany is close behind the USA (20). This underscores Germany's potential success factors in the context of digital continuity in engineering. At the same time, these key figures illustrate that there is a successful dissemination of research results as part of the Industry 4.0 platform, a part of the German federal government's high-tech strategy. In addition, the current activities of INCOSE in the field of artificial intelligence for Systems Engineering underline the increasing relevance of this topic. Against this background, when considering combinations of Systems Engineering and AI in research, the strong divergence between the USA (158), China (124) and Germany (35) must be subject to critical scrutiny.



Publication Year	2010	2011	2012	2013	2014	2015	2016	2017	2018
Total number of publications ("Systems Engineering")	**2.208**	**2.717**	**2.960**	**2.717**	**3.046**	**3.891**	**4.175**	**5.554**	**4.459**

Fig. 33: First approaches to Advanced Systems Engineering in an international comparison

First approaches to Advanced Systems Engineering in the international comparison: The dynamic changes in the technological landscape and working methods can be effectively countered with ASE.

The study shows a particular increase in publications when considering combinations of AI and SE as well as agility and SE. This confirms the view that we are setting the right priorities with AI and agility and that the corresponding potential benefits can only be tapped into quickly enough by joining forces with ASE.

6 Summary and outlook

Discussions with representatives from business and science confirmed the view that Germany still has some catching up to do in many areas of digitisation. The current study situation underlines this. In the case of key technologies, such as AI in particular, warnings are frequently given to the effect that an increasing backlog in international comparisons can significantly influence future added value. At the same time, it has been emphasised again and again that tomorrow's innovations will only be possible through the synergies generated by the interaction of different specialist disciplines. The executives and scientists interviewed therefore saw one **special innovative strength in the design of complex, interdisciplinary systems.** This will allow the actual market and customer needs to be addressed, securing added value in Germany over the long term.

The products of core German industries such as automotive or mechanical engineering remain in high demand internationally and are based on successful business models. It would be difficult for such knowledge-based competencies and qualifications in engineering that are right across the industrial added value chain to be adapted or quickly assembled by international competitors. **The competition between the economic powers to create innovative goods and services has not yet been decided.** The key will be technical solutions that create a high level of customer benefits and lead to successful business models, in particular those using smart, data-based services.

Digitisation, global competition, and the change in work structures will present organisations with new challenges. With this in mind, **the strengths of German companies in planning, development and producing complex systems with high demands on quality, innovation and commitment must be strengthened on a sustainable basis.** The change to autonomous, interactive, and dynamically networked products with an increasing software and service content will only be possible for those companies that have equally innovative and technically brilliant solutions in the associated added value creation.

The survey reveals two important points with regard to the role of engineering: 1) it can play a decisive role as an added value innovator in Germany and 2) it has so far mostly only been tacitly promoted or even treated as a secondary priority (both in research and in practice). Only now can new development methods and tools enable the skills required for global competition in tomorrow's added value. These include creativity, agility, or resilience. **This is why "Advanced Systems Engineering" represents change in German engineering.** It creates a framework in which the system-oriented and highly innovative approaches of engineering can be integrated and offers a model for the successful design of innovative products, services, and Product Service Systems as well as their development processes. It stands for a prominent role in the planning, development, and operation of the technical systems of tomorrow.

It is important that the leap innovations that are often required on the market performance side are accelerated, including in the area of development processes. It would be fatal to shape the innovative goods and services needed on the basis of incremental improvements in planning and development. This requires a **radical rethink and a paradigm shift in engineering.** Business and science must carry out pioneering work in order to research new forms of digitised and networked engineering at the same time.

Various research projects and activities supported by the "Advanced Systems Engineering" model will be dedicated to this task over the next few years. In order to implement this model, partners from science and business must work together on a holistic and future-oriented engineering strategy for Germany.

