acatech IMPULSE

Rethinking and Reframing Engineering

Challenges, Application Scenarios and the New Advanced Systems Engineering Model

Albert Albers (Ed.)

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NATIONAL ACADEMY OF SCIENCE AND ENGINEERING

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The acatech IMPULSE series

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Contents

Eight key messages 5

Project 6

1 What is Advanced Systems Engineering? 7
- 1.1 The challenge of complexity 7
- 1.2 Tackling challenges together using Advanced Systems Engineering 7
- 1.3 System of Systems (SoS) – where many systems interact 10
- 1.4 Tomorrow's methods 11

2 ASE application scenarios – today and in the future 14
- 2.1 The smart home 14
- 2.2 Autonomous driving with Advanced Systems Engineering 16
- 2.3 Creating transparent supply chains 19
- 2.4 Sustainable energy supply with Advanced Systems Engineering 21

3 Advanced Systems Engineering from a global perspective 23

4 The way into the ASE world 25

References 29

Eight key messages

1. In the age of globalisation and digitalisation, increasing numbers of components and software modules are being used in all sorts of products, from smartphones to modern vehicles and production plants. Nowadays, all these products and components are part of larger complex systems.

2. Given this increasing complexity, technical developments need to be viewed and designed as a system. This applies to products, related services and the underlying production systems.

3. As early as the product development stage, consideration must be given as to how a product can subsequently be embedded in the system. Socio-technical systems, which affect people's everyday lives, present a particular challenge here.

4. Increasing complexity means that traditional and established methods for developing products and production systems are now reaching their limits. The solution to this growing complexity is Advanced Systems Engineering (ASE).

5. Advanced Systems Engineering supports developers in their work by managing complexity and ensuring transparency between the various disciplines. In the future, it will only be possible to design complex, intelligent, connected socio-technical systems (known as Advanced Systems or AS) by adopting Advanced Systems Engineering.

6. Advanced Systems Engineering will ensure that industry remains competitive and future-proof in the long term, is sustainable, and meets all its customers' needs.

7. Cooperative and agile interdisciplinary work is a prerequisite for Advanced Systems Engineering. Tomorrow's engineers will therefore need to have not only sound expertise in their own discipline, but also a high level of skill in connectivity, systems and architecture.

8. The development of ASE concepts is still in its infancy. A concerted effort is required, especially from science and industry, to make Advanced Systems Engineering the new model for industrial development.

Project

Project management

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1 What is Advanced Systems Engineering?

The technical systems around us are becoming increasingly complex. Production lines are able to order spare parts when they run out. Medical diagnostic systems can independently examine radiological images for tumours and suggest cancer treatments to doctors, and in a few years' time cars are expected to drive themselves along motorways. Making this all possible are increasingly powerful mechanical components, microprocessors and intelligent software. Nowadays, many machines and devices are also connected via the internet and mobile communications with each other, as well as with service operations and control centres. These complex technical systems present huge opportunities. However, the growing complexity is making it more and more difficult for developers to design and create solutions for machines and devices, because they are intertwined in a way that is hard to grasp. The problem is that more and more experts from different disciplines are involved in the development of increasingly complex systems, and there is a need for these experts to communicate with each other. Until now, there has been no common "technical language" linking all the disciplines. Advanced Systems Engineering (ASE) aims to devise a common language that can handle this increasing complexity, making it possible for developers in the future to continue to create secure, reliable technical systems within a reasonable period of time.

1.1 The challenge of complexity

A good example of the enormous complexity of technical systems of the future is "fully-automated driving", where driverless taxis are expected soon to be able to navigate their own way through towns. Fully-automated driving demonstrates how close the interaction between various technologies will be. Autonomous taxis would be able to find the route to their destination by themselves and to avoid collisions. They would also have permanent access to traffic information and therefore be able to avoid traffic jams and arrive at their destination on time. Ideally, they would also have access to information about bus and train timetables, so that their passengers could catch their connections. Passengers could also be offered an entertainment programme. An autonomous taxi would also need to be able to communicate with payment systems, so that passengers could pay for their journey quickly and easily. More and more technologies and separate systems will therefore become increasingly interdependent as a result of the provision of future services such as the autonomous taxi.

It is no longer possible for a single person to develop such complex services and technical solutions. Instead, experts from many different disciplines will work together on the development of future technologies such as autonomous driving – mechanical and electronics engineers, software developers, economists, transport planners and traffic psychologists. This poses two challenges. The first is that experts with different areas of expertise use different technical jargon. A real-life example of this would be a visit to a doctor's surgery, where we often fail to understand the medical jargon being used. Cooperation partners will first of all need to find a common technical language, to ensure they can devise functional and secure solutions within a reasonable amount of time. Secondly, the complex development process needs to be transparently designed and communicated across all disciplines so that, despite the inherent complexity and the large number of people involved, no errors creep in and every stage of the development remains comprehensible.

1.2 Tackling challenges together using Advanced Systems Engineering

Until now, there has been no common technical language linking all disciplines that can be used when developing highly complex technical systems. We are not referring here to spoken communication – in that context, English is well-established as the global language. We are referring to a model language to describe complex technical interdependencies that can be used for all disciplines and that connects the disciplines at a superimposed level of communication. Given the increasing complexity of systems, this language needs to be developed as quickly as possible in the years ahead. The theoretical concept for this exists already – Advanced Systems Engineering, an extension of traditional Systems Engineering (SE). Systems engineering was devised in order to develop technical systems in major projects, such as large aircraft. However, it lacks a common language linking the different specialisations. The SE approach will therefore no longer be sufficient for the increasingly complex systems of the future.

> *We can't use 20th century methods to tackle the challenges posed by 21st century product development and production.*

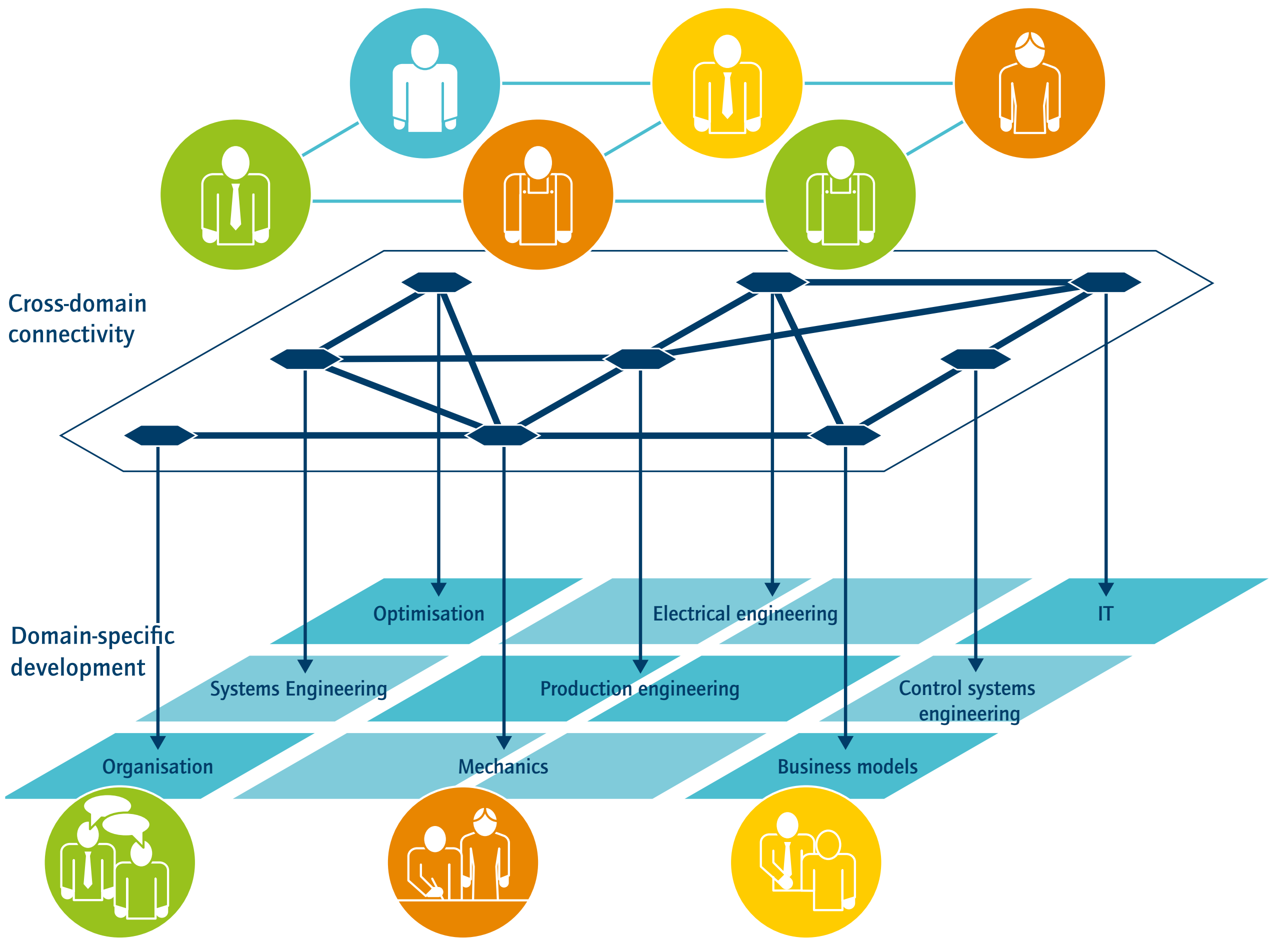

Figure 1: Continuous interplay between domain-specific development and cross-domain connectivity in Advanced Systems Engineering (Source: authors' own illustration based on Albers et al. 2021)

