COLLABORATIVE ENGINEERING

CHARACTERISTICS AND CHALLENGES OF CROSS-COMPANY PARTNERSHIPS IN THE INTEGRATED ENGINEERING OF PRODUCTS AND SUPPORTING SERVICES

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Peter Gabriel
Steinplatz 1
10623 Berlin
gabriel@iit-berlin.de

Authors
Dr. Matthias Künzel
Dr. Tom Kraus
Sebastian Straub LL.M.

Design and layout
Loesch*Hund*Liepold
Kommunikation GmbH
Hauptstraße 28 | 10827 Berlin
paice@lhlk.de

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Management Summary

Engineering is crucial for the economic success of products and services. However, the criteria for success change: Price, quality and functionality are no longer the only key factors. Instead, engineering increasingly creates the prerequisites for future business models by supplying supporting services and new ways of product upgrades. In the future engineering will accompany the entire lifetime of a product.

Against this background, it is extremely advantageous if operational interaction between companies, which is taken for granted today, also reflects in a process of collaborative engineering. In this way, manufacturing being strongly characterised by a division of labour and multi-component-systems can be mapped in a joint engineering process involving multiple companies. As a result, components and end products can be better coordinated in the initial design phase. Should any changes or further developments occur at a later point in time, component manufacturers, system integrators as well as new stakeholders can develop the system further without the need to carry out time-consuming data transformation or stock-taking processes.

Most of today's experiences in collaborative work can be found in research and development (R&D), i. e. primarily during the pre-competition phase. This interaction is often described by the catchword 'open innovation'. Close co-operation models have also made their inroads into manufacturing, one example being automobile production with its supplier network. Moreover, subcontracting engineering services have become common practice today. Subcontracting, however, refers to limited and rather temporary business relationships that are additionally based on clear-cut contractual relationships (commissioning). The collaboration model, on the other hand, is based on equality. Regional innovation clusters, for example, represent such an ecosystem aimed at equality and long-term strategic partnership that has proven to be economically successful in recent decades.

In the context of this study, face-to-face and group interviews were conducted with 36 experts from companies and research institutions in order to learn about their views regarding the challenges of collaborative engineering in the fields of technology, work organisation, economics and law and/or to obtain their feedback on a draft version in a review workshop.

It was found that it was still too early for a detailed strategic roadmap for the concrete implementation of collaborative engineering. The status quo and foreseeable steps to create the basis for collaborative engineering can nevertheless be well described:

From a technical perspective, foreseeable and necessary steps to take are the development of data and exchange formats being compatible across domains and value chains, the ability to ensure data consistency among collaborators and the development of tools that allow for a task-specific dimension reduction. Artificial intelligence will be included in engineering as a newly available capability. As an engineering tool, however, the employment of artificial intelligence will continue to be limited to routine tasks in the foreseeable future due to the technology's current state of development.

Whilst engineering, especially with regard to its creative component, is less likely to be fully automated, changes in work culture will definitely take place: Heterogeneous teams, agility and quasi-parallel work present new challenges. Regional and technical cultural differences can only be overcome by strengthening interdisciplinary communication skills and developing a culture of communication.

The challenge of data management and storage in future collaborative engineering is one example that illustrates the complexity due to the close interaction between different examination levels. Here, technical aspects as well as economic and legal factors will be crucial for all future developments. Both centralized platform concepts and decentralized peer-to-peer solutions appear to be promising and have their pros and cons for different use cases. Accordingly, it remains to be seen which solution for collaborative engineering and the associated value chains and business models will prevail in the capital goods industry.

The legal situation in collaborative engineering is worrying for users in various respects. Conventional approaches fail to map global value chains to national legislation adequately. Strongly internationalised copyright or patent law will have a key role due to the importance of the 'level of creativity' characterizing individual and collaborative engineering services from a legal point of view. On the other hand, the legal concept of 'data sovereignty' as the basis for business models in a data-driven economy is only in its early development phase. Elaborated contractual agreements can compensate for this, but might lead to an image of asymmetric market power.

The concept of the digital twin will have to be expanded in order to fulfil its key function as a virtual image of products, services and processes and to reflect all the observation levels relevant for the engineering process itself. This expansion will, for example,

- enable the simulation of business models for economic potential evaluation,
- incorporate information regarding the authorship and expertise of individuals,
- establish collaborative business and participation models
- and also take nationally applicable regulations and laws into account.

The expanded digital twin will hence become the key element of success for the widespread use of collaborative engineering.

1 Introduction

Collaborative engineering is a special form of cross-company collaboration that can take place at different stages of the lifecycle of technical plants, products, services and processes. Collaborative engineering is characterised by a parallel, collaborative work process involving several stakeholders (engineers, technicians and computer scientists) who usually work at different companies. What typically motivates collaborating companies is the generation of competitive advantages with regard to innovation, capacity or efficiency.

The consistent use of software tools for design, construction, simulation, testing, product data management and technical documentation during the design phase has long been common practice. This enables both shorter design phases and coordinated interaction between different disciplines (such as mechanics, electronics, software engineering) in the engineering process and hence more efficient solutions. Especially for long-lived assets, however, engineering is no longer limited to the early phases of the value chain. engineering has increasingly become a task accompanying the whole life-cycle, from system integration, ongoing operation, maintenance, retrofitting and system redesign, right through to dismantling.

It is likely that in the foreseeable future joint engineering processes involving different companies will be much more common in manufacturing. Already today the manufacturing sector is characterized by multi-component systems and a respective division of labour (integration of supplier parts). This way, it will be possible to better match supplier parts and end products with each other, create the basis for new services, increase resource efficiency and implement new product properties.

Requirements increase as cross-company collaboration in engineering advances: At a technical level, the software systems involved are becoming significantly more heterogeneous, and different working methods and processes must be taken into account. From an economic perspective, collaboration must pay off for all stakeholders, taking typical product lifecycles in the capital goods industry into account.

However, the prerequisites and success factors for collaborative engineering are still largely unknown. It is still not clear whether solutions and experience from other markets and ecosystems can simply be transferred to engineering as a key element of industrial value chains:

- Digital platforms have become tried-and-tested tools of the digital economy. In their current form, today's platform models, such as markets or open data-based systems, appear to be only conditionally suitable for engineering tasks since they do not adequately reflect economic interests, data storage periods, intellectual property issues and legal constellations.
- The differences that exist in legal systems can create a considerable degree of uncertainty with regard to collaborative engineering processes. In collaborative engineering, global value chains collide with regulations that are strongly influenced by national law and that have different interpretations of business models and different definitions, for example, with regard to copyright, data sovereignty or intellectual property law.
- Collaborative engineering will bring about changes in work organisation and management processes. The elimination of hierarchical structures and dynamic team compositions, for example, must be taken into account by appropriate management methods.
- At a technical level, the preconditions for a later integration of yet unspecified components or services must be created as early as during the initial engineering design phase.

In order to address these and other questions, the present study was prepared as part of the accompanying research programme PAiCE. For this purpose, 36 experts from companies and research institutions were interviewed or asked for feedback on a study draft versionwithin the framework of a review workshop.

Chapter 2 describes the methodology of the study in detail. Chapter 3 outlines the current debate among experts regarding the expanded concept of engineering and today's approaches to collaborative engineering. The main focus of this study is on the survey of experts regarding the practical challenges of collaborative engineering and initial approaches that were made to find solutions. These results are presented in chapter 4. Chapter 5 summarises the results of the interviews and analyses. Chapter 6 outlines first steps for the sustainable implementation of collaborative engineering and identifies challenges that have yet to be tackled.

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The responsibility for the content of this study lies exclusively with the authors.

2 Methodology

The methodological basis of the study was a multi-level approach consisting of literature research, structured discussions with representatives from business and academia and a final validation workshop (Fig. 1).

Fig. 1: Process model of the present study (© iit)

The results of the literature research and the analysis of the expert debate (chapter 3) clearly suggest that the future success of collaborative engineering will not only depend on technical preconditions, but that a multi-layered analysis model will be needed instead. These results served as a basis for developing a guideline for structured interviews with representatives from the industry and academia as well as with multipliers. The guideline first focuses on collaboration management, in other words the structural framework for cross-company collaboration, followed by the technical, organisational, economic and legal facets of collaboration (see Fig. 2).

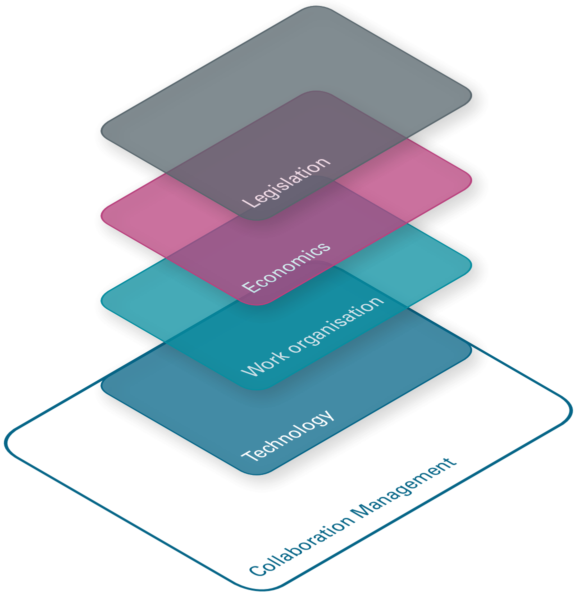

Fig. 2: Examination levels of collaborative engineering

On the basis of the literature research, a key question was aked and seven to eleven aspects were proposed for prioritisation and subsequent in-depth analysis at each of the five examination levels.

During the interviews, participants were first asked about the completeness of the given list of aspects and given the possibility to add further aspects to it and then the experts were asked to prioritise the aspects. Specifically, the interviewees were asked to define precisely one ‘Priority 1’ and one ‘Priority 2’ for each examination level. With this approach topics being of medium importance to the interviewees are at risk to become less visible in the overall analysis. However, this is compensated for by the clear focus on the most relevant topics identified by the interviewees. Given the very broad-based subject of the study, this approach was considered reasonable.

In a second step, a free discussion with the interviewees then addressed current questions and challenges of the respective aspects for priorities 1 and 2 (Fig. 3). Aspects supplemented by the interviewees could also be prioritised, but none of the supplemented topics achieved an outstanding position across the surveys, regardless of the differences in wording.

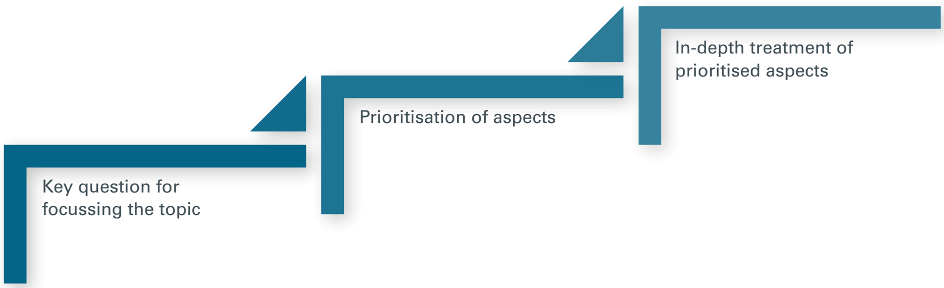

Fig. 3: Multi-stage interview design

When selecting the interviewees, attention was paid not only to their expertise in at least one of the four examination levels, but also to choosing a mixture of representatives along the value chain (research, engineering service providers, suppliers, OEMs) with experience in committee work, networks or analogous structures implying an additional high-level perspective of the interviewees to discuss topics such as collaboration management.

Some interviews were conducted as group interviews without changing the methodological framework. The results in question were fully included in the evaluation.

During a verification workshop, a draft version of the study was presented to a group of experts who were not involved in the interviews. In addition to the same selection criteria as for the interviewees, this group of people additionally had to meet the special requirement of being multipliers, for example, within the framework of cluster management or an industry network.

3 State of the professional discourse

Collaborative engineering implicitly refers to an extended engineering concept that goes beyond the initial design of plants, products, services or processes. This extension is described at the beginning of the chapter to outline the current technical discussion on engineering. Then, we take a look at different types of co-operation and collaboration between companies and present first practical examples.

3.1 Extending the term 'engineering'

The present study focuses the term 'engineering' strongly on the requirements of Industry 4.0 and its pioneer sectors (mechanical engineering, vehicle and plant construction), where the related fields of design technology, electrical engineering, electronics and information technology are of significance.[1] The lifecycle of products in these industries often ranges from many years to several decades and is increasingly characterised by product-related services. Business models that combine classic products ('hardware') with smart services on a customer-specific basis (European Commission 2012; Harbor Research Inc. 2014; acatech 2016) are becoming increasingly important. The expansion of product-related services and collaboration also represents a new potential for the regional economy. Hence, the global approach of digital platforms interacts with the value chains (Komninos et al. 2018).