7 Appendix

7.1 Accompanying research AdWiSE

Megatrends such as digitisation, sustainability and resilience will shape the added value of tomorrow. The economy is faced with the challenge of organising the creation of digitised goods and services in a future-oriented way. In order for this to succeed, new, innovative methods and tools for the design of complex technical systems are needed. For this reason, the German Federal Ministry of Education and Research published an announcement at the beginning of 2019 covering various joint projects that are developing solutions within the framework of Advanced Systems Engineering (ASE). The strategic and sustainable success of these joint projects is supported by the accompanying scientific project to support the networking of players in the interdisciplinary development of complex networked socio-technical systems for tomorrow's added value (Advanced Systems Engineering, AdWiSE). The AdWiSE project consortium includes acatech - German Academy of Science and Engineering, the IPEK - the Institute of Product Engineering at the Karlsruhe Institute of Technology (KIT) and the Fraunhofer Institute for Industrial Engineering (IAO), Mechatronic Systems Design (IEM) and for Production Systems and Design Technology (IPK).

The overarching goal of AdWiSE is the scientific groundwork, support, follow-up, and consolidation of ASE joint projects. In addition, the scientific analysis and future-oriented preparation of developments in the funded field of Advanced Systems Engineering as well as other content-related R&D activities are carried out. Furthermore, the project serves to accompany the funded ASE joint projects in the funding initiative in the sense of providing an effective and innovative support service in their networking, synergy enhancement, external presentation and in the pooling of resources in the transfer and follow-up of results.

The AdWiSE accompanying research is divided into three strands of action in the project period from June 2019 to December 2023:

Strand I
Scientific groundwork and benchmark

The scientific groundwork includes a systematic preparation of the subject of Advanced Systems Engineering, a survey of the current status in the worlds of science and economy and an international benchmarking operation all leading to the development of an ASE strategy and Roadmap 2035, including recommendations for action. A transfer concept is also being developed, which is made operational in the subsequent strands of action.

Strand II
Scientific support

In the second strand of action, the results of the joint ASE projects are continuously evaluated, internally and externally. The continuous cooperation and exchange of results with and between the joint projects takes place in groups with a different focus. This enables recommendations for action to be developed specifically for the problem and target group. For external evaluation, the transfer concept, the structured results processing and the focused and publicly effective communication of topics and content is carried out in various formats.

Strand III
Scientific follow-up, consolidation and utilisation

After the ASE joint projects are complete, the scientific follow-up and consolidation of the overall results takes place. Here, for example, project consortia are transferred to committees, a concept for bundling the transfer formats together is created and the target image and strategy are updated.

7.2 List of abbreviations

acatech	German Academy of Science and Engineering (dt.: Deutsche Akademie der Technikwissenschaften)
AE	Advanced Engineering
AS	Advanced Systems
ASE	Advanced Systems Engineering
ASPICE	Automotive Software Process Improvement and Capability Determination
BMBF	Federal Ministry of Education and Research (dt.: Bundesministerium für Bildung und Forschung)
CAD	Computer Aided Design
CPS	Cyber-physical Systems
DFG	German Research Foundation (dt.: Deutsche Forschungsgemeinschaft)
GfSE	German Chapter of INCOSE (dt.: Gesellschaft für Systems Engineering e.V.)
IKT	Information and Communications Technology
INCOSE	International Council on Systems Engineering
IoT	Internet of Things
KI	Artificial Intelligence
KMU	Small and Medium Businesses
MBE	Model-Based Engineering
MBSE	Model-Based Systems Engineering
OEM	Original Equipment Manufacturer
PDM	Product Data Management
PGE	Model of Product Generation Engineering
PLM	Product Life Cycle Management
PMTIO	Processes, Methods, Tools, Information Standards, Organisation
PSS	Product Service System
PTKA	Project Management Agency Karlsruhe (dt.: Projektträger Karlsruhe)
SysML	Systems Modelling Language
SE	Systems Engineering
SoS	System of Systems
TdSE	Systems Engineering Day
TU9	Association of nine technical universities in Germany
UML	Unified Modelling Language
XiL	X-in-the-Loop

7.3 Glossary

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7.5 Image directory

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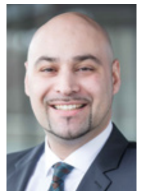

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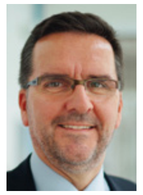

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