Such complexity can only be addressed by Advanced Systems Engineering.[1]

People have an unrivalled knack for working creatively and devising new solutions. However, the increasing complexity of technical systems, such as autonomous driving, is making it more and more difficult to have a complete overview and to devise the most appropriate solution. Were you to forget a payment system interface, for example, when developing a communication system for autonomous taxis, this could delay or jeopardise the entire development process later on. Advanced Systems Engineering would support the work of developers by managing complexity and ensuring transparency between the various disciplines. Mechanical engineers communicate using technical drawings, while software developers do so using program codes and programming languages. Advanced Systems Engineering would provide a higher level of communication. So, for example, the contents of a requirements catalogue or technical drawing can be presented using standard descriptions and especially diagrams that are intelligible and comprehensible to all.[2]

The development of a new product takes place in cycles in which synthesis and analysis occur in sequence. The process begins with the synthesis, the creative development work. This is followed by the analysis, which examines whether the solution devised meets all the desired criteria for the product being designed. If this is not the case, the solution must be refined in the course of the next synthesis step. This is why Advanced Systems Engineering is so important, because when complex technical systems such as autonomous driving are being developed, it is no longer possible for a single developer to have an overview of all the features of a product or all the criteria relating to that product. However, thanks to Advanced Systems Engineering, to the common language and to the computer programs and databases derived from it, all those involved can check the development status at once and make adjustments in good time. Moreover, each stage in the development is recorded in a way that is understandable for all. If errors or inconsistencies arise in the course of the development process, those involved can identify at what point of the synthesis-analysis cycle something went wrong.

Understanding the world as a „system“

In principle, a "system" comprises several elements that form an organised whole. A car with its many thousands of parts and its drive technology is an example of such a system. One can also regard a human being as a system consisting of body cells, within which a wide variety of metabolic processes take place. Right at the beginning of the 20th century, scientists started to address the concept of the "system". The Austrian Karl Ludwig von Bertalanffy is acknowledged as the founder of general systems theory. From the 1930s, he focused on the laws governing living and physical systems. He coined the term "Fliessgleichgewicht", meaning "flow equilibrium". According to this, the body of a healthy human, for example, is in a steady state – homeostasis. In the following decades, the concept of a system became popular in engineering sciences. Of interest initially was the fundamental question as to how technical systems are regulated and controlled. Systems research was given a boost by the Apollo programme developed by NASA (the US space agency) in the 1960s in preparation for the Moon landing. The Apollo programme was one of the most complex technical projects of its era. The aim was to develop a spacecraft and a Moon-landing vehicle that would be able to function at extremely low temperatures and especially in low gravity. Added to this was the "human system", the viability of which should not be impaired by the harsh conditions it would encounter.

It was in light of the complexity of the Apollo programme that the term "system engineering" was coined at this time. System engineering is an approach to the development of complex technical systems in major projects. Developers initially focus on how the end product would ideally look. Progress is made towards this objective in several process steps. First, the system is broken down into the various functions it must fulfil. The system can be subdivided into subsystems, each of which, from the software to the engine, is developed separately. Then the subsystems are tested in several cycles to ensure they work together properly, until finally all the desired requirements are fulfilled. System engineering is usually an

1 | See Dumitrescu et al. 2021.
2 | See Haberfellner et al. 2012 as well as Ulrich and Probst 1995.

interdisciplinary process, because major projects involve experts with a variety of specialisations.

Many technical systems have an impact on people's everyday lives. In this case, they are referred to as socio-technical systems. Driving a car is a simple example. The car system is controlled by the "human system". In turn, both are embedded in a dynamic system comprising many other road users – a comprehensive mobility system.

In product design, we are increasingly having to deal with unprecedented complexity.

1.3 System of Systems (SoS) – where many systems interact

The development of technical solutions and products will become more and more complicated in the future, because in everyday life we are no longer dealing with individual systems, but with increasing numbers of systems that interact with each other. Experts refer to this as a "System of Systems" (SoS). Although each individual system can act on its own (autonomously), entirely new objectives can be achieved by the interactions within the System of Systems. One example is the power grid of the future. In the past, electricity was generated in large power plants and transported through power lines across the country to towns and villages and then to houses. Now this traditional grid has been turned on its head. With biogas plants in the countryside, rooftop solar panels on houses, and coastal and offshore wind farms, there are thousands of electricity producers, both big and small, who feed electricity into the grid for distribution. Some households, if they have solar panels on the roof, are no longer just consumers of electricity, but can generate electricity and feed it into the grid. For some time now, smart meters have been installed in households across Germany that can communicate with the power grid via a router. So, for example, it will be possible in the future to charge your electric car from your home charging point when the market price for electricity is low. Conversely, your electric car can offer a means of storing electricity and it can then feed electricity into the grid when it can be sold at a good price. Thus the traditional power grid is gradually being transformed into a smart power grid, offering scope for many new business ideas. In the future, electricity could, for example, be traded directly and relatively informally between neighbours in a town or a district. A private individual with a photovoltaic system could supply electricity not only for themselves but also to neighbours who need it. Experts refer to this direct door-to-door supply of electricity as peer-to-peer trading. In the power grid of the future, many automated decision-making systems would interact in a complex and dynamic way – a typical System of Systems.

The smart grid of the future illustrates how many systems are able to interact nowadays – the wind farm as an electricity producer, the electric car as a means of storing power, private individuals who become electricity traders, and many more. In each case, it must be ensured that the power grid remains stable and that supplies to customers are secure. The System of Systems thus touches on a large number of technical, social and economic aspects. What is more, many dynamic processes are occurring in this System of Systems, making it very complex. Demand for electricity fluctuates in the course of the day. The output of photovoltaic systems and wind turbines varies with the weather and the price of electricity depends on whether power is being fed into the grid or consumed. Therefore, the System of Systems must constantly adapt to the environment. Traditional System Engineering (SE) can no longer handle this complexity. SE fails to deliver especially when the systems or parts of the systems, the software and the hardware, as well as external factors, start to interact dynamically with each other as well as interacting with the environment. System engineering can no longer manage this dynamic. The solution is interdisciplinary Advanced System Engineering, which provides a common language across all disciplines and system components. Thus it will be possible for developers to adopt a holistic approach to designing systems such as the power grid and the autonomous vehicle and to consider all aspects of the System of Systems. The fact is that until now there has been no technical support to ensure the reliable development of a System of Systems. Advanced Systems Engineering offers this support, with the result that it will be possible in the future to design optimal, secure Systems of Systems.

There is also a cognitive aspect to the technology. The system must have the real-time capability to adapt to its environment, learn new things and constantly self-optimise.

1.4 Tomorrow's methods

Until now, there has been no ready-to-use holistic ASE concept and especially no general-purpose ASE development tools for the design of the Systems of Systems. However, approaches that could be considered to be important components of Advanced Systems Engineering do already exist. These include Model-Based Systems Engineering (MBSE), where information about a technical system that is to be developed is no longer presented solely in the form of text documents, technical drawings or computer graphics (computer-aided design or CAD), but using centralised connected models based on graphic elements. Today, there are already internationally standardised modelling languages, such as the Systems Modelling Language (SysML), which can be used, for example, to present product features, requirements or system functions in diagrammatic form, as well as the ways in which they interlink, and can thus be used for various applications in the development and analysis of technical systems.

MBSE has a number of benefits. "A picture is worth a thousand words" rings true here, as content can be better visualised and understood from an image than from text documents or requirements catalogues. What is more, the interrelations between the graphic elements and thus between the different parts of a system can be modelled and demonstrated. Content that is relevant to those involved at a specific development stage can be highlighted, while less relevant content can be hidden. Moreover, visual representation is clearer than language, because linguistic comprehension can vary, depending on culture, origin, education and background. However, until now, many companies have hesitated to introduce MBSE, because of the initial extra cost. In addition to the usual development procedure, businesses face the challenge of incorporating information from technical drawings and CAD models or the results of simulations and tests into the MBSE model. However, the cost represents a good investment! In addition to quick wins such as the early identification of errors, there is great potential for enhancing the efficiency of the development process through the reuse over successive product generations of the models created.