With the demands placed on products for a digitally interconnected industry, the demands being placed on engineering are also changing at regular intervals, making it necessary to constantly extend the classic term 'engineering' (Künzel et al. 2016). A new feature added during the last decade is smart engineering for the design of communication-enabled, smart products and supporting services that have the potential to trigger sustainable change in information exchange and product lifecycle management (PLM) (acatech 2016, 2014). Another noteworthy manifestation is digital engineering which affects all phases of the product emergence process and includes, for example, predictive analytics and big data analyses, and ultimately enables traceability of product and production data even beyond company boundaries. A current study on the spread of digital engineering approaches in the manufacturing industry can be found in (Bitkom e. V. 2017). Virtual engineering can be seen as an extension of digital engineering and focuses on supporting the design of products, equipment or services using augmented and virtual reality representations and tools. Virtual engineering is another important extension of the engineering concept given the increased use of these technologies. Systems engineering, a long established discipline, is also of great importance for the development and efficient operation of complex systems. Due to increasing interconnection of subsystems in industry, systems engineering has become one of the key sub-disciplines of engineering. Simulation continues to be the most important instrument in this context with regard to the ideal system design and operation as a basis for decision support and process optimisation. When it comes to planning complex industrial plants, the concept of front-end engineering design (FEED) or front-end loading (FEL) was developed for basic and cost planning and serves as a basis for estimating technical, financial and time expenditure for implementing large-scale projects.

1 The methods of bioprocess engineering, which are often collectively referred to by the term 'bioengineering' are expressly not covered by this study.

3.2 The 'digital twin' approach and virtual image

Once the design phase has been completed, any re-design or extension of a product, process or service is very likely to generate significant costs. Simulation-based analyses for quantifying relevant technical properties are therefore part of the established portfolio of methods in the design phase of every sufficiently complex development. Respectively, simulations are used extensively today as a guarantee for high product and service quality and short development cycles. However, the relevance of virtual images of products, processes or even services is no longer limited to the design phase and to the beginning of the value chain. For example, the monitoring of operating data and its targeted transmission to manufacturers or service providers for monitoring or maintenance purposes is becoming increasingly common today. Based on sufficient and suitable operating and machine data, customer-specific predictive maintenance services are made possible due to virtual images. Since manufacturers and service providers can benefit from more realistic simulation possibilities due to the regular transmission of operating data by users, considerable quality improvements can be achieved on this basis when adapting or re-designing products, services or processes.

The concept of the 'digital twin', which contains a virtual image of real products or processes (Grösser), has recently become established in industry. Despite differing conceptions regarding the precise technical design, this virtual image generally contains a description of the elements and the dynamics of the associated real product, process or service as well as relevant status information throughout the respective lifecycle. The digital twin can thereby function as a real-time representation of its real-life counterpart, act as a memory for relevant lifecycle information or be used for simulations of all kinds. Within the context of Industry 4.0, the digital twin and its possible applications offer enormous potential for optimisation over the entire lifecycle, from integration and operation to maintenance and reusability.

The right design of a digital twin

- can support commissioning, upgrading or conversion of real systems significantly with virtual planning if the corresponding modularity and software interfaces are foreseen when designing digital images of systems or components (integration),
- enables time-efficient or energy-efficient operation of real systems if suitable information on system dynamics is available (operation),
- can help to predict failure probabilities and avoid machine outages if suitable information on system dynamics is available (maintenance),
- can help to achieve efficient reuse of elements or materials (in the case of products) if suitable data is available over the entire lifecycle (reusability).

All of the possible uses mentioned here are technical by nature. Furthermore, certain aspects of work organisation, such as user expertise, are already being considered in digital twins of complex products and systems in order to enhance the human-machine organisation. It goes without saying that the digital twin can itself become an economic factor given the possibilities for boosting the efficiency of products, processes or services. Since potential for economic collaboration can also be derived directly or indirectly via simulation, it is also conceivable that virtual images can support the assessment of collaboration potential. Given the right modelling of collaborative systems, it is theoretically even possible to consider different stakeholder interests that cannot be compared in quantitative terms in the design and operation of the systems on the basis of multi-objective optimisation approaches.

3.3 Collaborative engineering

Collaborative engineering requires two or more parties to share and modify a common pool of content in order to create something new. According to (Shen et al. 2008), collaborative engineering is a concept for optimising engineering processes to enhance product quality, reduce manufacturing lead times, make costs more competitive and achieve a better customer experience.

(Stiefel 2011) already analysed information technology approaches for cross-organisational data exchange, which could be used to support more efficient knowledge processing in collaborative engineering. Even at that time, hierarchical architectures were considered too inflexible to support collaboration networks of the future generation. Instead, architecture approaches of peer-to-peer computing were assumed to be more suitable. The goal was defined as the 'development of an approach for future loosely coupled collaboration platforms' taking into account important key IT technologies, such as 'service-orientated architecture (SOA) or model-driven software development (MDSD)' (Stiefel 2011).

In the meantime, the platform architecture has become established for many comparable tasks. Applications range from music distribution to trading in new and used goods in the private and business sector to mobility and many more. B2B businesses also rely on platform solutions in certain areas, but this has not yet become common in engineering. Swedish Jönköping University, for example, conducts scientific analyses on the root causes of this fact, highlighting challenges, peculiarities and a possible solution:

- The success of a platform ultimately depends on on the benefits and positive experience it offers customers. Customer satisfaction in industry often depends on highly customised products where engineering faces fluctuating requirements. This demanding task differs from that of companies who develop consumer products using fixed specifications and where product platforms or modular approaches have successfully enabled efficient adaptation. Such classic product platforms are often unable to fully support companies in such an environment (André et al. 2017).
- As part of this research, a design platform was created for engineering tailor-made products that goes beyond conventional platform concepts. The use of the platform provides a coherent environment for heterogeneous design assets by supporting both the design activity and the finished solutions (Elgh et al. 2017). The treatment of economic and legal issues was not examined.

The overall picture is that of a solid foundation of technical solutions for collaborative engineering which are an important basis for internal company processes. However, there is still no holistic analysis that includes the legal, economic and work organisation aspects which are all crucial for collaborative engineering beyond company boundaries.

3.4 Company cooperation and collaboration

The quality of cooperation between economically and legally independent companies can be classified according to three processes or mechanisms which differ in terms of their objectives and the intensity of interaction, i.e. coordination, cooperation and collaboration (Borsato und Peruzzini 2015). Whilst coordination usually requires a less extensive exchange of information in order to coordinate the content or timing of sub-tasks, cooperation and collaboration are characterised by several parties working together on a shared problem. Unlike cooperation, however, collaboration no longer allows for the division and delimitation of sub-tasks that parties can work on individually, so that this is usually where the greatest complexity of interaction arises. A clear hierarchical relationship exists between the three above-mentioned processes since collaboration always requires coordination and cooperation.

3.4.1 Typologisation

Cooperation or collaboration between two or more companies makes sense if real added value can be generated for all stakeholders. Such liaisons must therefore at least justify the effort needed to coordinate among the companies. Typical motivations for respective liaisons are access to new technologies, reduction of costs and risks, as well as strategic time and flexibility advantages (Jensen 2001; Moerman et al. 2016). (Wouters et al. 2017), for example, consider a defined common goal of the partners, the continuous synchronisation of activities, a sensibly managed exchange of data and, last but not least, a certain degree of complementarity of the partners' competences to be key conditions for successful collaboration.

Greater cost and time efficiency in the development and production of complex and sometimes customised products is a typical goal of cross-company liaisons in engineering. (Krause 2007) identify the following key requirements for successful collaborative engineering:

- the use of common ontologies to represent complex data models and knowledge representations,
- the integration of external processes into internal company work processes in conjunction with suitable technical security infrastructures to protect the companies' intellectual property,
- the appropriate coordination of technical and organisational processes.

Different types of cooperation and collaboration exist (see Table 1). Possible types include loose networks, typical manufacturer-supplier relationships and cluster organisations, as well as strategic alliances and system partnerships that differ, for example, in terms of integration depth, partner coordination and openness (Steinhorst 2005). Whilst typical networks and manufacturer-supplier relationships usually emerge from considerations related to products and projects, strategic alliances and system partnerships can also be geared to longer-term strategic goals, such as joint series development. Concrete framework agreements, time scales and the depth of integration of company divisions can be designed accordingly to meet the specifics of the given situation. Cluster organisations are also geared to long-term strategic objectives, but not at product or product group level, but at the level of industries or regional value chain networks (Meier zu Köcker et al. 2016).

At the same time, a distinction is also made between cooperation and collaboration on the basis of the dependence of the companies in the value chain or the value chain network, respectively. Vertical partnerships are configurations where companies at different market levels co-operate with each other. This includes the outsourcing of functional areas, partnerships along the value chain or franchising systems. Horizontal partnerships, on the other hand, are forms of cooperation and collaboration between companies of the same market level. This includes temporary liaisons or longer-term ties in strategic alliances or even cartels. Clusters comprise both horizontal and vertical cooperation with the additional involvement of research institutions.

In addition to the types of company liaisons presented here, there are also so-called co-creation processes where end customers – business customers and end consumers alike – can also be involved and play a crucial role in the different design phases, especially for products. This form of partnership can also be classified as a special type of collaboration. Co-creation does not necessarily lead to (open) innovation. From the point of view of manufacturers and service providers, however, the risk of 'misunderstanding customer needs' can to some extent be reduced by co-creative processes. Particularly in industries charecterized by constant technological innovation it is beneficial, if certain customer preferences can be identified from these co-creation processes. In the interest of correct terminology, it is important to note that the mere selection of, for example, given design elements or features is not yet considered to be co-creation. Surveys of customers show that they have a much more positive perception of companies that enable co-creative participation and that this also reinforces brand loyalty. At the same time, surveys of companies show that the main advantage of co-creative customer participation from the manufacturer's perspective is seen in the increased probability of satisfying customer requirements (Hitachi Europe Ltd. 2015).

3.4.2 Characteristics and best practices

It is apparent that awareness of the importance of networks and strategic positioning among companies in Europe is growing (Moerman et al. 2016). In this respect, collaborative engineering is just a small part of a new quality of cross-company co-operation. However, concrete examples of collaborative engineering are still relatively rare:

Manufacturer-supplier relationships, strategic alliances and system partnerships

Managing co-operation has become part and parcel of the day-to-day business of both companies and associations. Targeted and strategically initiated networks have proven to be a success factor for large companies (IBM Deutschland GmbH/XAX 2012). At present, '...the competitiveness of a whole series of industries is no longer conceivable without establishing a strong network of manufacturers, suppliers, complementors and customers' (Künzel et al., p. 16).

It can be seen that particularly innovation-intensive sectors (such as photonics, biotechnology) and industries where close cooperation with suppliers is common practice, such as the automotive (Morel et al. 2016; Ferreira et al. 2017) or the aviation industry (Baalbergen et al. 2017; Mas et al. 2013), excel in implementing innovative pilot projects of collaborative engineering. For strategic alliances that can drastically increase the capacity and technical innovation potential of companies, best practices are of great benefit since studies show that the failure rates of these alliances range between 40 and 70 percent (Moerman et al. 2016).

	Types					
Characteristics	Network	Cluster	Manufacturer-supplier relationship	Strategic alliance	System partnership	Co-creation
Scope	Concept development, series development and production	Concept development, framework conditions and strategy	Series development and production	Concept development, series development and production, strategy	Concept development, series development and production	Customised concept development and production
Integration depth of development	Very low to rather high	Rather high to very high	Very low to rather low	Rather high to very high	Rather high	Very low to rather low
Value creation stages	Horizontal, vertical	Horizontal, vertical	Vertical	Horizontal	Vertical	Vertical
Partner coordination	Federative, focal	Federative, focal	Focal	Federative	Focal	Focal
Capacitive redundancy	Single, dual, multiple sourcing	Single, dual, multiple sourcing	Dual, multiple sourcing	Single Sourcing	Single Sourcing	Single Sourcing
Competition	Open	Open	Open, restricted	Restricted, excluded	Restricted	Not applicable
Openness	Selective	Selective	Time-related, project-related	Selective, time-related	Project-related	No
Contract type	Informal/formal, multilateral	Formal and multilateral	Formal and bilateral	Formal and bilateral	Formal and bilateral	Formal and bilateral
Stability	Case-by-case basis, project-related	Long-term strategic	Case-by-case basis, project-related	Long-term strategic	Project-related, long-term strategic	Project-related
Autonomy	Balance, temporary imbalance	Balance	Temporary imbalance, dominance	Balance	Balance	Dominance

Table 1: Typology of cooperation and collaboration forms (based on (Steinhorst 2005))

Best practices can be derived from pilot projects as well as tried-and-tested workflows. One example of a strategic alliance is the involvement of three large German car manufacturers in the 'Here' map service which was established as a result of a common strategic interest. The partnership has led to the establishment and further development of industry standards for connecting services in vehicles from different manufacturers.

Co-creative processes

A majority of companies from the engineering domains have not yet integrated co-creative customer involvement into their internal processes. Developments in this direction are probably most evident in the automotive industry: For example, several car manufacturers operate co-creation labs or organise co-creation events in order to involve customers in the design phaseor the development of 'concept vehicles'. One example of such a concept vehicle is the MOIA shuttle from Volkswagen which is designed for ride pooling (Volkswagen AG 2017).

In the manufacturing industry, 3D printing (additive manufacturing) and corresponding 3D printing platforms are important enablers of co-creative processes. Today, 3D printing processes are increasingly used in most engineering sectors and beyond, for example, in plastics production, the chemical industry, mechanical and plant engineering as well as in the automotive and aviation industries. There is a clear trend towards the use of 3D printing services: In a cross-border company survey(Müller und Karevska 2016), a high share of respondents (41 percent) stated that their company was planning to buy components from 3D printing service providers in the future. Only a significantly smaller share (26 percent) consider using or purchasing their own 3D printers for additive component manufacturing. Since many customers do not have the required know-how, the role of 3D printing platforms or service providers is often not limited to printing, but also includes co-creative activities (Rayna et al. 2015). Due to the duplication and manipulation possibilities offered by 3D printing, there are special requirements on such 3D printing platforms for technical security solutions when it comes to handling IP management, traceability and the differentiation between legal and pirated prints (Engelmann et al. 2018; Holland et al. 2017).

Clusters

Industry-related network concepts go beyond the level of forms of cooperation between companies. Combining vertical value chains, the concept of strategic alliances and innovation processes leads to a new level of quality of covoperation. This cooperation is complemented by working together with universities, other research institutions and multipliers. Networking in this form is particularly important when it goes hand in hand with regional proximity and intensive co-operation. This is then referred to as a cluster. The competitive advantages of clusters are improved division of labour and positive external effects within the 'triple helix' of companies, research and multipliers (politics, business development, associations).

Especially for smaller companies, close networking with their environment is the perfect catalyst for combining their own skills and expertise with those of other parties. This applies both along the value chain and with regard to complementary competencies and resources.

Despite modern means of communication, the regional aspect, i.e. the geographical proximity of the individual stakeholders, is still a crucial component today. Clusters and networks that benefit from the geographical proximity of partners are more than just a loose association. Depending on their stage of development, they may even be viewed as virtual companies having long-term strategies that are supported and implemented by a targeted service portfolio. This requires professional coordination, usually in the form of cluster or network management (Müller et al. 2012). Research results suggest that powerful clusters can generate above-average economic benefits (Ketels und Protsiv 2013).

The engineering process often has a key role to play in transforming new technological or methodological approaches into innovative products and services that are connected to or based on such products. (Künzel et al. 2015) investigated the role of clusters in such collaborative innovation processes. One example of such an engineering-related cluster is 'it's OWL' (East Westphalia-Lippe region), an award winner within the framework of the top cluster programme of the Federal Ministry of Education and Research (BMBF) (Rothgang et al. 2014).

4 Challenges and solutions from an interdisciplinary expert's perspective

The interviews and review workshop with the experts primarily addressed the practical challenges of collaborative engineering and the currently foreseeable solutions from the academic and economic experts' perspective.

4.1 Collaboration management

4.1.1 The baseline situation

Collaboration is particularly widespread at pre-competition level: Collaborative R&D projects involving industry and research institutions are part of everyday life. The R&D programme of the German Federal Ministry for Economic Affairs and Energy (BMWi) for joint industrial research has been up and running for decades (Kind et al. 2013). At the competition level, which includes engineering, collaboration is subject to stronger restrictions. Despite a considerable increase over the last 20 years in the context of networks and clusters and under the buzzword of 'open innovation', collaborative work in engineering is less widespread as a key process for obtaining unique selling propositions.

Systematic knowledge about collaboration management and, in particular, of the 'soft' sociological factors for collaborative engineering is therefore limited.

4.1.2 Assessment from a practical point of view

The environment for cross-company collaborative engineering (collaboration management) was first discussed with the experts during the interviews. The aspects shown in Fig. 4 (left and middle) were put up for discussion in this context. The right column shows the aspects that were added during the interviews.

KEY TOPICS	SELDOM PRIORITISED	ADDITION
Common benefit/goal/motivation of collaborating parties (short/medium/long term)	Key persons who support and live co-operation	Development and training of a common (co-operation) culture/cultural openness in management/overcoming 'co-operation phobia' in industry
Competent network management	Complementarity of skills	No inclination towards collaborative work at schools, in training and further professional qualification
Focusing collaboration (selection and suitability of topics)	Development of normative rules for collaboration	Joint identification of collaboration partners
	Joint R&D projects	Platform technology
		Task management

Fig. 4: Key question – Collaboration management: Which general basic requirements do you consider to be most important for collaborative engineering? (© iit)

More than half of the experts rated the aspect *'common benefit/goal/motivation of collaborating parties'* as priority 1 or 2. This is by far the highest value for the key question regarding collaboration management. This is followed by the aspects *'competent network management'* and *'focusing collaboration'*. All in all, this prioritisation opens up a field for the structural framework between company strategy, benefit considerations and social competencies of key stakeholders. The additions made can be well-integrated into this field.

Benefit and motivation of collaborating parties

During the discussion on this topic, the experts voiced high and quite different expectations of successful collaborative engineering with regard to the aspects of time savings, enhancing quality and minimising risk during the development, production and maintenance process. The importance of long-term strategic collaborations that go beyond engineering became clear. Furthermore, several experts consider collaborative engineering as a mere sub-aspect of an entire collaborative value chain – in this respect, the other phases of the value chain and the complete product lifecycle must be included in the benefit analysis. Some interviewees also mentioned better knowledge of customer needs as motivation for entering into a corresponding form of cooperation.

Following the often time-consuming search for and identification of suitable partners and application spectra suitable for collaborative engineering projects, many experts believe that stakeholders need to define clear-cut development goals, suitably plan input requirements and regularly review benefits. According to several experts, appropriate basic and resource planning is indispensable, especially for complex joint development projects, so that joint strategies and business models can be implemented on the basis of realistic development budget planning. In plant engineering, front-end engineering design (FEED) or front-end loading (FEL) could serve as a model, especially if the agility of development processes with regard to customer integration is less important.

Another question was how qualitative goals of collaboration partners and the success of collaboration as a whole can be measured – the metrics of collaboration pose a challenge and are obviously handled differently by the stakeholders themselves when considering one and the same project.

The purely economic benefit of stakeholders in long-term collaborations is measured by the business and/or participation models and, in particular, by how these are structured over the entire lifecycle of products and services. At least one expert argued that such business models often did not include attractive participation in profits, for example, for system integrators, so that there was no incentive for costly developments of sustainable solutions, for instance, for optimising manufacturing processes across plant boundaries.

Competent network management

Together with the focus on collaboration, competent network management is seen as the second important challenge and success factor of collaborative engineering. In the interviews, it became clear that personal relationships and forms of communication are seen to be significant for success beyond the anonymous platform world. Several interviewees emphasised the importance of interconnecting people, key persons and basic values as well as the risk of 'talking at cross purposes'. It is also noticeable that experts repeatedly refer to regional proximity and cluster organisations as success factors, a fact that seems to directly oppose the possibilities of global digital collaboration.

Since the persons involved are potentially distributed across different hierarchical levels of the collaborating companies, which may have different organisation forms or cultural backgrounds, successful network management requires not only interdisciplinary but also intercultural and integrative skills, according to several interviewees. The willingness to be part of a 'philosophy of collaboration', which includes the sharing of certain basic values, was mentioned several times as a basic precondition which all stakeholders should fulfil to a certain extent. The same applies to company hierarchies along the value chain: During the actual joint development process, a level playing field of the co-developing companies must be ensured, regardless of possible dependencies between companies.

Focusing collaboration

Collaboration must be focused both at the individual company level (on which topics do I cooperate, what do I do on my own?) and at the network level (which topics do we tackle together and how?). Larger companies generally pursue a dedicated strategy for the topics where they enter into cooperative relationships (both in engineering and in other phases of the value chain) and which are shielded as core competencies. The experts believe that many smaller companies lack such a consequent orientation or that they find it difficult to achieve this since they are more dependent on market constraints.

The experts repeatedly emphasised the importance of a long-term collaboration strategy, considering that engineering increasingly takes place not only at the beginning of the value chain, but also repeatedly during the course of re-engineering, retrofit or other adaptation processes throughout the product lifecycle. At the same time, the initial engineering design provides the foundations for future use, options for business models and further development.

Lower-priority issues

- According to the experts, the *'key individuals who carry and live co-operation'*, are also particularly important. Although only a few interviewees considered this to be a collaboration management topic of the highest priority , many experts nevertheless stressed its importance in practice. Since key persons usually operate at different hierarchical levels and at the same time in an environment without a clear-cut allocation of leadership and responsibility, they need special qualities, such as good judgment, in case also on interdisciplinary and intercultural matters, as well as pronounced powers of persuasion.

- Some experts considered the topic *'development of normative rules for collaboration'* to be important, even though uniform process structuring as well as technical (interfaces) and legal implementation (handling of intellectual property, data sovereignty) are difficult due to the heterogeneity of collaboration forms. Some interviewees considered the issue to be unimportant, arguing that an excessively technocratic approach and regulation would be detrimental to successful partnerships.

- Several interviewees considered the development of a rather superordinate 'culture of collaboration' within companies to be an important precondition for collaborative engineering. The experts' statements on this topic ranged from the demand for *'management's openness in terms of company culture'* to the observation of *'cooperation phobia in industry'* to the demand to enshrine *'co-operation and collaboration firmly in education, and training and further professional qualification'* in order to establish a generally positive mindset for the topic of co-operation and collaboration at an early stage.

- The interviewees did not consider the topics *'complementarity of skills' or 'joint research and development projects'* to be particularly important or unimportant for the structural framework conditions and/or collaboration management. Practical *'joint identification of collaboration partners'*, the *'platform technologies'* that can be used for this purpose and efficient *'task management'* for collaboration were added by individual experts, but also rarely prioritised as a key topic.

4.2 Technical aspects

4.2.1 The baseline situation

Collaborative engineering is widespread within companies today. The desired ideal model is the consistent use of software tools for design, construction, simulation, testing, product data management and technical documentation. This enables both shorter design times and the coordinated interaction between different disciplines and hence also more efficient solutions. Considerable challenges also exist within companies, especially with regard to the interfaces between subject-specific tools and the semantic integration of data throughout the entire engineering process. It is easy to see that these challenges will take on a new quality in cross-company co-operation.

4.2.2 Assessment from a practical point of view

The technical aspects of future collaborative engineering were a focal topic in the expert interviews, also because the majority of the interviewees had a corresponding background. The aspects shown in Fig. 4 (left and middle) were put up for discussion in this context. In contrast to the previous level of the study, a priority 3 was additionally accepted due to the wide range of aspects (11 were proposed). All three aspects added by interviewees (right column) are relatively closely related to the proposed aspects.

KEY TOPICS

- Networking architectures/ exchange formats
- Ensuring data consistency/synchronisation of actions
- Artificial intelligence as a tool

SELDOM PRIORITISED

- IT security (authentication/identification/...)
- Unified semantics/formal languages ('high-level language')
- Visualisation/VR/MR/AR
- Assistance concepts for product experts, plant operators and maintenance
- Design options for autonomous production and flexibly interlinked manufacturing processes
- Long-term archiving, including migration, permanent twin
- Consideration of resource efficiency, sustainability beyond the entire system
- Cross-company process control systems

ADDITIONS

- Data integration/ model integration/ abstraction of sub-components
- Further development/ maintenance of classic basic technologies
- Synchronisation of technology lifecycles

Fig. 5: Key question – Technical aspects: In which phase/subdomain of collaborative engineering do you see the greatest technical challenges?