The preliminary stages of Advanced Systems Engineering include new approaches to product development that gradually become established in companies, such as the concept of Product Generation Engineering (the PGE model). The idea is that, when a technical solution is developed, not only the next product generation should be considered, but also future generations. Usually, every new product, such as a new car model, is based on a predecessor and a previous generation. The more complex technical systems become, the greater the development cost for the model in the new product generation, and the more worthwhile it becomes to look further into the future, so as to develop a technical solution that is useful in the long term. The first car manufacturers are already focusing on product generation engineering. Vehicles are being designed currently that will not come onto the market for another twelve years or so. This approach is interdisciplinary, very much in line with Advanced Systems Engineering. Experts are needed who can make reliable assessments as to how society is changing and what the future needs of users will be. Also required are experts who can assess the future evolution of new materials and production processes. Thus, the development of technologies, markets and business environments must be thought through in advance as part of strategic product planning. This is set out in the PGE model and consequently made available on an ongoing basis. Finally, you need the designers of the product generations, who implement all the interdependent boundary conditions and requirements in product solutions as part of a unified model, the PGE.

The concept of Product Production CoDesign (PPCD) points the way towards the Advanced Systems Engineering of the future. Until now, the process from product development to product manufacture has taken place in separate steps. First, the product is developed in several synthesis and analysis cycles. Then comes the design of the equipment and tools required and of the production line. The problem is that often it subsequently emerges that it would have been possible to optimise production by making minimal changes to the product during the development process, except that by then it is too late. PPCD involves a different approach. Consideration is given to the manufacturing of the product during the product development process. The future production system is designed at the same time as the product is being developed and the requirements placed on the product by the resulting production system are continually communicated and directly considered in the product design. This results in both cost and energy savings, making production more sustainable.

Another new methodological element is what is known as the digital twin of a product. A digital twin is a digital representation of a real product or process: i.e. a virtual copy that is updated in real time and contains information on how the real object functions and behaves. A digital twin can be used in the development process to conduct virtual tests before a physical product is manufactured. This makes it possible to gain an initial insight into the quality of the future product design at a very early stage of the product's development, meaning that it can be further improved as necessary. In the context of the Systems of Systems, the digital twin can also provide valuable contributions regarding the use of the product: e.g. in order to optimise the performance of a product or of production equipment or to carry out predictive maintenance. In the case of an autonomous vehicle, the digital twin can record in real time how the vehicle behaves and intervene to optimise this. Given the possibility that in the future there will be a digital twin in the cloud for every car on the road, every domestic washing machine and every piece of company equipment, it is already clear that we will not be able to deal with the resulting increasing complexity unless we apply Advanced Systems Engineering.

Product Generation Engineering (PGE) and Product-Production-CoDesign (PPCD) may not yet be as all-encompassing as the ASE solutions of the future. Nevertheless, they demonstrate how development processes might run one day and thus represent approaches for holistic Advanced Systems Engineering.

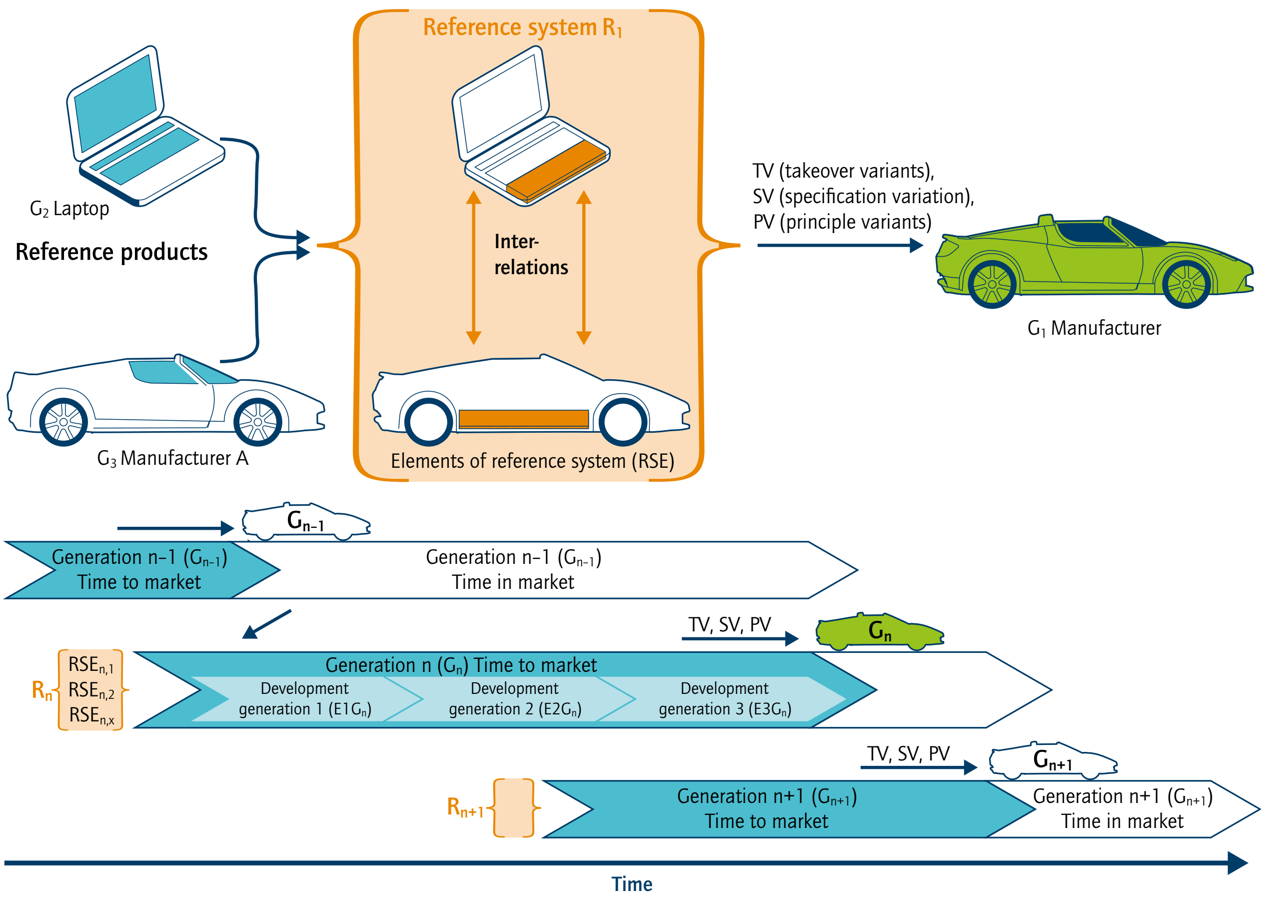

Figure 2: The Product Generation Engineering (PGE) model describes several generations of products and their interdependencies as a basis for Advanced Systems Engineering (Source: authors' own illustration).

Advanced Systems Engineering is required to ensure the next generation of washing machines and the next-but-one generation of cars are designed in a way that is better, safer, more sustainable and more holistic: i.e. for perfectly normal business operations, not just for fancy things. ASE helps tackle problems to which solutions have not been found to date.