The evaluation of the interviews showed that two topics are evaluated equally by about half of the experts with priority 1, 2 or 3 – *'networking architectures/exchange formats'* and *'ensuring data consistency/synchronisation of actions'*. Very fundamental questions, such as common exchange formats and data consistency, were therefore placed at the centre of the call for action, and this can be interpreted as an indicator for the considerable development effort that is still required. The first representative of technologically more demanding topics, i.e. *'artificial intelligence as a tool'*, follows at a considerable distance, with *'IT security'* as a basic competence coming up closely behind.

Networking architectures/exchange formats

Exchange formats across domains and value chains are a necessary basis for collaborative engineering. Many modern engineering software tools were developed more than 20 years ago and have since become powerful tools. This was accompanied by a domain-specific, application-orientated data structure. At the same time, this data structure was also frequently used as a unique selling proposition in relation to competitors. For around ten years, several stakeholders have been taking steps to overcome this situation with open source solutions in order to develop non-proprietary standards which some interviewees consider to be important.

Engineering across value chains poses another challenge that was addressed by several interviewees. Depending on the level of integration in which the designer works (strongly simplified: component – subsystem – system – environment), a completely different level of information detail is required. The system designer of a vehicle requires only a fraction of the product information which is relevant for the developer of a customer-specific electronic circuit in a vehicle and vice versa. If, in principle, all the available information were made available, both the developer and the designer would suffer an information overflow.

Several interviewees attached great importance to the emergence of non-proprietary standards for the development of basic models for engineering components. The long-term-emergence of such non-proprietary standards was considered possible by several interviewees referring also to formats, such as AutomationML as an open data format for data exchange or the open M2M communication protocol OPC-UA for industrial automation and corresponding communication possibilities. However, one challenge that is often seen is the development of sustainable operator models for the elaboration and dissemination of these standards.

With regard to the deployment of cyber-physical systems in the context of collaborative engineering, decentralised data storages, decentralised, semantic-free AI-based data exchanges, corresponding quality assurance programmes as well as suitable operating systems were discussed as technical requirements for an efficient data exchange. In the context of advanced models for engineering components and products, some interviewees also mentioned the substantial scientific backlog in terms of the lack of compatibility between different model types or classes in engineering disciplines, mathematics and computer science. The practical possibilities to use meticulously designed physical models for applications other than the originally intended simulation applications, or to use them at least in part, often prove to be very limited. Existing technologies and tools are therefore often not used simply because time-consuming manual adaptations of existing models are not carried out for economic reasons. Since the development of a 'universal model' is currently considered to be too ambitious, the development of methods and/or of a respective platform was addressed as an intermediate stage in individual cases and was described as meaningful. Such a platform could possibly enable the transfer of sub-models to different model classes at minimum losses in a automated manner. In this way, the focus of model development could possibly be shifted from a currently more IT-related approach to the actually required applicability in engineering.

Ensuring data consistency/synchronisation of actions

Ensuring data consistency and the synchronisation of actions, both often mentioned in the context of version management, are the next steps in the implementation of collaborative engineering after ensuring a seamless and loss-free data exchange. According to several experts, appropriate solutions can enable the highly desirable quasi-parallel work of several parties on the same project and hence significant time savings.

All experts agree that this effect has been solved for decades in distributed software development or also in classical databases. Although a data record can be read by many users or processes simultaneously, it can only be edited and stored by one user at a time and is therefore accessible only for this user during a certain period of time. In engineering, this problem cannot be solved so easily since considerably more extensive dependencies exist in this field. These challenges are less related to the actual engineering tool and more to consistency checks with respective higher-level systems.

Such aspects are independent of cross-company collaboration and also occur within a company. Several experts highlighted the problem of latency as a new challenge in cross-company collaborative engineering. Depending on the geographical distance between stakeholders, not only technical bottlenecks, but also significant runtime effects occur here. Real-time cooperation around half the globe is thus restricted by physical boundaries regardless of the available bandwidth. Also, latency times can cause synchronisation problems even when no real-time communication is required.

Artificial intelligence as a tool

Firstly, some experts claim that tools which use artificial intelligence (AI) methods and which are introduced as part of a cross-company collaboration have the potential to motivate employees to introduce collaboration on their own. This holds if such AI tools foster concrete improvements in working conditions and applies even if the AI tools are not specifically intended for the use in collaborative engineering. The examples mentioned included AI-based pre-sorting and analysis of data or AI tools for self-organisation.

AI can be integrated into the actual engineering process in different forms. On the one hand, AI can be 'built in' as a function within the engineering process ('AI integration in the object') and on the other hand also has the potential to support engineering processes ('AI as an engineering tool'). The experts mentioned, for example, predictive maintenance or energy optimisation of devices and systems as engineering-specific application areas of AI methods that could be classified as 'AI integration in the object'. The current focus is more on the provision of AI-based services.

Several experts believe that the use of 'AI as an engineering tool' to support engineering processes that go substantially beyond preliminary analyses of data and even include the (partial) automation of the actual engineering processes will be feasible only in the long term.

In both scenarios, the majority of the interviewees see considerable potential for efficiency, whilst at the same time certain challenges must be taken into account, such as robustness of algorithms, data quality and functional reliability as well as associated legal issues, such as liability for malfunctions.

Another aspect discussed was that, even though many AI procedures provide convincing results, their solution is not easily reproducible and deterministic, depending on the procedure used. This impedes the use of such methods in safety-critical applications and their engineering. Furthermore, at least one expert states that the large amount of data that is indispensable for the application of machine learning, for example, is often not available for engineering applications.

Lower-priority issues

- Several interviewees classified certain topics as 'boundary conditions' for successful collaborative engineering, thereby referring to topics that are technically necessary for implementation (must-haves) but do not have any real design features. Several experts included the following topics in this group:
  - *IT security*
  - *Consideration of resource efficiency, sustainability beyond the entire system*
- The interviewees gave conflicting statements on the subject of *'IT security'*: Many consider the topic of secure data exchange, secure storage and the right to be forgotten, with the characteristics mentioned above, to be one of the most important technical challenges in collaborative engineering. However, other interviewees stated that mature data security concepts have been around for some time and that the obstacles to integration into existing IT architectures are based on the cautious investment strategy of German companies. Similarly, the topic of *'IT security'* was assessed as important, but technically feasible for the operation of cyber-physical systems.
- The topic of *'unified semantics/formal languages ('high-level languages')'* was attributed by the majority of experts directly to the most important topic, i.e. *'networking architectures/exchange formats'*. Several interviewees, for example, highlighted the importance of unified semantics or formal languages as significant for the development of exchange formats, so that the experts rated the explicit semantic topic less often as priority 1, 2 or 3. A need for standardisation obviously exists at several abstraction levels (system level, automation level, component level).
- It is also noteworthy that relatively few interviewees rated the topic of *'visualisation/virtual reality (VR)/mixed reality (MR)/augmented reality (AR)'* as priority 1, 2 or 3. Some of these experts named the use of VR/MR/AR as the basis for virtual collaboration which is important, for example, when working on prototypes that are usually only virtually available or in the case of stakeholders working at different sites. These interviewees also stated that the use of VR/MR/AR would at the same time be conducive to employee motivation and willingness to collaborate. However, other interviewees described the topic as unimportant with regard to collaborative engineering since these tools would be more suitable for demonstration purposes rather than significantly facilitating the work of technical experts.
- What's more, a relatively small number of experts considered the technical topics concerning product lifecycles, such as *'long-term archiving, including migration/permanent twin'*, to be priorities 1, 2 or 3. The experts who considered these aspects to pose the greatest challenges for collaborative engineering stated that the availability of tools which are particularly suited for cross-cycle management of data, models and technol-

ogies was of particular importance. The fact that the interviewees attached a higher value to this complex of issues from an economic perspective (see 4.4) suggests that they consider the technical challenges at least to be solvable or even already largely resolved.

- A few experts identified further proposed topics, including a wide range from semi to full automation of cross-company processes and their increase in efficiency, to be one of the three greatest challenges. This includes the topic of *'assistance systems for product experts, plant operators and maintenance'* as well as *'design options for autonomous production and flexibly interlinked manufacturing processes'* and *'cross-company process control systems'*. The fact that the experts have not (yet) identified these aspects and the topic of *'consideration of resource efficiency, sustainability beyond the entire system'* as significant even though efficiency is considered to be the most important economic factor underlines in some way the high demand in the area of networking architectures and exchange formats.
- The experts added the following topics, which – even allowing for different terminology – remained isolated issues: the topic of *'data integration/model integration/abstraction of partial components'*, which is part of the extended realm of data exchange formats, networking architectures and semantics, the topic of *'synchronisation of technology lifecycles'* for the meaningful interpretation of overall architecture models and the topic of *'further development/maintenance of classic basic technologies'*.

4.3 Work organisation

4.3.1 The baseline situation

Regarding the risk of the computerisation of work, (Frey und Osborne 2013) estimate for the US that 47 percent of all activities will be exposed to a high risk of automation within the next one to two decades. Studies like this one clearly indicate that certain activities are susceptible to substitution whilst others, referred to as 'engineering bottlenecks', are less prone. The latter belong to the following three groups (description according to (Bonin, Georgy und Zierahn 2015)):

- Perception and manipulation activities in complex and unstructured environments, such as identifying and eliminating errors or responding to unplanned events.
- Creative-intelligent activities, including design, such as activities in the creative industries, classic R&D activities or the development of new business models.
- Socio-intelligent activities, such as sales or care which are characterised by the special importance of emotion, the right interpretation and, in particular, the intelligent response to emotion.

With the classification of essential engineering work in (Künzel et al. 2016) as creative processes, the probability of complete automation of engineering activities can hence be classified as low. This, however, does not rule out a shift in the range of tasks and the use of algorithms for routine or analytical work.

4.3.2 Assessment from a practical point of view

The economic aspects for cross-company collaborative engineering were discussed during the interviews. The aspects shown in Fig. 6, column 1 and 2, were put up for discussion and supplemented by further aspects (column 3).

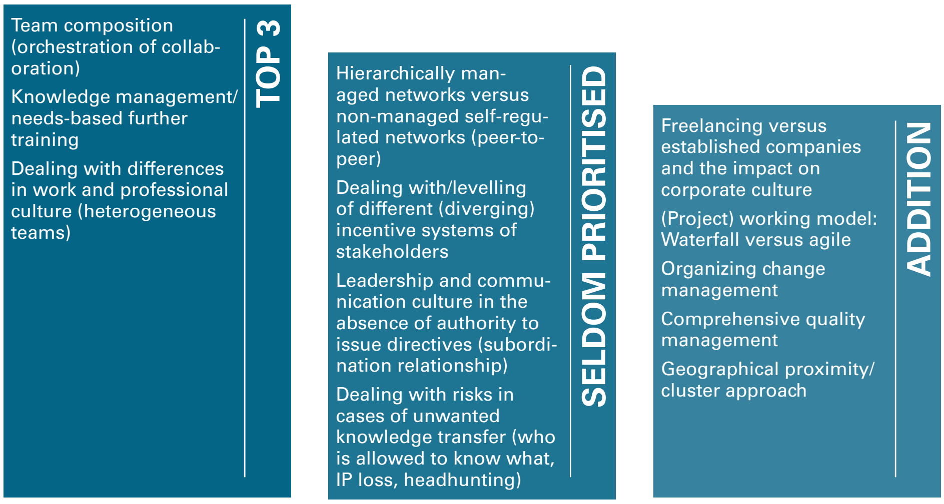

Fig. 6: Key question – Work organisation: Which aspects of work organisation are important for the future success of collaborative engineering?

The experts rated the structuring of the team under the aspects of heterogeneity, leadership methodology and orchestration ('team composition') as by far the most important aspect. The topic of *'dealing with differences in work and professional culture'*, which comes third, is relatively close to this topic and also points to necessary changes compared to 'classic' (project) management processes and methods. High priority is also attached to 'knowledge management' and 'further training', which suggests a change in competence requirements. The proposed additions are very similar to the initially proposed aspects and can be easily integrated into these.

Team composition/orchestration of the collaboration

Digitalisation goes hand in hand with a change in process management which some interviewees considered to be crucial for successful orchestration. To a much greater extent than classical methods, digitalisation enables the continuous adaptation of work processes to changing environmental conditions (agility), whilst retaining most of the classic sub-tasks, such as resource allocation and models as well as the continuous improvement process.

At the same time, several experts see new aspects becoming important: Quasi-parallel work with close interaction or dependency of different domains and collaboration over longer geographical distances require a new quality of synchronisation of processes. Also, respective permissions in the collaborative design process should be easily adaptable and determinable for each individual stakeholder.

Some experts suggest that these trends are accompanied by the need to establish efficient and dynamic management structures (business rules). Decision-making structures, role distributions (rights and duties), partnership models and interfaces must be developed further or redefined. The involvement of expert personnel in decision-making structures and processes is vital for the efficient allocation of resources and successful process management. However, generally accepted solutions for evaluating collaboration (metrics) are still lacking since the quality and degree of success of the results of co-operation and collaboration are judged quite differently by different stakeholders.

Knowledge management/needs-based further training

Quality education and continuous further training in the respective engineering discipline are already standard practice today in order to keep pace with technical progress. At the same time, the role of professional experience should not be underestimated, particularly for a successful deployment. Despite professional further training being an important element in the development of expertise in engineering. However, the experts believe that the employment of training programmes can vary significantly among disciplines and companies. Widening the focus in order to obtain a basic understanding in topics of neighbouring domains can be beneficial for collaboration. This goes hand in hand with a new quality of knowledge dynamics. However, these effects are not restricted to cross-company collaboration or the engineering domain.

With cross-company collaborative engineering, the previous 'splendid isolation' of those involved in the design process is broken up into two directions, i.e. cross-domain cooperation and direct interaction with external engineering partners. In this context, the experts agree that there is a need to develop new communicative skills for multilateral cooperation and an understanding of the counterpart in order to engage in other approaches and methods or to coordinate with them. This change requires the qualitative reorientation of expertise and hence leads to new further training requirements. The range of measures mentioned here extends from communication training to new methods of narrative knowledge management (expert community) and project management (flexibility, agility).

Some experts believe that the further development of non-technical skills in particular can also lead to conflicts of interest or motivation. This concerns, for example, the degree to which exclusive expert knowledge is shared which might also affect associated unique selling propositions.

Dealing with differences in work and professional culture

According to the experts, special attention should be paid to overcoming cultural differences between closely related domains (for example, computer science and engineering). Interdisciplinary approaches are described as weak in the manufacturing industry.

Furthermore, patterns differ strongly between stakeholders with different professional backgrounds. Different views are widespread in specific sectors, for example, with regard to the interpretation of tasks, the assessment of one's own expertise or the question as to when a result can be regarded as achieved.

On the whole, many experts consider the mutual understanding across industrial and intercultural boundaries to be a key factor for successful collaborative engineering and regard the development of a common communication and language as a major challenge. Intercultural differences in working cultures must be taken into account. Examples quoted by some experts include the specifics of Anglo-American, German and East Asian corporate cultures.

The corporate cultures of established companies, especially of manufacturing companies, were also claimed to be different from those of start-ups. Concepts common in start-up companies are often unacceptable to established companies. Examples of this are agile project management where projects are continuously developed in an exchange between client and contractor, or the 'minimal viable product' (MVP) which is presented to the client at the earliest possible point in time and then incorporates the client's feedback in subsequent development efforts.

Lower-priority issues

- The question as to whether collaborating teams should be *'hierarchically managed'* or whether a *'non-managed self-regulated'* organisation of teams is even necessary in order to achieve innovation was identified as an important design element by almost as many interviewees as the topic of *'dealing with differences in work and professional culture'*. Strict hierarchical structures and inflexible sets of rules were generally viewed critically in the interviews. However, it was also noted that the concrete design of a collaboration network should depend on the respective specialist and working cultures.
- Several experts stated that one of the major challenges is to create a *'culture of leadership and communication in the absence of authority (subordination relationship)'* which represents a new quality of leadership culture for many companies and is not defined by strict rules, but ideally emerges through the competence and human empathy of those in power.
- According to some interviewees, *'change management'* has a very important role to play which the interviewees understood to be the targeted support and facilitation of changes in management and organisational structures. This concerns, for example, the breaking up of classical, pyramidal and hierarchical structures, i.e. overcoming a department and division-based mindset. Such organisational forms are in conflict with the claim of collaborative engineering when it comes to optimising the entire system in terms of its business model or overall strategic goal.
- Some experts referred to the value of the *'geographical proximity and cluster approaches'* between stakeholders as a basis for sustainable trustful cooperation (see the description of the cluster approach in chapter 3.4.2). They referred, for example, to the trust already generated before in other contexts, lower necessary adjustment and coordination efforts and regional value chains that have developed.
- The suggested topics of *'dealing with/levelling of different (diverging) incentive systems of stakeholders'* and *'dealing with risks in case of unwanted knowledge transfer'* were only very seldomly prioritised. Some interviewees added challenges in conjunction with the implementation of special *'(project) working models'*, such as *'freelancing'* within *'established companies'* and *'agile project management in contrast to the waterfall model'*. The importance of *'comprehensive quality management'* was also pointed out.

4.4 Economics

4.4.1 The baseline situation

Digital and interconnected business processes were first established in the B2C world. Digital platforms can trigger disruptive changes in existing customer-vendor relations, causing new business models to emerge (Engelhardt et al. 2017). This means that entire rolls in previous value chains can be omitted or substantially changed. The scale effect inherent in a platform supports potential monopolisation trends, especially in the case of highly standardised offerings or processes.

Put simply, two types of platforms can be distinguished:

- Transaction-based marketplaces where the operator plays a neutral role without being involved in the contents. The operator then only acts as an agent between providers and prospective buyers (for example, ebay).

- Open, data-based systems: where the operator bears substantial joint responsibility for the contents through quality control, approval procedures or similar activities. These platforms are open to different providers (for example, MindSphere).

The above-mentioned economic laws are equally valid for the B2B market, but the framework conditions are sometimes very different, ranging from higher demands on reliability, smaller lot sizes, high need for individualisation, lower standardisation potential and more complex (mostly multi-part) copyright constellations, to the handling of highly complex data structures (André et al. 2017).

It is not yet possible to predict today whether centralised data management based on the platform model or a decentralised peer-to-peer model will prevail in collaborative engineering. Fig. 7 shows examples of advantages of central platform and distributed peer-to-peer solutions. It can be assumed that competition between the two concepts will be decided on the basis of the dominant (present and future) business models in each sector. This does not rule out hybrid solutions, such as those already in use today for advertising on websites.

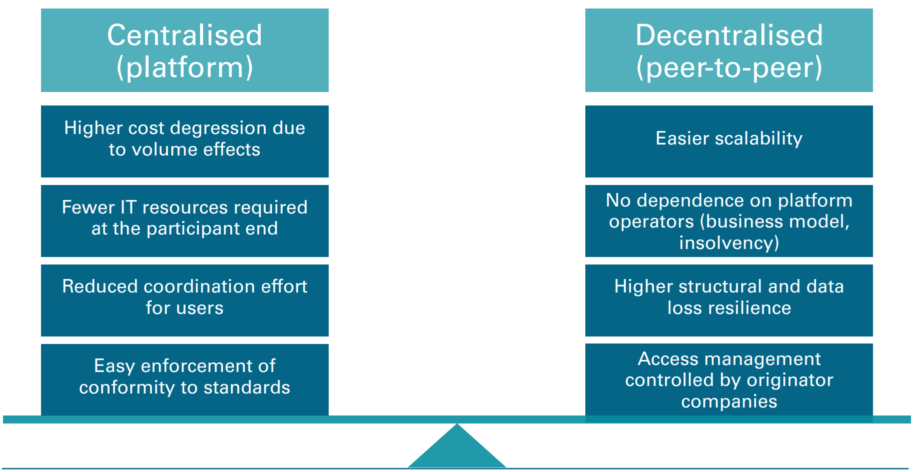

Fig. 7: Comparison of examples of advantages of platform and peer-to-peer solutions (© iit)

4.4.2 Assessment from a practical point of view

The economic aspects for cross-company collaborative engineering were discussed during the interviews. The aspects shown in columns 1 and 2 in Fig. 8 were put up for discussion and supplemented by further aspects (column 3).

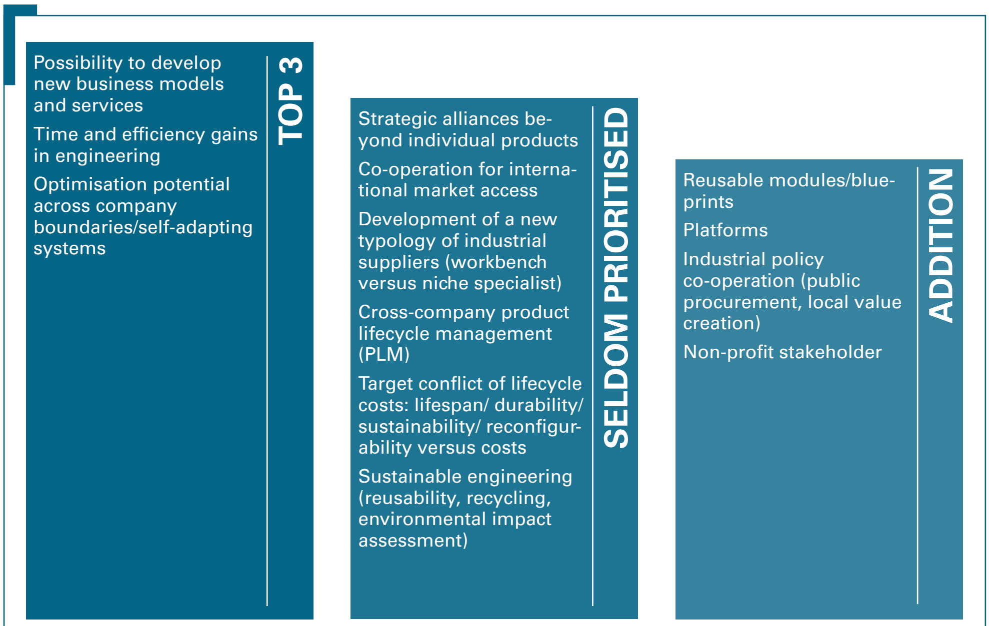

Fig. 8: Key question – Economics: What are the important trends/drivers in the economics of collaborative engineering?

More than half of the experts rate the aspect of *'possibility to develop new business models and services'* as priority 1 or 2 in terms of the most important drivers for the economics of collaborative engineering. This is followed by the topics of *'time and efficiency gains'* and *'optimisation potential across company boundaries/self-adapting systems'*. Next up is *'strategic alliances beyond individual products'* as a topic that is closely related to collaboration management and already highlighted in chapter 4.1 . The topics of *'cross-company PLM'*, *'target conflicts of lifecycle costs'* and *'sustainable engineering'*, which were given less priority individually, were considered by several interviewees to represent the common topic area of *'product lifecycle management'*. In case of a retrospective summary of the three originally proposed topics, the new topic of *'product lifecycle management'* would come second in the list of most important trends/drivers in the economics of collaborative engineering along with the *'time and efficiency gains'*.

The opportunity to develop new business models and services

Engineering itself being state of the art is less at the heart of entirely new business . However, engineering must lay the foundation for implementing new business models.

It became clear in the expert discussions that a new product culture goes hand in hand with new service-orientated business models. This cultural change requires an adequate transformation phase, especially in the established production world, and is strongly dependent on the respective industry. Furthermore, some companies have not yet developed a reliable basic philosophy, so that several experts observed a considerable degree of insecurity as to how customer loyalty (beyond lock-in models) can be achieved and maintained in a service-orientated environment. Many new collaboration opportunities and business fields are opening up for engineering, strengthening post-sales cooperation with customers and between companies alike. Several experts mentioned the example of diagnostic systems (condition monitoring, predictive maintenance) which must be integrated in addition to classical design tasks and enable the monitoring of plants irrespective of their location. Other conceivable activities include certain services, such as product processing or the design of test plans right through to the leasing of complete factories for which real approaches already exist in countries such as China. Engineering tasks are generally becoming more diverse, and more specialists will probably have to be involved. According to experts, maintaining the right focus in future will be one of the most important tasks, especially for mass producers and service providers.

Some interviewees also consider the development of new business models to be an effective "lever" for innovation processes. Examples include licensing and leasing concepts for digital twins or suitably designed profit-sharing models over a certain period of time if the development or utilisation of a digital twin will generate profits or higher optimisation potential. Some interviewees saw the Internet of Things as an enabler of far-reaching integration of production and services, but they also saw it as a bridge to the independently listed topic of 'strategic alliances beyond individual products' since a complete product lifecycle simply cannot be managed without new partnerships.