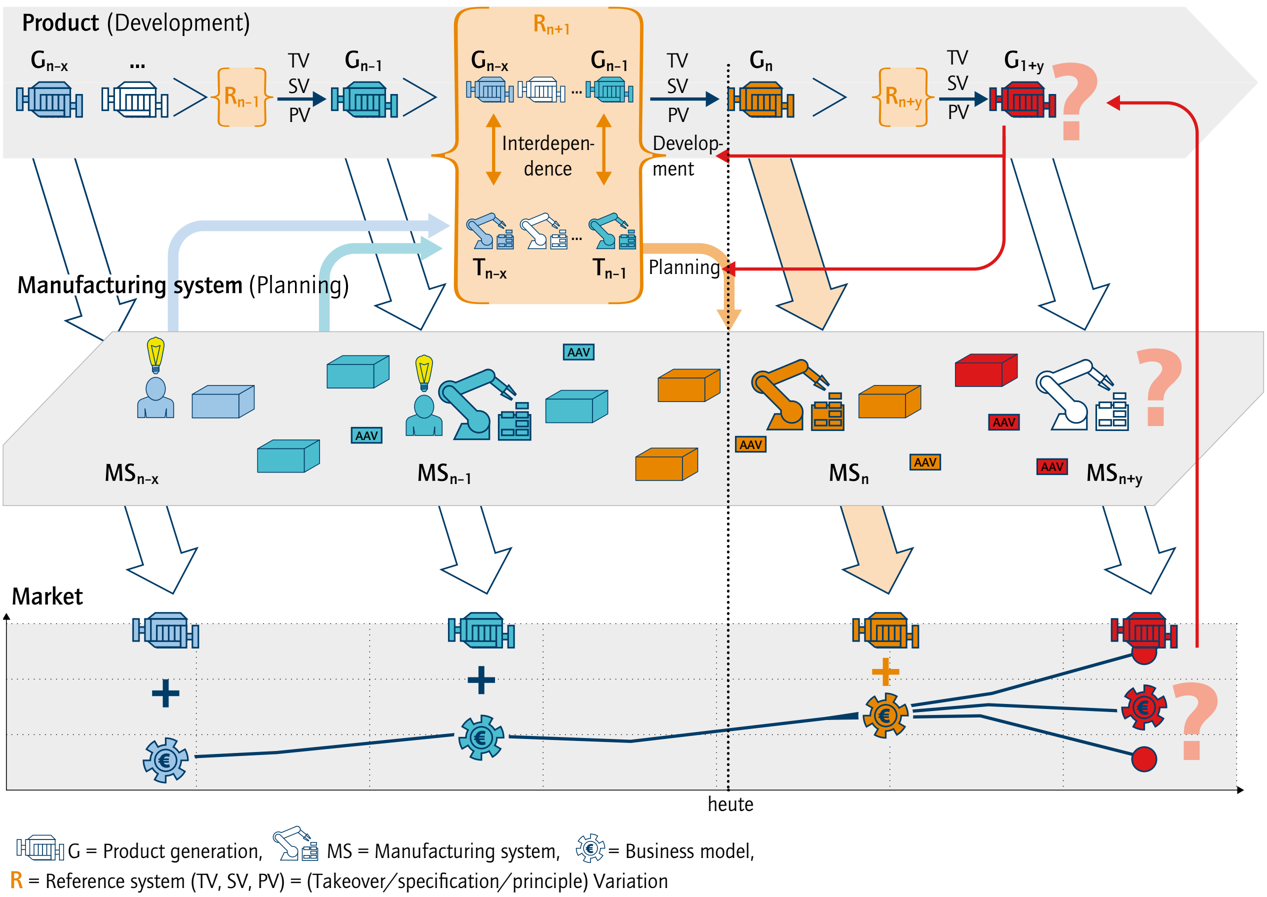

Figure 3: Product-Production-CoDesign. An Approach on Integrated Product and Production Engineering Across Generations and Life Cycles (Source: authors' own illustration based on Albers et al. 2022)

2 ASE application scenarios – today and in the future

The full complexity of the Systems of Systems is best explained using specific application scenarios. These demonstrate how many technical and social aspects will be affected in the future by these systems. The following examples also demonstrate that in the final analysis only Advanced Systems Engineering can bring together the many different aspects and specialist disciplines to devise holistic, sustainable and highly-effective solutions for the whole of society.

2.1 The smart home

The Systems of Systems of the future are no abstract concept. On the contrary, many Systems of Systems will have a significant impact on our everyday lives, starting in our own homes. For some time now, smart home technologies have been becoming more popular. It has long been possible to dim your living room lights using your smartphone or to have a quick look at your garden at home while you are on holiday via a surveillance camera. These are functions that are already inexpensive to purchase, as even discount stores and major furniture chains have for some time now supplied equipment for the smart home. It takes just the touch of a button on your mobile phone to extend the awning or switch on the garden sprinkler. If the technology is combined with a smart speaker, everything can be switched on and off with a voice command. The smart home of the future should be able to do even more, using a smart meter, for instance, to interact with the electricity grid.

The washing machine provides a good example of the great variety of things that will be possible in the future. Today, we already have washing machines that can be controlled via a smartphone app. In the future, it is conceivable that a washing machine would be able to calculate from its wash cycles how much detergent it has used. If required, it could order fresh supplies by itself. In the smart home of the future, all appliances would be linked via the smart meter. This would have the advantage that you would be able to take readings about the status of each appliance from any of the others. If you were working in the kitchen, you would be able to check on the oven display how far the washing machine located in the cellar had advanced through its programme. In the future, all home appliances should also be able to communicate with each other. The washing machine could, for example, send the tumble dryer information about its current load so that it can pre-set its programmes accordingly to easy-care or synthetics. Smart meters and the smart home also enable communication with the electricity grid, so that the washing machine or dishwasher can be operated at certain times of day based on the electricity price. When the price is low, they will switch on automatically and, if there are solar panels on the roof, the smart meter can switch on the appliances when the sun is shining.

The washing machine example demonstrates how, in a few years' time, many systems will be interacting, even in an apparently simple everyday application. In the future, it is likely that many more features will be added. The smart home and the smart meter make your own four walls into a System of Systems, in which equipment technology, communication systems and the electricity grid interact in a dynamic way. Advanced Systems Engineering will therefore make the successful development of appropriate technical solutions an absolute necessity in the future.

Compounding the problem is the fact that technologies are being newly developed and improved nowadays at a very fast rate. It would be expensive and not sustainable to throw away electrical appliances such as a washing machine after only a few years and replace it with a new one which complied with the latest smart home standard. Manufacturers must therefore ensure that a washing machine can be kept up-to-date, by providing it, for example, with interfaces for new features or new software standards from the outset. Advanced Systems Engineering makes it possible to gauge accurately any future needs and the technologies that will be required, because it regards a product, from the very beginning, as an entire holistic system. What is helpful here are methods such as product generation engineering, whereby when a technical solution is being developed, it is not only the next product generation that is considered, but also future generations. Given the rapid development of the smart home, manufacturers should take greater account of these aspects in the future, if they would like to continue to sell long-lasting products to their customers.

Advanced Systems Engineering is the methodology required to develop systems in such a way that they can communicate with each other.

Tomorrow's smart home

In the smart home of the future, all appliances should be connected to each other via smart meter. All household appliances should be able to communicate with each other. The smart home and the smart meter make your own four walls into a System of Systems, in which equipment technology, communication systems and the electricity grid interact in a dynamic way. Advanced Systems Engineering will therefore make the successful development of appropriate technical solutions an absolute necessity in the future.

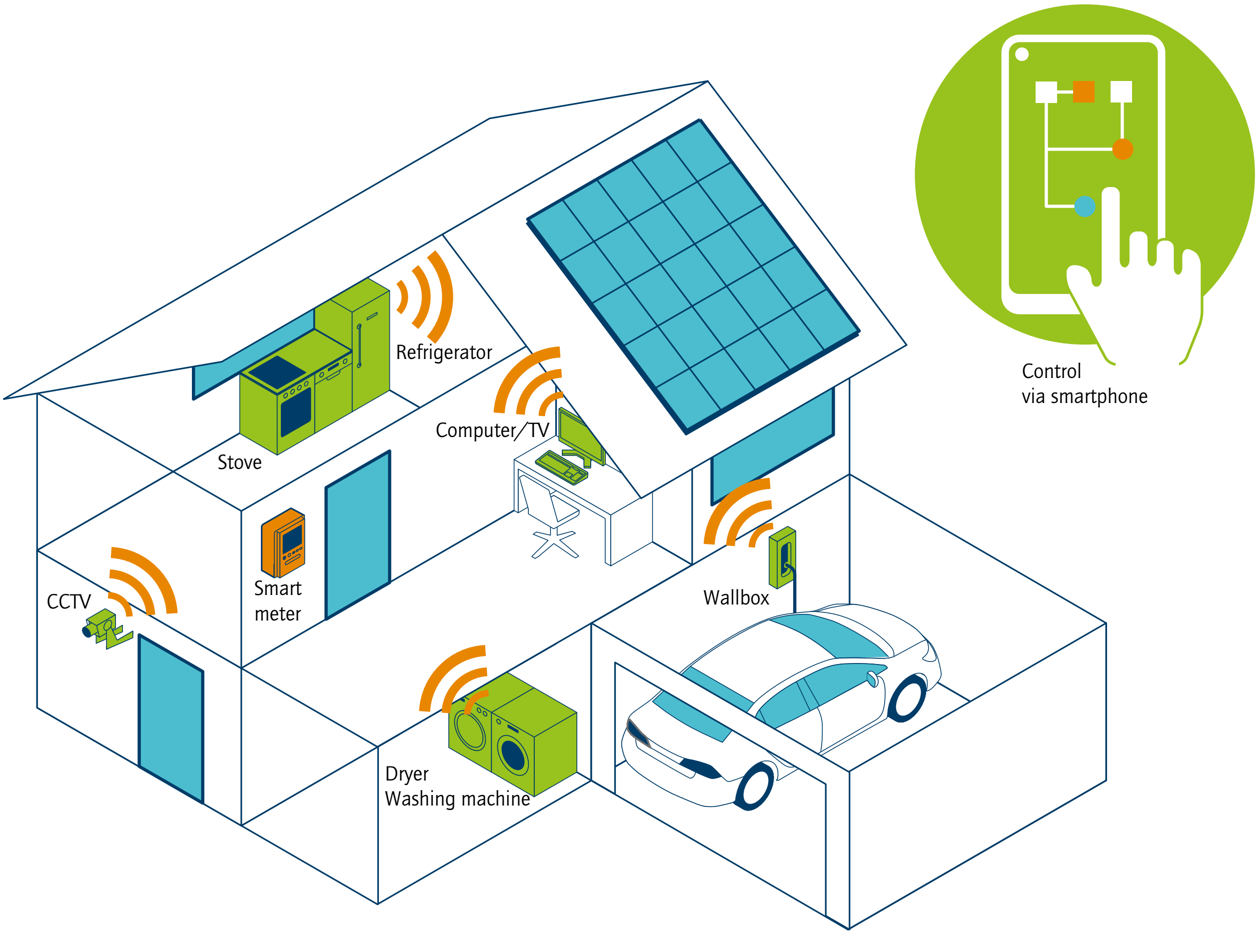

Figure 4: Exemplary illustration of a smart home with several interconnected appliances (Source: authors' own illustration)