Time and efficiency gains

Many interviewees consider the increase in speed and efficiency to be two of the key objectives and therefore also as the yardstick for the quality of collaborative partnerships in engineering which must at least compensate for communication losses in the medium to long term. Especially in engineering companies that have limited experience with collaboration, a significant relative increase in efficiency can often be achieved with suitable partners through well-designed synchronisation and/or optimised scheduling and targeted knowledge exchange.

In the everyday economic life of collaborative engineering, a majority of experts identify a wide range of issues that often touch upon legal aspects as well. In some cases, these go beyond collaborative engineering and affect different stages of the value chain.The weighting in the distribution of additional income from subsequently implemented business models is, for example, often distributed according to the economic strength and bargaining power of the companies involved. Against this background, especially smaller companies are extremely concerned about being 'ripped off'. Many interviewees saw an important challenge in the creation of integrated business models that give all stakeholders an appropriate share in the overall profit.

Several experts also considered the involvement of customers or 'prosumers' (i.e. persons who are both 'producers' and 'consumers') in engineering processes to be crucial for time and efficiency gains. Feedback mechanisms can be integrated into development through co-creative processes that can be designed in different ways, thereby also strengthening customer loyalty. The targeted exchange of knowledge and flexible production structures are seen as a way to respond potentially faster and more efficiently to changing customer requirements on this basis.

Optimisation potential across company boundaries/self-adapting systems

In one expert interview, the optimisation potential across company boundaries was described as the 'bait par excellence' and in a second interview as 'the central topic of the horizontal integration axis of the German reference architecture model for Industry 4.0'. Within the framework of the actual collaborative engineering process, it must be possible to overcompensate for the additional costs of initialising and coordinating collaborative action.

Different forms of collaboration also result in different needs for coordination which many interviewees discussed in depth. Several experts voiced the opinion that a (smart) factory-as-a-service concept, for example, where connections to the foundry model of the semiconductor industry were also pointed out, results in a customer-centred coordination process in which platforms can play an important role. In the case of vertical, diagonal or horizontal mergers, the coordination process is potentially more complex if decision-making processes are expected to involve all or at least some of the stakeholders in a similar way.

If the aim is to achieve an actual optimisation, an agreement must be reached between the stakeholders as to which target parameters, such as product quality, production costs, throughput times or wear processes are to be optimised. According to the experts, the (further) development of digital twins of real processes is an important basis for the technical realisation of optimisation potentials. Potentially conflicting optimsation goals can result from different interests and potentially conflicting goals and can call for suitable coordination processes, even including conflict management.

According to the experts, the crucial element must be the optimisation of the product as a whole and not just the improvement of individual components. Since every stakeholder can address the entire property and capability chain (even if they have no access to the data in individual cases), optimisation in the sense of resource efficiency (VDI-Richtlinie 4801, Blatt 1) is possible across the entire value chain, including the entire product lifecycle. However, conflicting objectives, such as those relating to follow-up business, must also be regarded as an obstacle in this context.

Many interviewees considered the issue of the appropriate distribution of profits to be a major challenge since it is difficult to measure or quantify the added value in the engineering process.

Lower-priority issues

- Several interviewees attached significant importance to *'strategic alliances'*, especially for 'big' topics and because complete product lifecycles can be covered much more effectively in respective partnerships. Platforms can play a facilitating role in finding partners, providing services as well as developing partnership models and strategic visions.
- Quite a number of experts believe that the digital mapping of complete product lifecycles, which should be feasible via manufacturer-neutral platforms in the form of *'cross-company product lifecycle management (PLM)'*, is important for cross-system economic assessments of *'lifecycle costs (lifespan, durability, sustainability, reconfigurability)'* and for the consideration of *'sustainable engineering'* ('sustainability-by-design'). Several experts therefore consider these three topics to constitute a 'joint topic of product lifecycle management (PLM)' which, together with *'time and efficiency gains'*, would even take second place among the most important economic trends of collaborative engineering. It was also sometimes argued that a system change was urgently needed in

order to achieve a uniform PLM system landscape and to prevent lock-in effects which could be expected due to the increasing spread of proprietary solutions. In the context of sustainable implementation in strategic alliances, however, the question of attractive incentive and business models covering the product lifecycle arises once again.

- Several experts believe that the economic potential of *'sustainable engineering'* has not yet been exhausted. One respondent believed that the legislative framework designed to take sustainability into account should be defined by the legislator and/or via eco-certificates, also due to diverging stakeholder interests, and should include the aims of recyclability and recoverability. The foundation for these aims can be laid already in the initial design phase of engineering processes.
- Only a few experts considered the topics of *'cooperation for international market access'* and *'development of a new typology of industrial suppliers'* to be important. Some respondents added the topics of *'reusable modules ('copy & paste')'*, *'industrial policy co-operation (public procurement, local value creation)'* as well as *'platforms'* in conjunction with economic challenges. Another idea that was mentioned was to commission a *'non-profit party'* as a coordinator to warrant a high degree of neutrality.

4.5 Legislation

Cross-company exchange of information and data in collaborative engineering processes raises a number of legal issues relating to the handling of existing intellectual property rights (such as copyright or patent law) which are introduced as part of or as a result of partnerships. However, it remains unclear whether and to what extent rights of use exist with regard to the operating data generated during the lifecycle of a product and to whom this data can be legally assigned.

4.5.1 The baseline situation

The importance of data as an asset has increased considerably in recent years. According to a study by the European Commission, the value of the European data economy will total EUR 739 billion in 2020 and account for 4 percent of the European gross domestic product (European Commission 2017). More and more business models are based in part or even completely on the generation, collection or evaluation of data. This makes the question as to who actually 'owns' data or, in other words, who exercises data sovereignty increasingly important. This applies specifically to collaborative engineering, where it is crucial to know who may evaluate and use the operating data generated by plants and machines..

Besides the question of the legal treatment of data, intellectual property (IP) rights also have an important role to play in the context of collaborative engineering processes. Partnerships between companies to implement engineering projects requires the exchange and sharing of information among several parties. What's more, co-operation typically also results in the development of new products. From this, in turn, intellectual property rights can be derived for the products of the cooperation. Possible forms are industrial property rights such as patent, design or utility model law. Furthermore, copyright law guarantees the protection of a person's intellectual property as well as the protection of structured data collections in the form of databases.

Moreover, the question of data sovereignty and the handling of IP rights must frequently be considered in an international context. Especially when collaborative engineering is conducted across borders, diverging regulations from different jurisdictions may have to be taken into account.

4.5.2 Assessment from a practical point of view

The legal aspects for cross-company collaborative engineering were finally discussed during the interviews. It should be noted that none of the interviewees is a trained lawyer. The results hence reflect the views of users or parties affected by legal issues. For this reason, the results of the interviews in this chapter will be supplemented with short legal explanations. The uncertainty among technical experts regarding the consequences of legal regulations for collaborative engineering became repeatedly obvious during the discussions. Legal experts agreed to this and confirmed a lack of or unconsolidated case law or jurisprudential interpretation and, above all, referred to the importance of contract design.

Irrespective of this, the same methodology as for the other observation levels was applied and the aspects shown in columns 1 and 2 in Fig. 9 were discussed and supplemented.

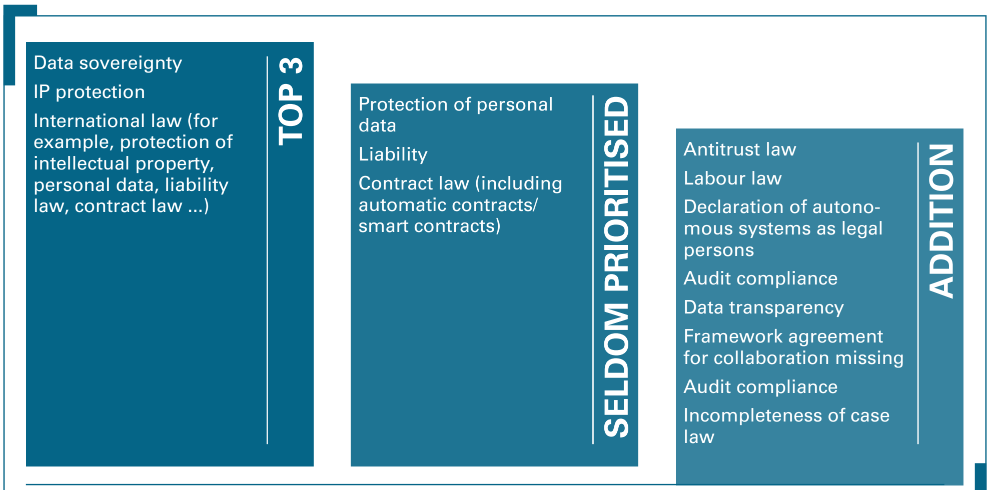

Fig. 9: Key question – Legislation: What future legal challenges do you expect for collaborative engineering

The prioritisation by the interviewees in this case painted a very clear picture. The three areas of 'data sovereignty', 'IP protection' and 'international law' were by far the most frequently mentioned issues in this order. Among the additions, the topic of 'antitrust law' is considered to be a particular challenge.

Data sovereignty

With regard to the use of data, the majority of respondents emphasised the different interests of manufacturers and operators of assets. While manufacturers want to use data for the further development and improvement of their products, operators focus on the evaluation of operation-related data. According to many respondents, the lack of legal regulation permitting this data to be unambiguously assigned to an authorised party leads to legal uncertainty among companies. The problem that data cannot be allocated increases with the number of parties involved in the development or operation of assets, so that the interviewees called for the creation of a binding legal framework. In this context, one respondent referred to the absence of a legal concept of 'data ownership' (similar, for instance, to ownership of intangible assets, such as money in a bank account) as a structural shortcoming. However, several interviewees stated that the creation of a 'data ownership right' would only make sense with supranational coordination, for example, within the scope of international agreements, since collaborative development processes between companies increasingly take place across borders and extend across different jurisdictions. If collaborative engineering itself is carried out via a platform, potential data assignment rights must also be taken into account, which, in the opinion of some respondents, must be seen in an international context, for example, if the platform is operated in a foreign jurisdiction.

Legal discourse: The concept of ownership and data

In contrast to physical objects, there is currently no independent concept of data ownership (Ensthaler und Haase 2017) in German law. Data cannot be the subject of a sales contract or a transfer of ownership due to lack of physical quality. Although efforts are being made at the European level to regulate the handling of data, the focus in this case is primarily on personal data, i.e. information relating to an identified or identifiable person (for instance, the EU's General Data Protection Regulation or the planned e privacy regulation). With regard to the creation of a genuine data ownership right, the EU sees a need for action (European Commission 2015), but this objective has not yet been implemented in the form of a regulation or directive. The logical conclusion is hence that any rights to use data must be contractually regulated from the point of view of applicable law. To this end, the parties involved must conclude an agreement in such a way that the exclusive or limited right of use of certain data is granted to a contractual partner. The legal basis for the transfer and use of data is then a contractual obligation.

IP protection

Collaborative engineering implies the mutual exchange of knowledge and know-how. According to several interviewees, the use of intellectual property in a project requires contractual safeguards that strictly limit use to certain purposes. Following termination of the partnership, it must be ensured that the information and knowledge provided remain with the rights owner and are not used for other purposes by cooperation partners or customers or sold to competitors. The risk of loss or infringement of IP rights is increased by the fact that partnership often crosses borders, making it more difficult to enforce claims. In this context, one interviewee saw the need to regulate IP law issues in the context of protection and marketing concepts, whilst another interviewee took a critical view of the future applicability and manageability of copyright law in the context of collaborative engineering processes. One respondent described the clarification of contract law issues in this context as important, but at the same time identified the concerns associated with IP law issues as the main obstacle to collaborative engineering.

Legal discourse: Intellectual property

The protection of intellectual property is governed by the standards of intellectual property law, such as patent and copyright law. These rules emerged from international agreements, some of which were already concluded in the 19th century and hence belong to the oldest areas of international business law (Groeben et al. 2015). Intellectual property protected by law guarantees the exclusive power of disposal over the intellectual property, which also includes the exclusion of use by third parties. At the same time, the right owner is entitled to claims in the event of infringement. Furthermore, intellectual property can also be protected as a trade secret under the act against unfair competition.

International law

A high degree of internationalisation can be found in collaborative engineering processes. According to the majority of interviewees, platform-based partnership can and will take place across national borders, which means that (sometimes very different) national legislations must be observed. Reflecting demand for rule-compliant cooperation or collaboration, many companies are interested in the harmonisation of laws and regulations within the scope of international agreements. The interviewees literally quoted, for example, 'the lack of a legal definition of the state of the art in China' and 'the general right to use data in the US'. The slogan of the missing 'laws for the Internet nation' used in an interview is an apt description of the situation in this respect. Some interviewees believe that platforms should also be designed in such a way that the requirements of the respective jurisdictions involved are recognised and taken into account in each case.