2.2 Autonomous driving with Advanced Systems Engineering

Germany in 2050: Most cars, trucks and buses are electric and drive autonomously. Vehicles are equipped with cameras, sensors and intelligent software that enable them to detect obstacles within fractions of a second and react accordingly to avoid them. Moreover, the vehicles communicate with each other via ad-hoc networks: i.e. dynamic intervehicular communication networks that are spontaneously generated. This means that cars can warn each other about accidents that may be hidden behind a bend or obscured by fog. Trucks on the motorway can also form dynamic convoys, where they travel one behind the other like railway trucks in order to save energy. Trucks in the convoy could also work together to ensure that other motorists enter and exit the convoy safely. Of course, vehicles also have contact via mobile communications with digital road signs and traffic control centres that constantly provide information about issues such as sudden congestion and traffic jams or speed restrictions, thereby preventing accidents and significantly improving road safety.

The autonomous driving example illustrates once again how various systems interact and also the fact that future systems must be able to react in a dynamic way to changes in their surroundings and to self-optimise. Obviously, cars have been equipped for more than twenty years now with systems that can react dynamically to changes, systems such as the Electronic Stability Programme (ESP) which prevents the vehicle from skidding. However, these are separate systems that have an individual impact on vehicle handling. With autonomous driving, on the other hand, we are dealing with a socio-technical System of Systems that connects people and technology in a particularly complex way. If there is a thunderstorm, for example, a systems autopilot will need to consider far more aspects than for normal driving. It will need to adjust the speed of the vehicle and its braking to take account of the wet road. It will need to anticipate aquaplaning. It will need to be more careful when overtaking. However, above all, it will need to be aware of the sudden change in behaviour of other road users. The main technical challenge here is to evaluate the behaviour of non-automated road users, such as pedestrians and cyclists and also vehicles still being driven by people. Experts anticipate that it will only be a few years before vehicles will take over the driving on clear stretches of motorways. In complex areas such as on construction sites and above all in normal road traffic, it is expected to take a few decades before cars can cope with automated navigation. This is also due to the fact that it is not possible to comprehend the complexity of these Systems of Systems with present-day development tools. This will require Advanced Systems Engineering. To prevent accidents, autonomous driving has to be extremely safe and resistant to error. A precondition of this is that vehicles understand each other and react to each other. Pedestrians and cyclists as well as non-autonomous vehicles must also be considered and technically described in the systems. Future Advanced Systems Engineering methods will enable these human objectives to be much better realised in the course of the development of products and production systems.

Autonomous driving with Advanced Systems Engineering

Private taxis and minibuses are becoming increasingly popular in cities because they are more flexible than city buses, trams and underground systems. They can be summoned to your front door and take you directly to your destination. In the future, private taxis and minibuses are expected to drive autonomously through city centres. the concept of autonomous urban private taxis or minibuses is a System of Systems within which many different technologies interact. People will only use this system if they have confidence in it. Here too, due to its holistic approach and the common language employed by engineers as well as lawyers, Advanced Systems Engineering offers the opportunity to arrive more quickly at a safe solution and a secure System of Systems.

Figure 5: Exemplary illustration of a connected traffic system (Source: authors' own illustration)

Travelling safely on the road with Advanced Systems Engineering

Private taxis and minibuses are becoming increasingly popular in cities because they are more flexible than city buses, trams and underground systems. They can be summoned to your front door and take you directly to your destination. In the future, private taxis and minibuses are expected to drive autonomously through city centres. Driverless minibuses are already being tested on a limited basis in some German towns and these are expected to supplement existing bus and rail services in the future. As described above, the concept of autonomous urban private taxis or minibuses is a System of Systems within which many different technologies interact. People will only use this system if they have confidence in it, especially when it comes to transporting children safely to their destination (see diagram). Safety has many aspects that need to be taken into account when developing the System of Systems. One of the questions that needs to be asked, for example, is who is responsible if there is an accident: the vehicle manufacturer, the taxi company or the subcontractor who supplied the distance detection radar? These legal aspects need to be considered when developing the System of Systems. Advanced Systems Engineering makes it possible to take all these things into account and to describe them in the technical models.[3]

It is a particular challenge for developers to make a system so safe that it reacts correctly in every situation. Accidents and malfunctions must be avoided at all costs if customers are to have confidence in the system. For this reason, technical systems nowadays are validated and verified on a regular basis in the course of their development. The validation process examines whether the product actually meets customer expectations. For an autonomous taxi, this would mean transporting a person safely and in comfort from A to B. During the verification process, in turn, tests are conducted to ensure that the vehicle is constructed in such a way that it meets certain constraints. Does the software that controls the airbag sensor work quickly enough? The problem is that it is not possible to run through and pre-test every conceivable everyday scenario involving people that might arise in road traffic situations. Conventional systems engineering has its limitations. Here too, due to its holistic approach and the common language employed by engineers as well as lawyers, Advanced Systems Engineering offers the opportunity to arrive more quickly at a safe solution and a secure System of Systems. Customer confidence is a crucial factor in deciding whether a technology becomes established in the market. It only takes the slightest thing to go wrong for customer approval to fall. Autonomous systems will therefore only become established in the market if most people accept the technology. Only if all the developers involved communicate perfectly with one another will it be possible to give customers a feeling of security. Advanced Systems Engineering can make a significant contribution here. A core element of Advanced Systems Engineering is a holistic approach to delivering reliability when it comes to the design of complex technical systems. This requires features such as security, reliability, availability and confidence, which are of vital importance, especially in the highly-connected digital world of the Systems of Systems.

3 | See KIT Mobility Systems Center 2017.

2.3 Creating transparent supply chains

These days nothing can be done without computer chips. They are built into cars, smartphones and industrial robots. Supply bottlenecks as a result of Covid-19 have resulted in many places in the past two years in production restrictions and even stoppages, especially in the automotive sector. In January 2021 alone, around 15 percent [4] fewer vehicles were produced than at the same time in the previous year, despite demand remaining at a consistently high level. The example of tiny chips shows how easily the close-knit network of global supply chains, streamlined as it is to achieve maximum efficiency, can unravel.

Essentially, global value chains can be regarded as a vast System of Systems. If one link in the chain is broken, all the subsequent links are affected. A smartphone consists of many different components which are produced by a large variety of suppliers from all over the world. If there is disruption at a major supplier, the entire production system no longer functions. To avoid situations like this, it is crucial for companies to keep an eye on their whole supply chain. That is a challenge, because the supplier is dependent in turn on its own suppliers. Staying with this analogy, attached to each link in the chain is another autonomous system – another company with its own production methods and its own supply chain. Thus, the global value chain rapidly morphs into a particularly complex System of Systems (SoS).

An automotive manufacturer may need to keep an eye not only on the microchip market, but also on the chip supply chain, which goes back as far as the raw materials. Every blind spot in the supply chain carries the risk of the chain breaking unexpectedly at that point. Advanced Systems Engineering can help to identify the blind spots. Thanks to its holistic approach, the many interdependencies between the various stages of the value chain can be described and can be presented in an easily comprehensible model. Many parties are involved in globally connected production and the transport of goods. The common language provides, for the first time, the transparency required to understand the global network in all its complexity. Ultimately, it will be possible as a result to collect all the key information about each link in the supply chain and to share that information – along all the links in the chain, both within and outside the company, with partners, colleagues in the field and experts from different disciplines, and also with lawyers, ethicists, controllers, logistics specialists, risk managers or buyers. All in all, Advanced Systems Engineering, with its potential for transparent modelling and interdisciplinary connectivity of people in complex value creation processes offers the opportunity to know at any time what is happening where and when. Advanced Systems Engineering can also help with the implementation of the German Federal Government's new Supply Chain Due Diligence Act. [5] According to the law, German companies must ensure in the future that all their suppliers along the production chain are providing their workforce with fair working conditions.

Safety and Security

In technical and IT systems, the German language uses the term "Sicherheit" to mean two different things that are expressed in English using two different terms: "safety" and "security". The term "safety" refers to occupational or operational safety and means that a technical solution is so safe that people and the environment are protected from harm. The term "security", on the other hand, focuses on measures and technologies that are used to protect systems against various types of threats and attacks and to ensure the confidentiality, integrity and availability of data. It includes data security and the security of software and digital infrastructure. The term cyber security is also frequently used. Techniques such as encryption technology and authentication methods are used to protect IT systems against attacks.

4 | Federal Statistical Office of Germany 2021.
5 | See Act on Corporate Due Diligence Operations in Supply Chains 2021.

Creating transparent supply chains

These days nothing can be done without computer chips. They are built into cars, smartphones and industrial robots. Supply bottlenecks may cause production restrictions and even stoppages in many places. Global value chains can be regarded as a System of Systems. Every breakdown in the supply chain carries the risk of the chain breaking entirely. Advanced Systems Engineering can help: Thanks to its holistic approach, the many interdependencies between the various stages of the value chain can be described and can be presented in an easily comprehensible model.

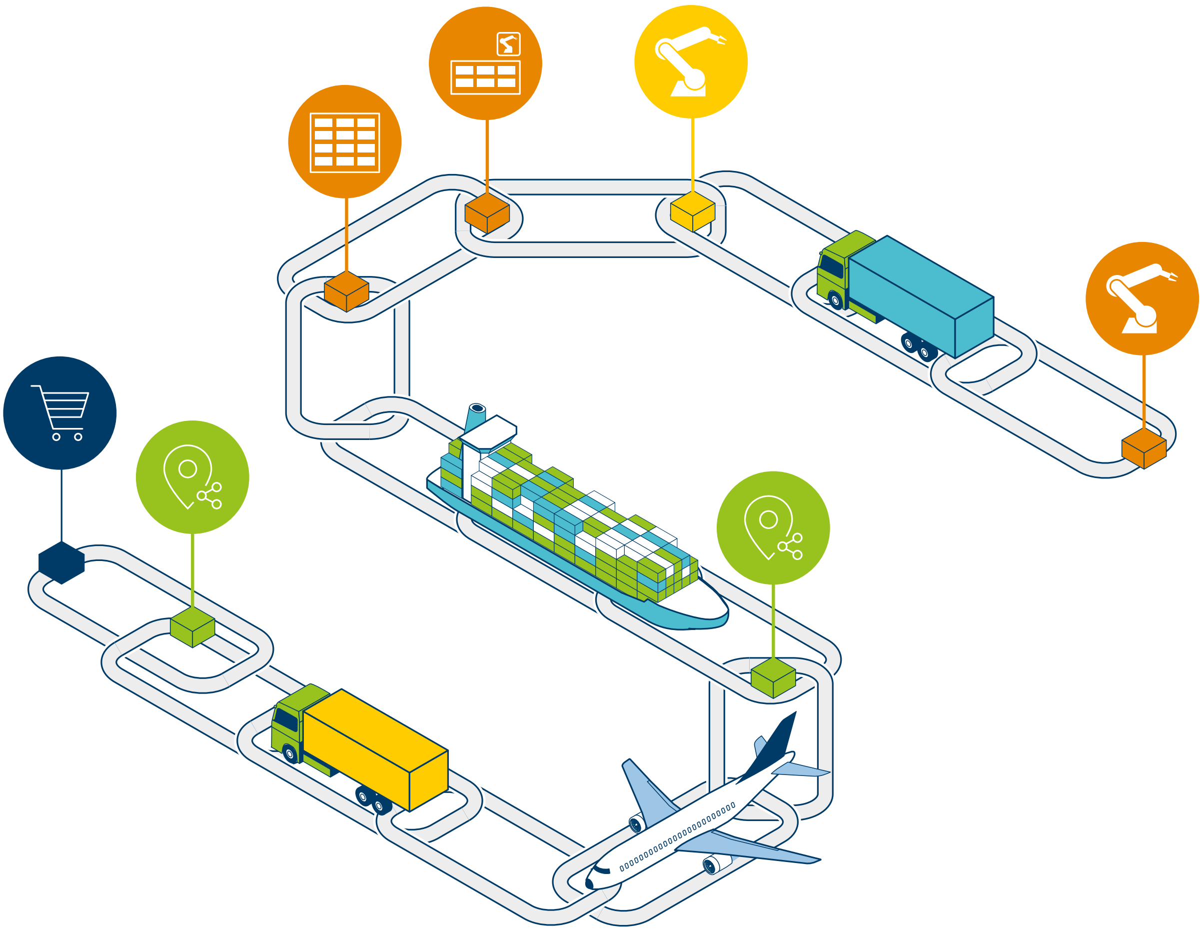

Figure 6: Global supply chain connectivity (Source: authors' own illustration)

2.4 Sustainable energy supply with Advanced Systems Engineering

In view of climate change and recent sharp rises in the price of oil and natural gas, renewable energy is becoming increasingly important. In Germany, over forty percent[6] of electricity production already comes from renewable sources, because more and more wind farms and photovoltaic systems feed their electricity into the power grid. One of the main reasons for this is that PV systems have fallen in price over the past few years, so that increasing numbers of homeowners can afford to buy solar roof panels. That creates its own challenges:

Over the next few years, there will be more movement than ever in the power grid, as a result of the many households feeding electricity into the grid from their solar panels and also of the growing number of electric cars, which increase electricity consumption in a residential area. If in the future many people in a particular area plug in their electric cars after work, small local power transformers will quickly be overloaded. In addition, the electricity supply varies constantly depending on the weather. On sunny days, solar panels produce more electricity than is needed. On rainy days, they do not supply enough electricity. For some time now, PV systems have therefore been combined with power stores.

To strike a balance between production, consumption and storage, small distribution networks in towns and districts need to become smarter. This can only be done by using artificial intelligence, as electricity has to be fed into the grid from numerous systems, and storage and consumption need to be coordinated and harmonised with the entire electricity grid. Advanced Systems Engineering can help here. One example is regional solar power producer associations, whose members offer each other solar energy and storage capacity when they do not need it themselves. Moreover, the producer association is connected to the grid and can therefore be active at a supra-regional level. All in all, the many small PV systems can provide relevant amounts of electricity. If on the other hand there is an oversupply of electricity in the grid, storage systems are used. The producer association thus functions as a small power plant. Advanced Systems Engineering will be a crucial factor in the future design of such flexible Systems of Systems, enabling the many different elements of an intelligent power network (the smart grid) to be linked together and described in a model – electricity production and storage in many small systems, trading between the members of the producer association, and communication with the supra-regional power grid. The real challenge here is managing the large volumes of data that will need to be exchanged between the many producers and consumers. This includes creating standardised interfaces, so that the information can flow unhindered. Such data systems are so complex that it will scarcely be possible in the future to design and implement them without using Advanced Systems Engineering.[7]

Overcoming the challenges presented by the climate crisis will only be possible if we adopt technical solutions. In the future, we will use Advanced Systems Engineering to design sustainable and reliable technical solutions to these challenges.

6 | Federal Statistical Office of Germany 2022.
7 | See Fehrenbach 2019.

System of Systems – the power grid of the future

The traditional power grid is gradually being transformed into a smart power grid. In this power grid of the future, many automated decision-making systems would interact in a complex and dynamic way – a typical System of Systems.