Legal discourse: National law versus the globalised economy

Industrial property rights and copyright are geographically limited because national laws can traditionally only be enforced within the respective national borders. In order to maintain certain minimum standards, the so-called duty of national treatment was created within the framework of international agreements, such as the 'Agreement on Trade-Related Aspects of Intellectual Property Rights' (TRIPS Agreement) (World Trade Organisation; Bundesregierung 30.08.1994). This means that foreign holders of intellectual property rights may not be placed in a position worse than that of domestic holders of intellectual property rights. The prohibition of discrimination thereby achieved ensures that a holder of a protective right receives sufficient protection for his intangible assets in all signatory states.

Lower-priority issues

- According to some interviewees, new forms of collaboration with dynamically changing constellations trigger new *"liability"* issues, which cannot always be clearly reflected by contract law and which will require technical expertise for their assessment. The involvement of technical examination organisations was sometimes discussed in order to examine warranty issues in developments from collaborative engineering.
- Some interviewees also raised the issue of *"contract law"* as an important challenge, several times in the context of blockchain and distributed-ledger technologies in relation to automated contracts ('smart contracts'). Standardisation would represent an important step towards legal certainty here.
- *'Protection of personal data'*, which, according to the interviewees needs to always be considered in an international context, was given a lower priority in terms of real challenges.
- Interviewees also addressed '*questions of antitrust/ cartel law'* in conjunction with horizontal cooperations. This may lead to restrictions under competition law especially in cases where the object of an agreement is a joint economic exploitation.
- One interviewee suggested *'the declaration of autonomous systems as legal persons'* in order to address liability issues, for example. Corresponding considerations also exist in the field of autonomous systems, i.e. the idea of granting digital entities a legal personality, so that they themselves can be holders of rights and obligations and are liable for their own fault.
- Some interviewees also added the other topics of *'labour law'*, *'data transparency'*, *'framework agreements for the preliminary phase of collaboration'*, *'audit compliance'* and *'immature jurisdiction'*. However due to the prioritisation of other topics by the interviewees those topics were not discussed in depth in the context of the greatest legal challenges.

5 Conclusion: The main features and challenges of collaborative engineering

The expert interviews highlight the basic outlines and fundamental challenges for all considered facets of collaborative engineering. Quite different states of development were observed in the different observation areas. Whilst the questions in the technical area, for example, are relatively clearly focused and can be dealt with in succession, the methodological approaches, especially in economic and legal areas, still need to be explored. Strong cross-references exist between the five levels of consideration, i.e. collaboration management, law, economics, work organisation and technology. This clearly shows that collaborative engineering requires holistic thinking and acting.

5.1 Collaboration management

There can be no doubt that collaborative engineering offers significant opportunities in terms of saving time, enhancing quality and minimising risks in development, production and maintenance processes. Better knowledge of customer needs is another motivating factor.

The definition of clear-cut development goals, appropriate cost and time planning as well as regular benefit reviews are the basis for sustainable and successful collaboration. It is particularly important that engineering will cover the entire service life of products in the future. Engineering is then often part of a long-term (strategic) collaborative partnership that goes beyond the actual engineering.

Combined with a focus on collaboration, competent collaboration management is a success factor of collaborative engineering. Personal relationships and forms of communication are of key importance. Furthermore, geographical proximity has an important role to play as a success factor which is directly opposed to the possibilities of global digital collaboration at this point.

In collaborating companies, the persons acting are potentially distributed across different hierarchical levels. This requires not only interdisciplinary, but also intercultural and integrative competence, i.e. a willingness to be integrated into a ‘philosophy of collaboration’.

The classic anonymous platform world cannot meet the demand for building trust. The importance of networking key individuals and fundamental values becomes evident. This requirement is much easier to meet with geographical proximity. Existing cluster organisations and their members often already meet these requirements.

As with other areas of collaboration, for example, in R&D, the strategic decision on which topics a company enters into such a collaborative process is crucial for sustainable success. Collaborative engineering calls for an adapted company strategy and new management methods.

5.2 Technical aspects

In this context, the focus lies on the shift towards exchange formats across domains and value chains. Irrespective of cross-company collaborative engineering, but as a necessary prerequisite for it, such universal exchange formats form the basis for the complete digitalisation of value chains throughout the entire lifecycle. Besides the need for standardisation, this requirement for consistency means that it must be possible to extract from the total data volume – i.e. the data pool – the concrete data subset that need to be considered for respective engineering steps. This generates challenges of dimension reduction and relevance assessment. The ability to generate suitabledata extracts is not only a technical challenge, but also interacts directly with questions of work organisation and work psychology.

When it comes to non-proprietary exchange formats, promising concepts are under development, such as AutomationML. The extensive preliminary work necessary for wide-spread use often first requires the identification of economic foundations in the sense of sustainable operator models.

Collaborative work is inconceivable without ensuring data consistency. What has been standard technology in databases for decades has yet to be resolved for the extensive dependency structures that exist in engineering. Global collaboration must also take latency times due to geographical distances into account. IT security as a focal aspect is assessed differently in terms of development requirements, however, without denying its importance.

Artificial intelligence (AI) will be considered as a newly available capability to be integrated into engineering. If AI can be designed in such a way that it meets the requirements for functional safety and robustness of algorithms, it can significantly change core areas of automation. With regard to supporting engineering itself, AI offers considerable long-term potential.

5.3 Work organisation

Engineering is subject to the general trends of future value chains and work organisation structures in the digitalised economy. Changes are expected with regard to team structures in terms of heterogeneity, leadership methodology and orchestration. Agility, quasi-parallel work with close interaction or dependence and collaboration over longer geographical distances present new challenges. Management structures will have to adapt to changed decision-making structures, role distributions and partnership models. Interdisciplinary and interregional cooperation requires overcoming cultural differences.

Besides the ongoing need for professional training, the development of new communication skills for multilateral co-operation and an understanding of one's counterpart will become increasingly important. Conflicts of interest or motivation can also lead to a need for knowledge management.

The forms of leadership of collaborative teams are becoming more heterogeneous, with a trend towards 'managed self-organisation' being expected here. Conflicts can result from different quality requirements and objectives of team members.

5.4 Economics

The optimisation potential across company boundaries is the 'bait par excellence' for collaborative partnerships in engineering and it is described as the central topic of horizontal integration within the German reference architecture model for the Industry 4.0 (RAMI 4.0). The integration of customers or 'prosumers' into engineering processes also represents a new quality of value chains.

The benefits resulting from this process change must outweigh the loss in coordination. Although engineering will continue to play a key role in the economic success of products and services, the criteria for success will change: Price, quality and skills will no longer be the only key factors. Instead, engineering will develop the foundations for possibilities to support parallel business models and services throughout the entire lifecycle of products.

The question of data management in future collaborative engineering is an example that illustrates the close interaction between the observation levels where technical as well as economic and legal aspects will be crucial in future developments. Both platform concepts and peer-to-peer solutions are in principle able to meet the technical requirements and are accompanied by inherent advantages and disadvantages. Which solution or hybrid form of solution will prevail for collaborative engineering and the associated digitally supported value chains and business models in the future may well depend on the respective industry and application. The more decentralised, proprietary and complex the value chains in an industry are, the less important the advantages of platform concepts.

Engineering will in future be much more closely integrated into the overall economic view of the lifecycle and associated business models. Service-orientated business models will only become established after a transformation phase of varying length. This involves major uncertainties with regard to the existence of established business models and the timing and extent of the transformation.

It is obvious that engineering can create the basis for post-sales cooperation with customers. Engineering tasks will increasingly include an economic component that goes beyond the consideration of production costs. However, this also goes hand in hand with uncertainty as to whether it will be worthwhile for all parties in the value chain to participate in the future. This uncertainty often becomes apparent already in the incapability to design appropriate profit-sharing models for service providers which handle long-term tasks such as the development, hosting and continuous updating of a digital twin enabling process optimisation. Such shortcomings could have an inhibiting effect on the transformation of business models.

The problem of the appropriate distribution of generated profits can generally pose a major challenge, because value creation in the engineering process is difficult to measure or quantify, for example, when collaborative partnership is not aimed at cycle times or production rates but product quality.

5.5 Legislation

There is significant uncertainty among "engineering users" regarding the legal situation in collaborative engineering. This is all the more true as global value chains collide with national jurisdictions. Existing laws are primarily aimed at intellectual property rights, such as copyright or patent law. It is especially copyright law that plays an important role in this context, as engineering services regularly reach the level of intellectual creativity that is required under copyright law. At the same time, however, there is no provision on data sovereignty that finally answers the question regarding the allocation of operating data to a defined beneficiary. This leads to legal uncertainty and may even endanger business models. The assignment of data to a beneficiary can only be effected on a contractual basis. Such contractual provisions are certainly a key element, but they can endanger the business models especially of weaker parties, such as SMEs who are facing an asymmetrical distribution of power, and ultimately threaten value chains and system business models. Experience from collaborative development projects shows a clear asymmetry of power between research institutions, SMEs and large corporations. This specifically applies to business models that are based on a long-term approach, as is customary in the capital goods industry. Furthermore, questions of data sovereignty also impact the platform architecture, which ideally reflects existing data use rights also from a technical perspective.

On the whole, such unresolved legal situations represent a significant risk, especially for smaller companies. The situation is more favourable with regard to copyright and patent law (as well as other intellectual property rights) because the protection of such intellectual property is largely harmonised by many international agreements, however, with the caveat that the owner of the property right will not always be able to take action against infringements abroad. Nevertheless, previous experience shows that such difficulties can be overcome with acceptable effort even in collaborative engineering.

6 Steps for implementing collaborative engineering

Collaborative engineering across company boundaries is already being practised today, but in view of the considerable potential for innovation and increased efficiency, only to a relatively small extent. The main obstacles that can generally be identified are the effort to coordinate planning and coordination processes that must be economically compensated for in every collaboration, and the inadequate performance of the interfaces currently available. Essential challenges in conjunction with communication and coordination tasks were identified at all levels of consideration in the expert interviews.

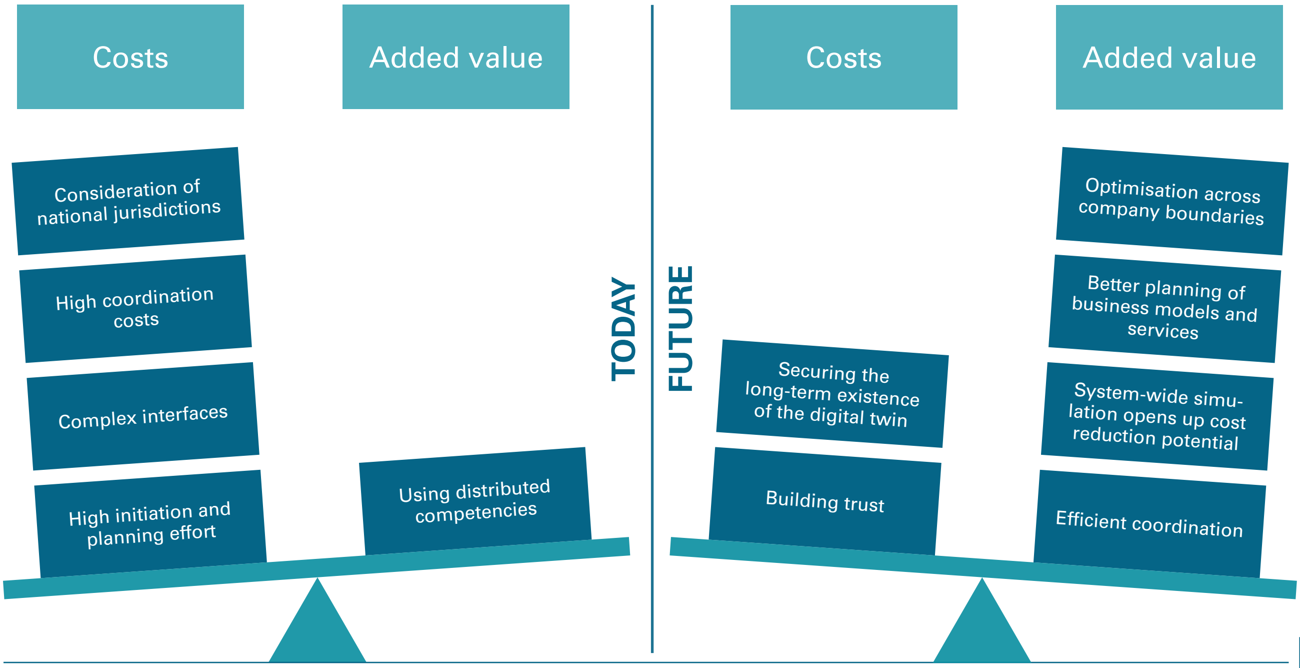

Fig. 10: Success factors of collaborative engineering

The development of technical solutions to support collaborative engineering interacts closely with the development of new business models and value chain structures as well as the further development of work organisation methods. The influence of applicable law must also be considered. As a result of this complex situation, the use of collaborative engineering is not yet widespread (Fig. 10, left). Thanks to foreseeable technical developments (for instance, the possibility of system-wide simulation, better infrastructures for digital services) and expected adjustments to the legal framework (for example, liability in collaborative engineering projects), it will be possible in the future to make better use of the potential of collaborative engineering (Fig. 10, right). However, this does not necessarily mean that the added value will benefit all current participants in the value chain.