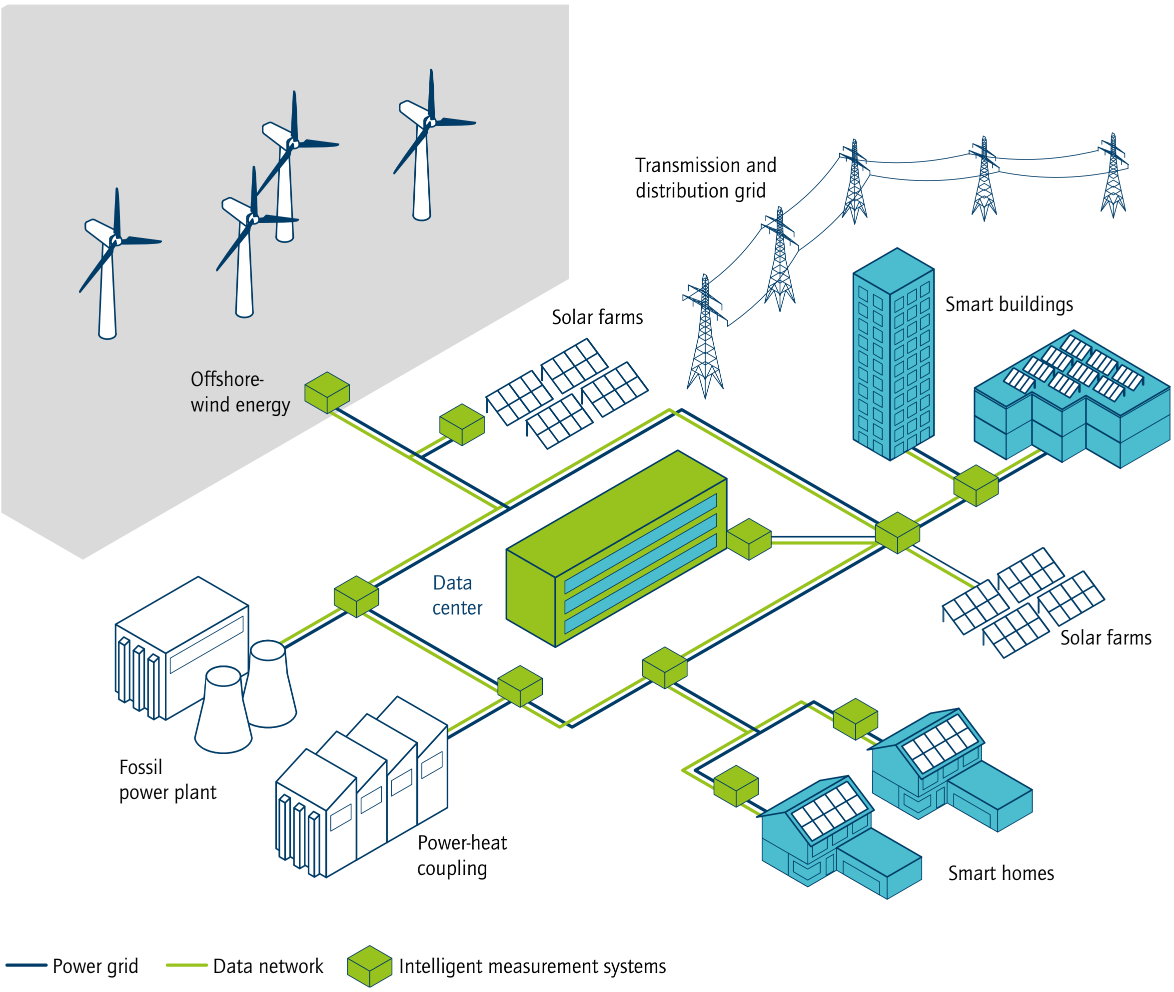

Figure 7: Illustration of a modern intelligent electricity grid as a System of Systems (Source: authors' own illustration)

3 Advanced Systems Engineering from a global perspective

Designing innovative products and business models, especially in complex Systems of Systems is becoming increasingly important. This raises the question as to how well-positioned Germany is here in the face of global competition. One analysis shows that Germany is quite well-placed compared with other nations, but that in some areas it still has significant ground to make up.[8]

Germany's innovative strength is based on research and development. It is thanks to R&D that Germany is among the world's leading innovators. Above all, German companies have excellent links with scientists and benefit from this particular type of application-oriented research, working alongside Germany's higher education institutions. At the same time, companies have international links with other national economies in the form of supplier networks and development partnerships. For many years, the world's technology leaders have included not only Germany, but also the USA, Japan and the UK. However, this situation is changing. Now countries like South Korea, Singapore and China are strong and innovative competitors. This is demonstrated by their increasing success with technologies such as electromobility and artificial intelligence, which are heavily driven by research.

Systems engineering plays a key role in the development of such challenging new technologies. The industrial nations have recognised systems engineering as a key competence in the race for the future. If here you look at the number of publications as an indicator of relevance in research, then the USA, China and Germany are the leading players. All three countries significantly stepped up their research activities between 2012 and 2018. The growth in the number of publications shows that Germany, with an annual increase of eight percent, is expanding its systems engineering research much faster than the USA, where the increase was four percent per annum. China is increasing the number of its publications each year by 33 percent – an impressive figure. However, systems engineering in China is less concerned with the holistic, systematic approach practised in Germany. Instead, it is a subsection of control and automation technology. Direct comparisons between China, Germany and the USA are therefore difficult. What is certain is that the holistic ASE approach being described here is not yet the focus in China, which puts the impression of that country's dominance into perspective. However, with regard to Germany, the aim is to invest huge efforts in continuing to strengthen its position in ASE research and thereby to create a solid methodological basis for German companies, enabling them to remain successful in the future in the face of global competition.

In comparison to the rest of Europe, Germany is also a pioneer in systems engineering research. The driving force for this is the close relationship between science and industry in university research and applied research, as is the case for example at Germany's applied research organisation, the Fraunhofer-Gesellschaft. Other examples include basic research institutions such as the Max-Planck-Gesellschaft and the Helmholtz Association.

In the field of research into methods and processes for the design of complex Cyber-Physical Systems (CPS) such as those in autonomous vehicles or connected robots in production as a core component of Advanced Systems Engineering, it is clear to see in general that the number of research publications in Germany on the topics of digital twins and PLM is the same in absolute terms as the number of such publications in the USA and China. However, German research into agility in engineering, creativity in engineering and artificial intelligence in engineering is in certain areas significantly less than the amount of such research in the USA and China.

Needless to say, having a smaller number of publications on the topics of creativity or agility in engineering does not automatically mean that German engineers are less creative or agile. On the contrary, they are among the most creative people in their profession worldwide and in 2021 they again filed the second largest number of patents in the world. However, the numbers indicate that the USA and China are focusing very strongly on the topics of agility, artificial intelligence and creativity in engineering. To contribute towards ensuring Germany's competitiveness in the future, it is essential to increase the amount of research in this area and for this research to be implemented in practice in Germany.

Advanced Systems Engineering will significantly drive forward today's solution approaches. The lesson we need to learn from the international comparison is that there is a need for innovation and ground to be made up, especially in the areas of artificial intelligence and agility. Even if Advanced Systems Engineering

8 | See Dumitrescu et al. 2021.

poses a technological challenge, it also provides a tremendous opportunity for Germany, which recognised early on the strategic importance of a systemic holistic approach. To ensure or indeed strengthen Germany's technological lead and economic position on the global markets of the future, and thereby also to preserve jobs, further investment in research and development in the area of Advanced Systems Engineering is absolutely essential. Only thus can Advanced Systems Engineering form the backbone of future value creation.

As is demonstrated by the growing publication and research intensity in other countries, the window of opportunity for this is narrow. Meanwhile, Germany's global competitors have also recognised the importance of holistic design of complex technical systems for future value creation in those countries. They have long since greatly intensified their research in this area. As a result of the strong world-leading links it has established between science and industry and its early focus on the challenges of designing complex cyber-physical systems, Germany is in an excellent starting position. However, the time has now come to act, to engage in research and to invest in Advanced Systems Engineering.

4 The way into the ASE world

As mentioned above, a ready-to-use toolbox of ASE methods and applications does not yet exist. This raises the question as to what is needed to turn theory into practice. As Advanced Systems Engineering is based on an interdisciplinary approach, it is clear that Advanced Systems Engineering will only succeed in Germany if it becomes a major joint project between industry and the recognised research institutions in all the relevant areas. A strategy comprising six action points will provide the way into the ASE world.[9] These action points need to be addressed to secure the future of jobs in Germany and also to ensure the country's prosperity.

1. **Strengthening strategic competence.** Companies must be able to draw up a strategic plan for their business model, starting with the development of the product all the way through to the product being used by the customer. Know-how is often lacking here, especially in small and medium-sized enterprises. On the one hand, this means looking outward, identifying developments in the company's environment at an early stage and categorising them in relation to the company's business model. On the other hand, it means looking inward, in order to make a realistic assessment of the skills and weaknesses within the company and to remedy any shortcomings. This is the basis for strategic planning.

2. **ASE platform – orchestrating the wide range of activities.** Advanced Systems Engineering is a task that must be undertaken jointly. It will only succeed if all the specialists from the various fields coordinate their actions. To achieve this, a national ASE platform should be created in Germany that brings together all the parties from industry, science, government and civil society. The aim should be to establish Advanced Systems Engineering under the slogan "German Engineering" as a globally recognised standard for training engineers in the system language for designing cyber-physical systems and in the development of methods. The purpose of this German platform is also to keep an eye on and anticipate global developments.

3. **Promoting innovations in methods.** In accordance with the ASE approach, systems as well as Systems of Systems will need to be planned differently in the future, based on a methodology. This means that hardware, software and the environment should always be considered as a single entity. The systems and especially the software should be planned so that they can always be adapted in line with new requirements and technical developments while continuing to function properly. This is the only way in which systems can be developed that will satisfy sustainability and reliability requirements. The longer a product or system can be used, the more sustainable it is.

4. **Further intensifying cooperation between industry and science.** Knowledge transfer must become more firmly embedded as the third pillar of the German higher education system, after research and teaching. The unique cooperative relationship in Germany between industrial research and research in higher education institutions must be developed even further for the future. As a unique selling point for Germany as an industrial location, this cooperation is crucial to future success. New regional and national leading-edge clusters in Germany can help to pool skills from industry and the higher education institutions.

5. **Enhancing education and professional development.** The shortage of skilled workers in Germany compared with leading industrial nations is its Achilles heel in the race to head up the design of innovative technical solutions of the future. Although there are certainly individual initiatives throughout Germany that aim to inspire young people to take an interest in Mathematics, IT, Natural Sciences and Technology (known in German as MINT subjects), large-scale campaigns have been lacking up to now. Serious efforts are therefore required in the area of education and professional development to increase Germany's chances in the global competition for innovation. Taking this into consideration, there is a need to strike out in new directions. Highly effective ways to enhance professional skills are industry placements for school pupils and students and interdisciplinary study programmes covering ASE methods and processes. Practice-oriented project assignments and a professional development campaign can make a significant contribution towards addressing the shortage of skilled workers. As Advanced Systems Engineering involves a number of new methods and new ways of thinking, people aged 50+ should also be considered and mobilised here. Advanced Systems Engineering will continue to develop in a dynamic fashion as time goes on. Individual lifelong learning will therefore be required so that the workforce is always in a position to face the new challenges.

9 | See Gausemeier et al. 2022.

Nurturing key skills in the engineers of tomorrow

Encouraging cross-functional thinking and working

The system in Advanced Systems Engineering is synonymous with heterogeneity and complexity. A variety of disciplines have to work together. Ultimately, it will only be possible to build products such as cars and aeroplanes by working in large teams. Cross-functional thinking and working will need to be included in university curricula. It does not make sense here for the overall goal to be "general engineering studies", given that the person who knows a little about everything in the end knows nothing at all! However, the key message is that concepts introduced for one domain may be transferable to another domain and that Advanced Systems Engineering lays the very foundations to support future cross-functional thinking. Competence in ASE needs to become a matter of course in all science and engineering disciplines! To give but one example, it would be practical as well as cost-effective to set up joint interdisciplinary projects in the form of placements, in which 3D printers were used for the mechanics, FPGAs for the electronics, and the processors on them for the software of a system solution. This would enable students from different domains to learn about, practise and experience Advanced Systems Engineering together!

Enhancing modelling skills as a key foundation of system design

The model is the modern workhorse of science and technical system development. However, according to George Box, all models are false and only some are useful. This core insight, formulated originally for statistical models, applies generally in science. Newtonian mechanics and Bohr's atomic model make it possible to understand a number of effects and can be used as a basis to design systems. However, they have their limitations regarding the speed of light and atomic structure. Education about modelling, opportunities and limitations associated with models, and the connection with statistics and abstraction must begin in school. These topics should constitute a key part of the course or feature prominently in the school curriculum. Incidentally, many measures taken during the Covid-19 pandemic may have increased people's knowledge of the opportunities and limitations associated with models. This basic understanding is thus not only indispensable for Advanced Systems Engineering, but also of general social relevance.

6. **Introducing more widely new ways of working.** Advanced Systems Engineering can only be successful if those involved learn and apply new ways of working. These include aspects such as agile working in flat hierarchies and flexible project-oriented structures. New business models in the platform economy may arise in this way. More cooperation is also required at a European level, in order to set joint standards for new engineering tools and to remain globally competitive. Last but not least, there will be a need to keep an eye on digital sovereignty and to set European data protection standards.

In the future, Germany should continue to occupy a leading position internationally in the engineering of technical and socio-technical systems. This is how we intend to face the key challenges of our time such as digitalisation, energy supply, mobility and sustainability and to emerge from the imminent upheaval as a winner.

A new model for Advanced Systems Engineering

As Advanced Systems Engineering is based on an interdisciplinary approach, it is clear that Advanced Systems Engineering will only succeed in Germany if it becomes a major joint project between industry and the recognised research institutions in all the relevant areas.

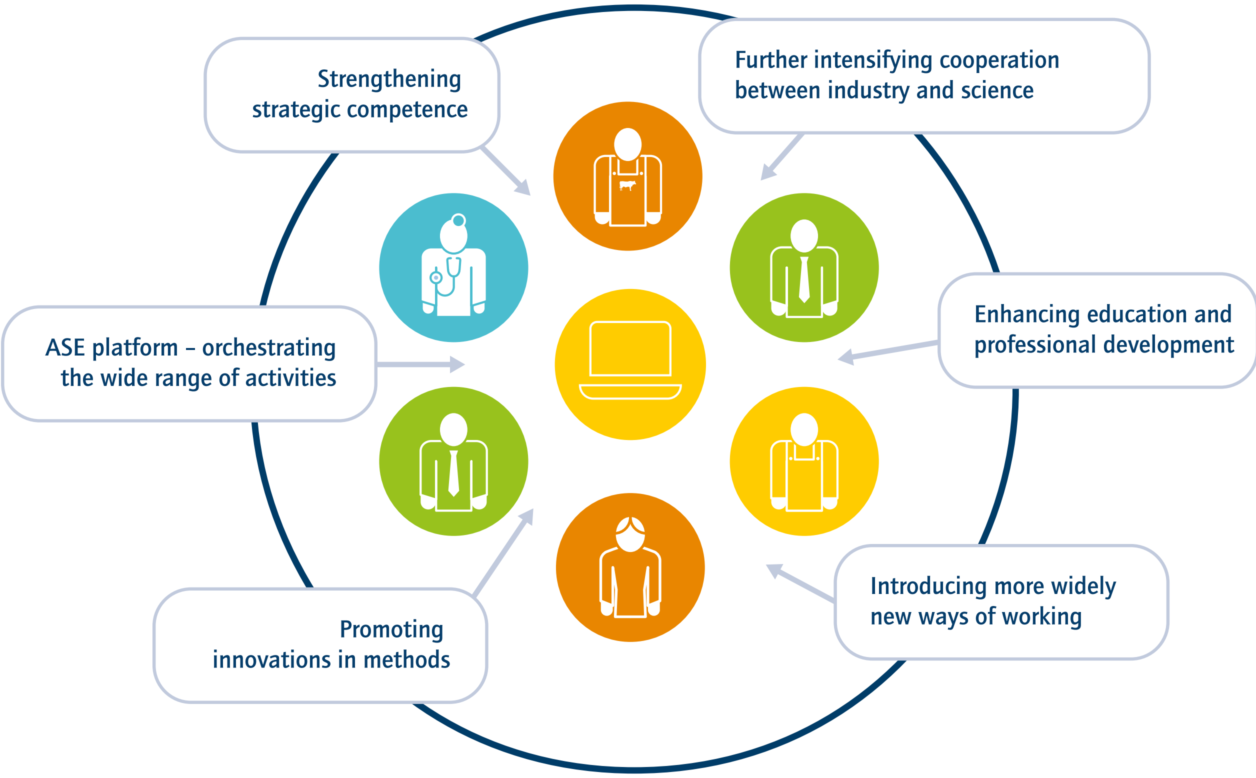

Figure 8: Model for Advanced Systems Engineering (Source: authors' own illustration)

Encouraging the younger generation to study MINT subjects (Mathematics, IT, Natural Sciences and Technology)[10]

The shortage of skilled workers in Germany is particularly noticeable nowadays in technical occupations. Therefore, it is important that both girls and boys are introduced early to technology. As women have until now been underrepresented in technical professions, it is particularly important that we reach out at an early stage to girls and inspire them to engage with MINT subjects. According to the current "MINT Nachwuchsbarometer", a survey of young people about careers in science and engineering, subject choices for boys and girls have changed little in the past few years. "In physics and technology, boys predominate. Only 25 percent of those who choose to do an advanced physics course as part of their school-leaving examination in Germany are girls, while young women comprise only 11 percent of those participating in training in MINT subjects, and only 25 percent of those who embark on an engineering degree are women." This underrepresentation of girls and women in MINT subjects continues from early years education through to higher education or training, and finally to the choice of career. To counter the shortage of skilled workers, education and professional development in MINT subjects must be made more attractive for girls and women. It is also necessary to inspire more people overall to engage with these subjects – including older workers from other professions and of course talented people from other countries and regions. In addition to the new technical approaches and methods, these aspects are key to the promotion of Advanced Systems Engineering.

10 | See acatech/Körber Foundation 2021.

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The technical world around us is becoming ever more complex and interconnected. This is a world in which autonomous cars will need to consider other vehicles and road users, a world where electricity systems will depend on the coordination of thousands of solar systems, wind turbines and electric cars. Driving this transformation are increasingly powerful mechanical components, microprocessors and intelligent software, all connected to each other and to control centres via the internet. In the future, more and more experts from different disciplines will need to work together to develop such complex systems.

However, until now, there has been no common “technical language” linking all disciplines, complicating and slowing down the development of new technology. Advanced Systems Engineering (ASE) will provide a solution to this in the future, by devising a common language that can handle this increasing complexity. ASE will ensure clear communication between experts from different disciplines, so that in the future they will be able to continue to develop secure, reliable technical systems within a reasonable period of time.