It is still too early for a strategic roadmap towards collaborative engineering. From the discussion with the experts, however, it became clear that the vision of the digital twin must be significantly expanded in order to create suitable framework conditions for efficient collaborative engineering. However, other important technical, organisational, economic and legal challenges will remain.

6.1 The extension of the digital twin concept

Collaborative engineering requires not only new conceptual approaches at the discussed levels of technology, work organisation, economics, law and collaboration management, but must also be supported by digital tools. An extended digital twin is the core element to bring the different levels together. The virtual image of a product (or a plant or factory) is influenced by all levels of consideration discussed in this study, whereas the level of collaboration management has an indirect impactin terms of creating the necessary preconditions for collaboration.

Besides the more technical applications of digital twins, other applications can also have a special role to play in collaborative engineering. On the basis of extended digital twins, it is therefore conceivable to support the assessment of economic potential, which can be enormously important during the identification and planning phase of company collaboration. System operators can use suitable virtual images in order to estimate not only whether a new component, a new service or a new (sub)system will fulfil required characteristics, but possibly also to investigate what efficiency increases can be achieved through integration and what integration and operating costs must be expected.

In summary, the digital twin, which has so far been a purely technical-structural description, interacts with other influencing factors. The existing model of the digital twin should therefore be extended beyond the previous levels of consideration of technical aspects and (with some limitations) work organisation:

- Technical aspects: The digital twin of a product (or of a plant or factory) initially represents a virtual image of the elements and dynamics of its physical counterpart whose changes are continuously recorded during the course of the product lifecycle. The digital twin thus describes the technical properties of the respective physical counterpart over the course of time and bundles information from its own development and production via the integration of (sub)systems right through to its subsequent dismantling. Significant development potential can be opened up by exploiting the possibilities of system-wide optimisation on the basis of extended digital twins to a much greater extent than before in order to increase the efficiency of products, assets and factories. However, the general usability of digital twins for the quantitative simulation of product, subsystem and overall system behaviour must be further expanded, with the semantic integration of data and models playing an important role in this respect.
- Work organisation: Systems already exist today that take into account information regarding the expertise of individuals or other aspects of work organisation in digital twins of complex products and systems in order to enhance the human-machine organisation. One example is the possibility to map necessary qualification certificates in aircraft maintenance. The use of extended digital twins can significantly facilitate the targeted exchange of information, promote improvements of man-machine organisations and also support the development of an optimised process management in terms of work organisation.
- Economics: Simulations and forecasts based on virtual images and used, for example, for efficient technical design, commissioning or control, can already be used today, depending on the application, in order to assess the economic potential of products, product adaptations and services and to identify collaborative business and participation models on this basis. If corresponding virtual images of complex systems (for

example, production plants, chemical plants, etc.) suitable for quantitative simulations are available, the concrete effects of process adaptations, service integration or failure reductions can be analysed on the basis of simulation scenarios and then often be evaluated on the basis of economic parameters (cycle times, production rates). The potential benefit of predicting economic effects in this way is very high, especially for collaborative engineering, and can be realised by extending simulation possibilities on the basis of extended digital twins. However, this always presupposes that the economic parameters can be derived from technical parameters, which is often the case. Knowledge of the economic potential of assets, products, services or processes over their entire lifecycle is the ideal basis for designing business and participation models. Suppliers can also derive their business model from this.

- Legislation: The legal framework provides the basis for the design of the digital twin.. Consequently, only information and usable operating data that is in compliance with the applicable regulations and laws can be stored in the digital twin and made available to third parties. Furthermore, the digital twin may contain information on authorship and related information as to who is entitled to remuneration from certain cases of use or who may use certain data of the digital twin and for what kinds of purposes (for example, a component manufacturer in aggregated form without a real-time stamp). In view of international business partnerships, the potential relocation of workplaces or the trade in products, assets or services, this has consequences for the design of (extended) digital twins.

On the basis of the digital twin, a cross-system understanding can be developed which, however, takes into account aspects of work organisation, economics and – to a lesser extent – legal aspects above and beyond technical considerations. The result is the role model of the extended digital twin (Fig. 11). Exploiting the resultant potential and added value calls for close interdisciplinary co-operation. Examples are shown in Table 2.

	Creation	Operation	Redesign	Recycling
Technical aspects	Simulation-supported initial design, consideration of real operating data and requirements	Adaptive process control, predictive maintenance	Redesign, retrofit, production conversion	Documentation of material data for dismantling and reuse
Work organisation	Manufacturing organisation, building competencies	Maintaining competencies, occupational health and safety, process planning	Change management	Occupational health and safety in the context of contained hazardous substances
Economics	Simulating new business models	Identifying, assigning and evaluating operating costs and performance indicators	Simulating new business model/market expansion	Revenue from reuse
Legislation	Data protection, environmental law (for example, REACH[2])	Employee rights	New market = different law	Regulations for the disposal of pollutants

Table 2: Examples of possible use of the extended virtual image for the levels of examination

2 REACH = Registration, Evaluation, Authorisation and restriction of CHemicals (Regulation (EC) No 1907/2006)

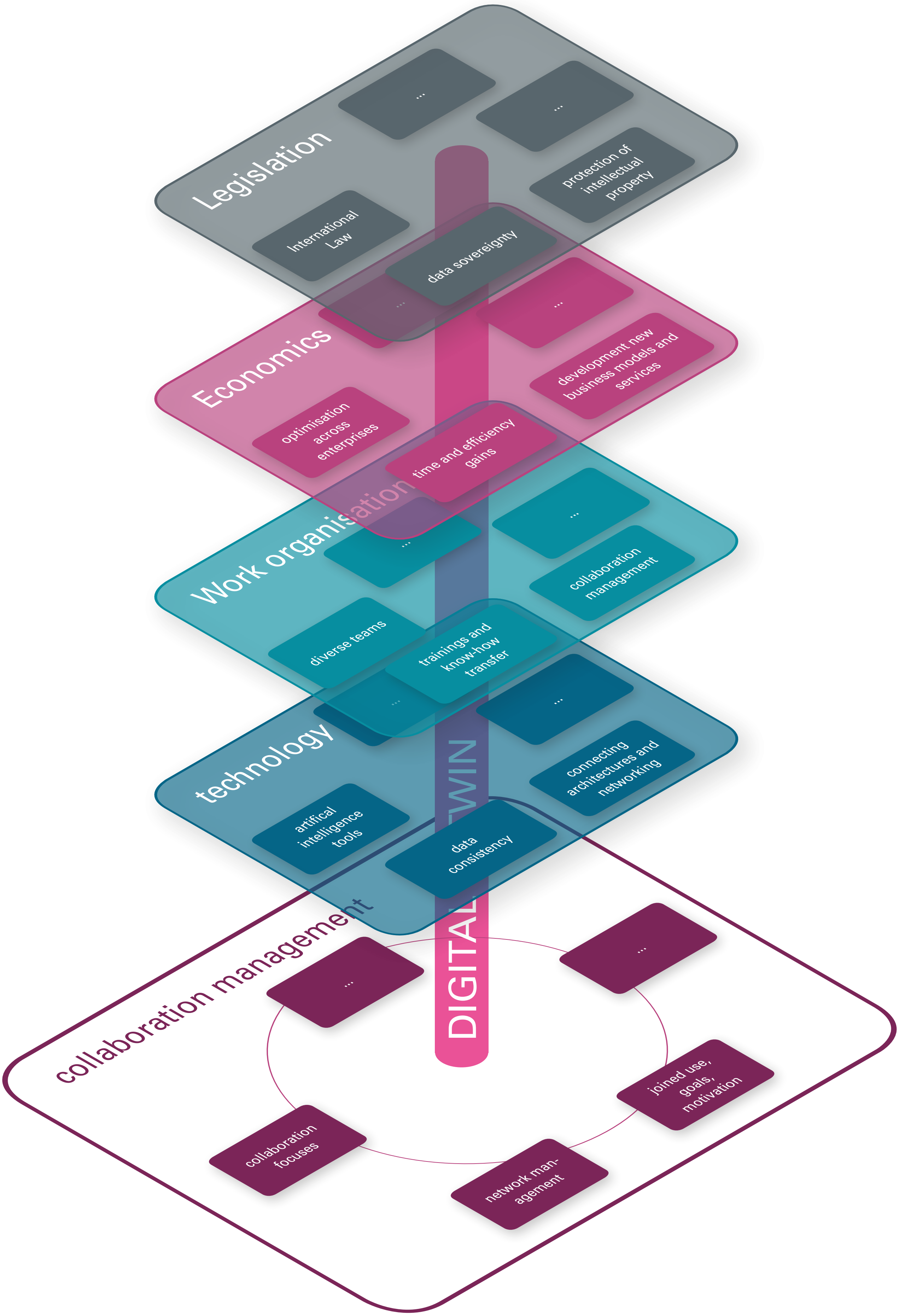

Fig. 11: Extended digital twin (© iit)

6.2 Open challenges

Due to the legal, economic and technical reasons discussed above, classical platform concepts appear to be of limited suitability for engineering tasks beyond standardised activities and modular concepts.

On the technical level, complexity, interfaces, data volumes and consistency pose high demands which are already being addressed by academia, thus gradually expanding the potential and field of application. One particular challenge is still the required longevity of information, which in some cases exceeds current innovation cycles in information technology by more than one order of magnitude.

Some of the economic and legal framework conditions for collaborative engineering platforms have yet to be developed. With regard to global engineering processes, the highly internationalised legal framwork for copyrights and patents certainly represents a good starting position for global collaborative engineering processes.

Several questions will have to be answered in the future in order to enable the broad success of collaborative engineering. The presentation of these unanswered questions deliberately ignores the distinction between technology, work organisation, economics and legislation. Their order is of no significance.

- The existing state of scientific and technical work in the standardisation of exchange formats and the establishment of semantics and reference architectures still limit its use in industrial environments. The nature of these exchange formats has a significant impact on the market, so that both technical and industrial policy aspects must be taken into account. Standardisation is necessary and should be strengthened, in particular, at the international or European level.
- The potential and the use of artificial intelligence methods in engineering processes and the interaction of AI with humans in this process need to be investigated further. Due to the relatively limited availability of data and the widespread use of engineering models in engineering, ‘hybrid’ AI approaches and methods that exploit the availability of engineering models should be explicitly included, also with respect to the optimisation of the efficiency of the overall systems..
- It is important to develop an understanding of collaborative engineering processes where an international “follow-the-sun partnership model” is more successful and where the advantages of regional collaboration dominate. The complexity of tasks, their modularisation, the share of creative sub-solutions and the need for coordination between the technical domains appear to be key influence factors.

- Engineering is just one part of the value chain in the respective industries. A business model describing how collaborative engineering as a special innovation process will be embedded in value chain networks in the future and how it will interact with other phases of the value chain can help to identify added value. Business and incentive models are needed as a precondition for an extended digital twin. The analysis of business or incentive models for the preventive provision of resources (computing capacity, interfaces, etc.) for still undefined services in decentralised provider structures (non-OEM systems) has yet to be carried out.
- To ensure the success of collaborative engineering, the questions surrounding data sovereignty and IP law still need to be answered in order to eliminate existing concerns among large groups of potential users. Best-practice examples or guidelines would have to be provided to demonstrate how collaborative engineering can be made contractually and economically sustainable for all parties involved. This applies not only to the handling of data, but also to the handling of IP rights that are introduced in collaborative engineering processes or emerge as a result of partnerships. The handling of data and IP rights must be considered in an international context.

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